Characterizing the Variability of Phosphorus Export from Urban Stormwater for Potential Treatment Strategies

2018-2019 Sampling Results

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1. Introduction

Seasonal degraded water quality conditions in the Charles River, MA, is largely due to eutrophication resulting from an excess of nutrients, such as Nitrogen and Phosphorus, altering the natural ecological balance and resulting in excessive primary production. Even though Nitrogen is the key limiting nutrient in coastal primary production (Howarth & Paerl, 2008; Ryther & Dunstan, 1971), Phosphorus has been identified as the limiting chain link for eutrophication in many fresh surface water systems. However, the presence of bioavailable Phosphorus in natural water system is typically limited. The major influx of Phosphorus in an urban watershed is surface runoff from impervious areas. In general, urbanization increases the area of impervious surfaces contributing to the washing off of particulate and dissolved Phosphorus (Petrone, 2010). This increase in Phosphorus loading in urban watersheds due to changes in land use can be comparable to the agricultural loading of Phosphorus in rural watershed (Omernik, Abernathy, & Male, 1981). Several studies have linked the increase in impervious surface area to increased concentrations of Phosphorus in stormwater runoff. Thus, the U.S. EPA places restrictions on the discharge of phosphorus from point sources in many urban watersheds where receiving waters are impaired.

For the Charles River, the Massachusetts NPDES Phase II MS4 permit requires that communities not exceed annual phosphorus loadings specified in the Total Maximum Daily Load analysis (Massachusetts Department Of Environmental Protection et al., 2007). This regulation requires the City of Cambridge to reduce its total phosphorus export by roughly 65% of its current estimated contribution. To meet the Total Maximum Daily Load (TMDL) allocations for phosphorous, the City developed and is currently executing projects and tracking tools for reducing phosphorus such as structural and non-structural Best Management Practices to treat stormwater prior to its entering receiving water. While treating all stormwater runoff is not possible, one potential approach is to use a flow control system to selectively divert portions of stormwater with high Phosphorus content to treatment systems or to the sewer for treatment at the Deer Island Wastewater Treatment Plant (Bedoya, Pisano, & O'Riordan, 2014). For example, a flow diversion device could be triggered by velocity, where velocities can be set to capture relevant shear stress values for the particulate material moving in stormwater pipes. This requires an understanding of total phosphorus and total solids particle size distributions. In this study, we focus on characterizing total phosphorus and solids concentrations associated with different particle size fractions in event stormwater runoff from select sampling sites distributed throughout the City of Cambridge, MA. Stormwater samples were collected roughly each hour during nine storm events from four different watershed with distinct land use and land cover patterns over the period June 2018 through June 2019. Results and analysis of these samples are presented in this report.

2. Background

The Charles River drains approximately 308 square miles distributed throughout 35 communities serving as a recreational and socio-economic center. Before 1900, the Charles was mostly used for transportation of goods and a source of power for nearby industries. The construction of dams to produce hydropower not only caused flooding, but also changed the natural habitat pattern of the migratory fish and hampered the assimilatory capacity of the river. Construction of the dam near the mouth of the estuary created a freshwater lake presently known as the Lower Charles River Basin. With the expansion of urban development, industrial, domestic and combined sewer overflows (CSOs) discharging into the Lower Charles lead to degraded water quality. Efforts have been taken to eliminate these outflows and separate the existing CSOs into sanitary and stormwater sewers, for treatment of the sanitary flows. While the overall water quality in the Lower Charles River continues to improve, water quality still degrades during wet weather conditions due to pollutant wash-off (e.g., phosphorus) by the stormwater leading to algal blooms in the summer (Figure 1). In general, roughly half of the phosphorus in the river comes from industrial, commercial, and dense residential areas with high impervious cover and enters the Charles River via stormwater runoff, while the other half is contributed from WWTF, open land, forest, agriculture, low and medium density residential area (Massachusetts Department Of Environmental Protection et al., 2007). Thus, the MS4 permit is designed to reduce these point load discharges. This permit is based on the TMDL of Lower Charles River which uses Chlorophyll-a as a surrogate water quality target and considers

Figure 1: Algal bloom in Lower Charles River,2019

Phosphorus to be the primary pollutant of concern responsible for the proliferation of undesirable cyanobacteria (blue-green) algae species in the Basin. Moreover, to design a stormwater diversion system for reducing Phosphorus loading, total solids load needs to be considered. Increased particulate total solids increase turbidity of the receiving water system that will block the sunlight, decrease water temperature, reduce primary production and destroy the overall ecosystem. Failure to remove total solids might also lead to upstream flooding by clogging at the end of the pipe. In an urban watershed, the release and transport of particle of various sizes is related to the rainfall and runoff intensity. The size of watershed and its surface conditions/material contribute to runoff magnitudes and the resulting total solids concentrations in stormwater. This particulate material is also known to transport trace metals (e.g., lead, copper, cadmium, zinc), polycyclic aromatic hydrocarbon (PAH), phosphorus, nitrogen etc.(Legret & Pagotto, 1999).

3. Methods and Materials

3.1 Study Site

In this study, storm water samples are collected from four drainage area with different land use characteristics (i.e., mostly residential and commercial) in the City of Cambridge, MA (Figure 2).

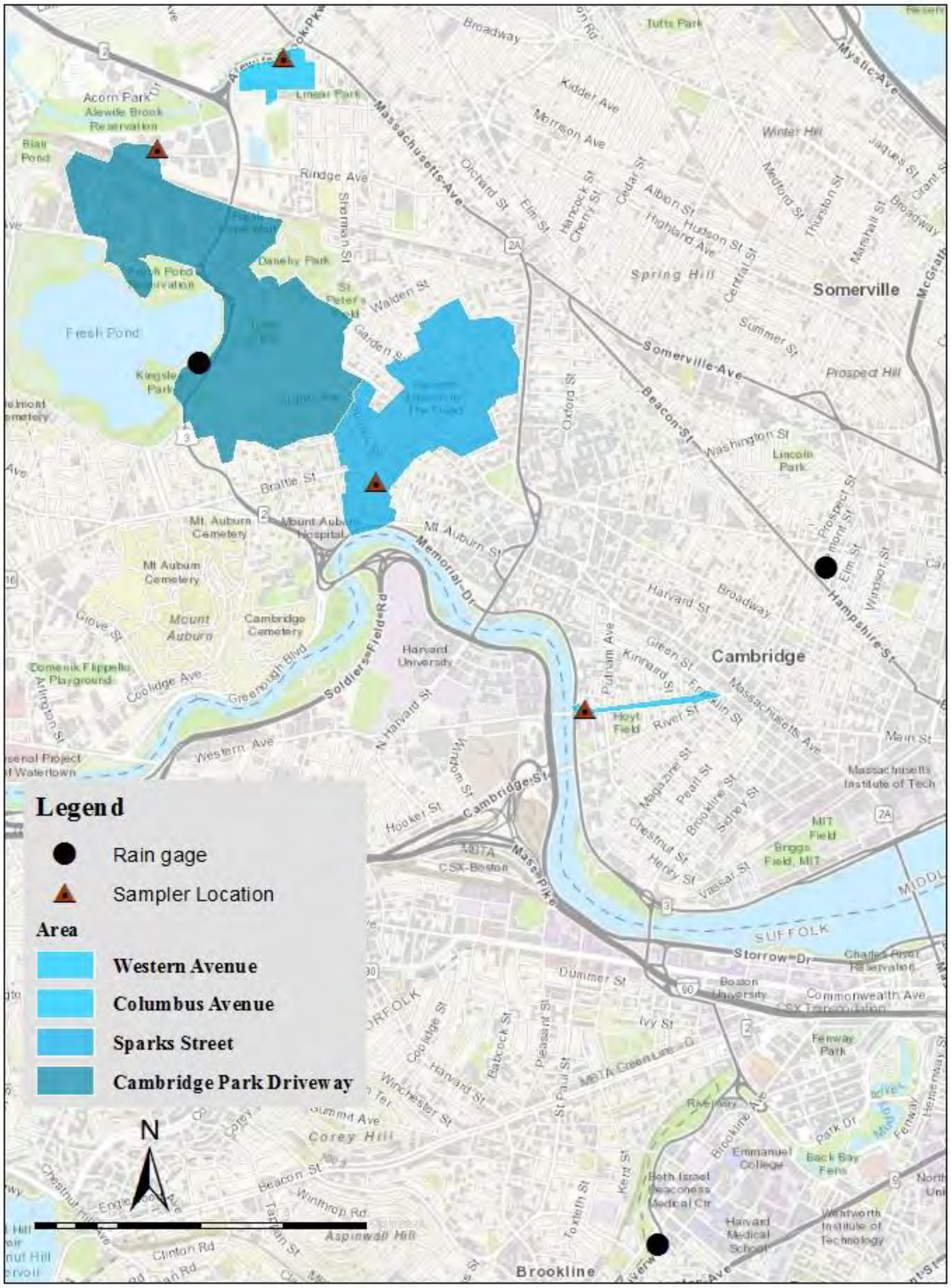


Figure 2: Study Sites

These sites were selected based on their existing stormwater sampling infrastructure (i.e., discussed below). Among the sites, Cambridge Park Drive, Columbus Avenue and Sparks Street have a mix of residential and commercial development, while Western avenue consists of mostly roadway drainage. Samples are also collected from a constructed stormwater wetland in Alewife to observe its performance in attenuating nutrient loads. The summary of the site characteristics is shown in Table 1.

Table 1:Site Characteristics

Sites	Land cover & Land use	Impervious area (%)	Impervious area (Acre)	Drainage Area (Acre)
Cambridge Park Drive	Urban Commercial, Residential	64	237	372
Sparks Foster Street	Urban Residential	58	115	198
Western Avenue	Urban Road	84	7.12	8.52
Columbus Avenue	Urban Commercial, Residential	69	17	24.2

3.2 Sample collection and analysis

Composite (1-hour or 45-minute) stormwater samples for six (6) storm events and non-composite samples of 30 minutes interval for three (3) events were collected from June 2018 to June 2019. The composite samples were collected at an interval of 15 minutes. The stormwater flows were sampled using Teledyne ISCO 6712FR Refrigerated Autosamplers with vinyl suction lines with a polypropylene strainer attached to the end. Each autosampler (Figure 3) was fitted with twenty-four 1L polyethylene sample bottles. The sample bottles were acid washed before each of the sampling events. A peristaltic pump draws the water sample through the strainer. Pre- and post-sampling purging ensures minimum cross-contamination between samples. The triggering of the ISCO sampler was controlled by clock time. The time to initiate the sampling procedure was determined based on the weather forecast prior to the event. No other sites had dry weather flow except for Sparks street. Water samples were preserved in a 4˚C refrigerator immediately after collection. Additional event data such as flow, velocity and depth of flow was collected using a velocity meter at an interval of 15 minutes. A Sonde Multiprobe was used to continuously monitor a suite of sensor data: pH, temperature, salinity, specific conductivity and turbidity at one site: Cambridge Park Drive, which is the largest of the four drainage areas.

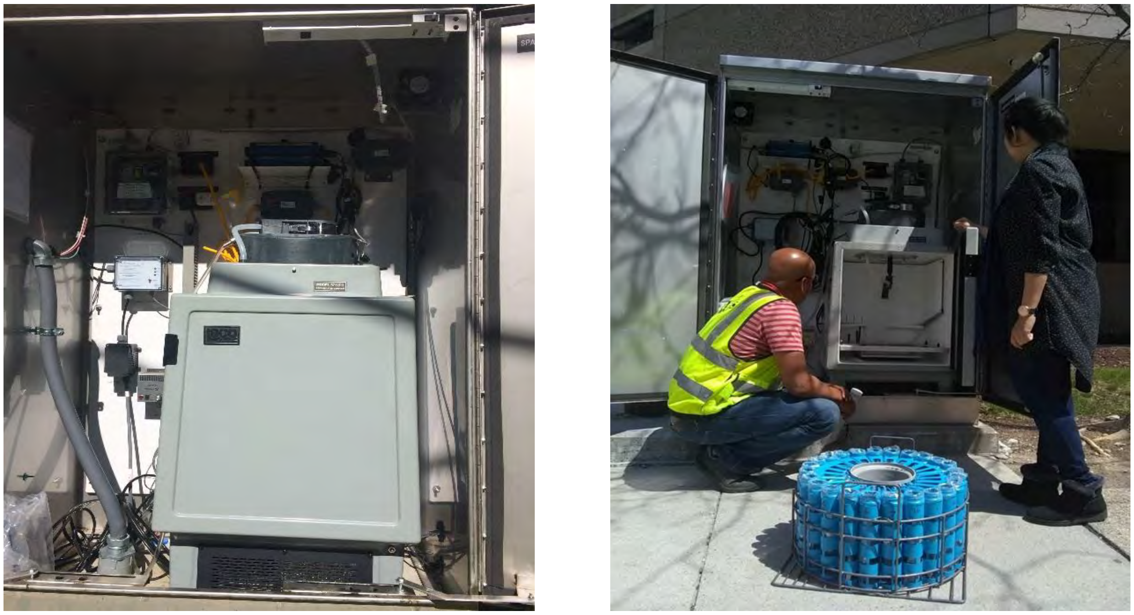


Figure 3: (left) ISCO automated sampler and (right) stormwater sampling and monitoring

Samples collected from June 2018 to December 2018 were divided into six subsamples based on particle size: unfiltered, filtered through 250, 100, 50, 25, and 10 μm filters. In 2019, samples were divided into unfiltered, filtered through 100, 50, and 25 μm and dissolved phosphorus. The initial analysis of 6 events in 2018 showed not much difference in concentration of Phosphorus associated with 250 and 100 micron filtered sample. Vaze and Chiew's study with grab sample showed that most of the particulate Phosphorus was associated with particles less than 150 micron (Vaze & Chiew, 2004). The samples were then analyzed for total phosphorus using Hach kits (Total Phosphorus by the PhosVer® 3 Ascorbic Acid method with Acid Persulfate Digestion: EPA Compliant Method 4500-P E. Product # 2742645). The samples were also measured for total solids according to APHA Method 2540- B (Total Solids Dried at 103–105°C).

3.3 Quality assurance and quality control (QA/QC)

Quality assurance and quality control (QA/QC) were ensured by the measurement of sample duplicate and reagent blanks. Holding time for total Phosphorus and total solids measurement was 28 and 7 days, respectively. Sub-samples were preserved at a pH of less than 2 and refrigerated at 4°C. Reagent blanks were measured in each batch of analysis and used to adjust the spectrophotometer reading. Standard curve was produced for each batch of total Phosphorus analysis. To determine the unknown concentration from the absorbance value of the spectrophotometer, standards of known concentrations are used to produce a standard curve which is used as a reference. The correlation coefficients (R) for the standard curves were all greater than 0.995. For total Phosphorus measurement, each sub-sample was analyzed in duplicate. Thus, for the 1,661 sub-samples obtained, a total of 3,322 sub-samples were analyzed for TP. For total solids, every tenth sample was run in duplicate. For all duplicate samples, the relative percentage difference (RPD) between sample duplicate pairs was determined:

$$RPD = \frac{|D_1 - D_2|}{(D_1 + D_2)/2} * 100\%$$

where, D_1 is the measured value of first duplicate and D_2 is the measured value of second duplicate. Overall, the RPD between sample duplicates ranged between 0-18%. Percent recovery values were within 90-110%. The results and analysis reported herein are based on the mean of each duplicate pair for TP and a combination of individual sample results and, when available, the mean of the duplicate pair for TS. Table 2 provides an overview of the experiment methods.

Table 2:Summary of Experimental Methods

Analyte and unit of measure	Laboratory	Technique	MDL	MRL	Method	Reference
Total Solids (mg/L)	Northeastern University	Gravimetric	-	9-5200	Standard Method 2540-B	Standard Method,2005 (APHA)
Total Phosphorus (mg-P/L)	Northeastern University	Spectrophotometer/ Colorimetric	0.01	0.02-4.6	USEPA 365.2	Hach Company,1998

3.4 Land cover and land use

In order to characterize land cover and land use patterns, 30m x 30m resolution land cover data were obtained from MassGIS Land Cover Database 2016 ("MassGIS's Online Mapping Tool (OLIVER)," 2016).The data included categories for open water, developed area (low, medium, high density), forest, herbaceous/grasslands, emergent herbaceous wetlands. The City of Cambridge GIS Impervious Surface 2010 dataset was used to estimate the impervious areas. This dataset has a resolution of 1m x 1m and includes buildings, roads, parking lots, brick, asphalt, concrete, man-made compacted soil or material such as mining or unpaved parking lots (no vegetation present) as impervious surface. These datasets were overlaid with City of Cambridge study area boundaries to extract site specific information. Table 3 lists the fractions of land cover and land use classes for each study area.

Table 3:Land cover distributions

MassGIS 2016 land cover classification	Cambridge Park (Acre)	Western Avenue (Acre)	Columbus Avenue (Acre)	Sparks Street (Acre)
Commercial	80.7	0.2	7.5	2.0
Industrial	56.2	5.9	5.6	59.4
Mixed use, primarily residential	4.2	0.0	0.0	0.6
Open land	19.1	0.2	0.8	2.2
Residential - multi-family	85.6	1.8	5.2	46.5
Residential - single family	36.6	0.2	2.6	74.1
Forest	89.9	0.2	1.4	13.6
Developed Open Area and Impervious	17.0	5.9	5.6	59.3
Water	0.0	0.0	0.0	0.1
Total Area (Acre)	372	8.52	24.2	199

3.5 Event Summary

Runoff samples for nine (9) storm events were collected between June 2018 and June 2019. The number of samples and the interval of sampling were decided based on the weather forecast. Data from three different rain gauges were used to estimate total rainfall. For Cambridge Park Drive, Columbus Avenue and Sparks Foster Street, the rain gauge near Fresh pond gate, Cambridge, MA (USGS Site ID: 422302071083801) was used. For Western Avenue, Cambridge Department of Public Works rain gauge was used for samples collected between June 2018 and November 2018 and USGS Muddy river, MA (USGS Site ID: 01104683) was used for samples collected between March 2019 and June 2019 when the rain gauge at the CDPW was not operative. NCEP/CPC Four Kilometer Precipitation Set, Gauge and Radar data was also used to compare with the available rain gauge data. Table 4 provides a summary of the sampling events and total rainfalls.

Table 4: Summary of the sample collection

Event	Start Date &Time	End Date &Time	Site	Composite Samples Collected	Total Rainfall (in)
1	06-04-18 05:30	06-04-18 15:30	Cambridge Park*	10	0.49
	06-04-18 05:30	06-04-18 15:30	Columbus Avenue*	10	
	06-04-18 06:30	06-04-18 15:30	Sparks Foster*	9	
	06-04-18 06:30	06-04-18 15:30	Western Avenue**	6	0.69
2	06-28-18 07:00	06-28-18 15:00	Cambridge Park*	8	1.24
	06-28-18 07:00	06-28-18 15:00	Columbus Avenue*	8	
	06-28-18 07:00	06-28-18 15:00	Sparks Foster*	8	
	06-28-18 07:00	06-28-18 13:00	Western Avenue**	6	1.28
3	08-11-18 09:00	08-11-18 17:00	Cambridge Park*	8	1.07
	08-11-18 09:00	08-11-18 16:00	Western Avenue**	7	0.43
4	09-10-18 17:00	09-11-18 05:00	Cambridge Park*	12	1.10
	09-10-18 17:00	09-11-18 05:00	Western Avenue**	12	1.24
5	11-09-18 19:00	11-10-18 02:30	Cambridge Park*	10	1.24
	11-09-18 19:00	11-10-18 02:30	Columbus Avenue*	10	
	11-09-18 20:00	11-10-18 02:45	Western Avenue**	9	1.38
6	12-21-18 19:00	12-22-18 10:00	Cambridge Park*	10	1.24
	12-21-18 19:00	12-22-18 10:00	Columbus Avenue*	8	
7	03-22-19 03:00	03-22-19 14:30	Cambridge Park*	24	0.65
	03-22-19 03:00	03-22-19 13:00	Columbus Avenue*	21	
	03-22-19 03:00	03-22-19 14:30	Western Avenue***	16	0.68
8	05-13-19 18:00	05-14-19 04:00	Cambridge Park*	21	0.56
	05-13-19 18:00	05-14-19 03:00	Columbus Avenue*	19	
	05-13-19 18:00	05-14-19 04:00	Western Avenue***	14	0.57
9	06-11-19 12:00	06-11-19 08:30	Cambridge Park*	18	0.67
	06-11-19 12:00	06-11-19 08:30	Sparks Street*	18	

*USGS Site ID: 422302071083801, Fresh pond gate, Cambridge, MA rain gage.
** Cambridge Department of Public Works rain gage.
*** USGS Site ID: 01104683, Muddy river, Brookline, MA rain gage.

3.6 Rainfall Data Analysis

In this study, total rainfall from two different sources (USGS fresh pond rain gage and CDPW rain gage) are obtained and the rainfall totals area calculated from the 15-minute interval rain gage data. Samples were collected from rainfall events with total rainfall greater than roughly 0.5 inches. The peak intensity of these events ranged from 0.2 to 1.4 in/hr. Event durations ranged from 4 to 16.5 hours. Antecedent dry periods were defined as the duration between the beginning of the subject event and the end of the last event that generated runoff (at least 0.1 inches of rainfall). Table 5 provides a summary of the rainfall characteristics for each event.

Table 5: Summary of hydrologic, sampling -based indices for the events analyzed

	Date	Total Rainfall	Mean Rainfall intensity	Peak rainfall Intensity	Duration	Antecedent dry period
Based on USGS gauge		(in)	(in/hr)	(in/hr)	(hours)	(hours)
Event 1	06-04-2018	0.49	0.05	0.20	4.0	349.20
Event 2	06-28-2018	1.15	0.11	1.36	7.5	76.25
Event 3	08-11-2018	1.06	0.10	1.16	5.5	35.50
Event 4	09-10-2018 to 09-11-2018	0.97	0.09	0.36	12.3	458.40
Event 5	11-09-2018 to 11-10-2018	1.08	0.11	0.44	7.3	70.50
Event 6	12-21-2018 to 12-22-2018	0.65	0.06	0.28	10.3	102.48
Event 7	3-22-2019	0.56	0.05	0.36	11.3	149.04
Event 8	5-13-2019 to 5-14-2019	0.63	0.06	0.22	16.5	21.12
Event 9	6-11-2019	0.67	0.07	0.46	8.5	312.00
Based on Cambridge DPW gauge						
Event 1	06-04-2018	0.69	0.09	0.27	7.67	349.20
Event 2	06-28-2018	1.14	0.16	1.32	7.33	3.50
Event 3	08-11-2018	0.63	0.14	0.63	4.67	35.50
Event 4	09-10-2018 to 09-11-2018	1.37	0.11	0.48	13.33	458.40
Event 5	11-09-2018 to 11-10-2018	1.51	0.19	0.48	8.00	70.50

4. Results and Discussion

4.1 Total Phosphorus Concentrations

The temporal variability of Phosphorus concentration associated with different particle size can be observed from figure 4-7. Among the runoff sample collection sites, Cambridge Park Drive drained the largest watershed area. The maximum observed unfiltered phosphorus concentration was 4.58 mg-P/L and minimum was 0.05 mg-P/L. The peak concentration was observed at or immediately after the peak rainfall. Since the peak concentration is related to time of travel and rainfall intensity, the timing of the maximum concentration can be explained by the above watershed area and rainfall characteristics. Previous studies have tied the application of de-icing chemicals and the accumulation of pollutants in the snowpack during the winter period to an increase in stormwater pollutant load (Valtanen, Sillanpää, & Setälä, 2014). A study in Minnesota showed that decomposition of accumulated leaf litter during winter contributes almost half of the annual total dissolved phosphorus loading(Bratt et al., 2017). The situation gets worst during a rain-on-snow event, flushing of soluble and particulate phosphorus from the impervious surface and snowpack increases the overall pollutant load(Oberts, 1994). Our study shows that even though planning of urban runoff pollutant reduction is based on summer water quality data, a significant attention needs to be paid to the snowmelt pollutant runoff. Figure 4 shows rainfalls and event concentrations for each particle size class.

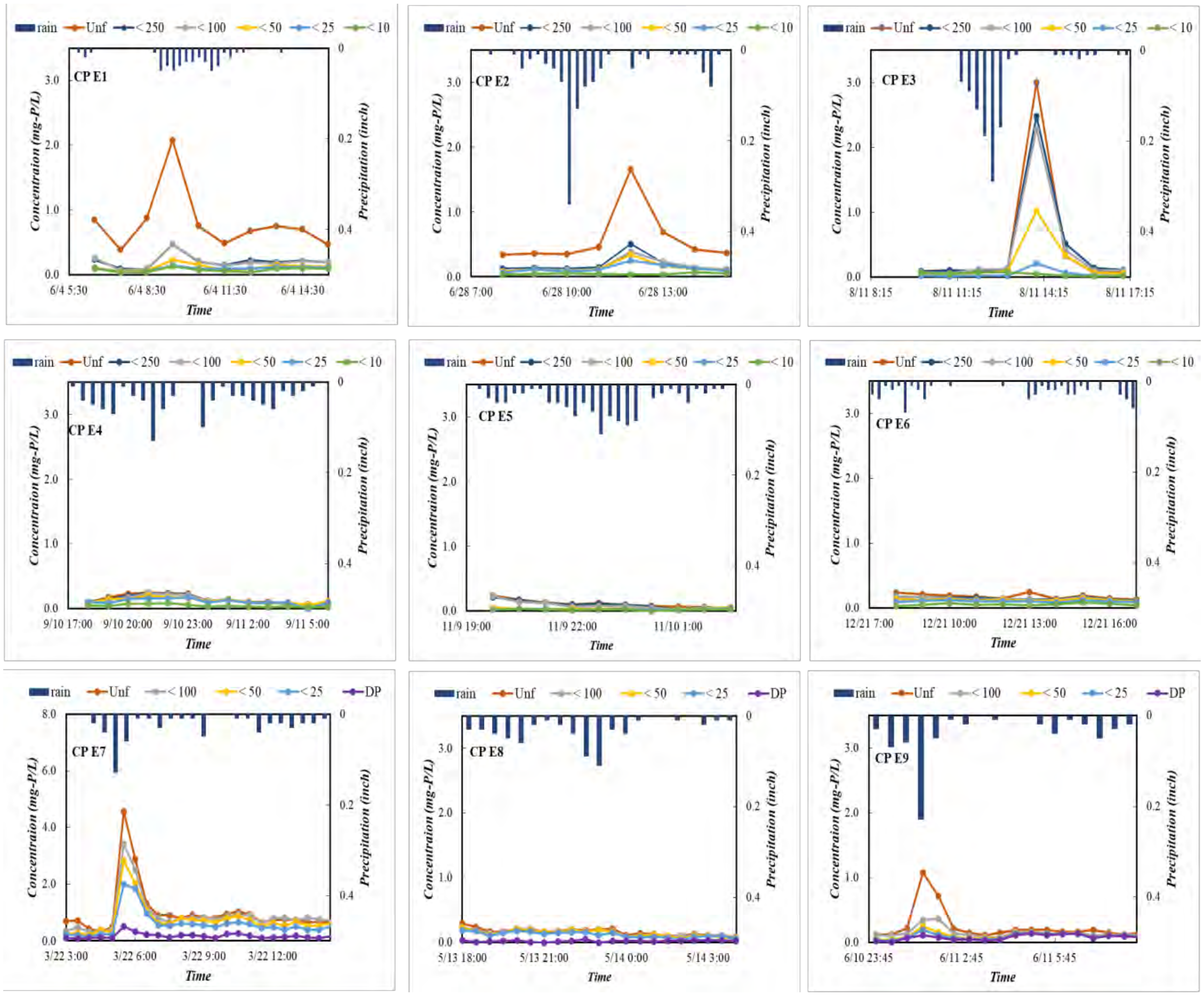
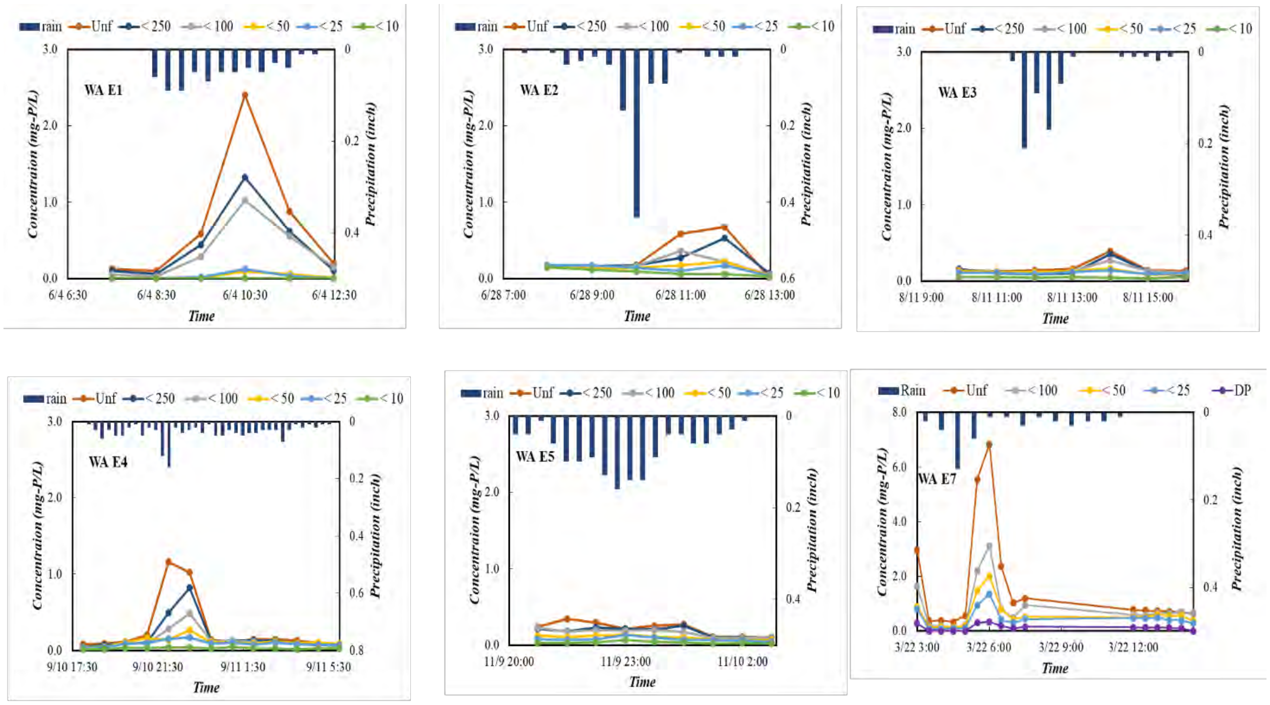


Figure 4: Cambridge Park Drive event rainfall and phosphorus concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 μm filters)

Compared to other sites, Western Ave has the smallest watershed. However, the phosphorus concentration of this site is high due to its being almost completely impervious and having short travel distances to the storm drain. The storm water from this area drains the nearby roadway. Only the dirt, leaves and roadway surface pollutants get washed into the storm sewer during storm events. However, at the end of the trunk sewer, backflow from the Charles River was observed.

Figure 5 shows rainfalls and event Phosphorus concentrations for each particle size class of Western Avenue.



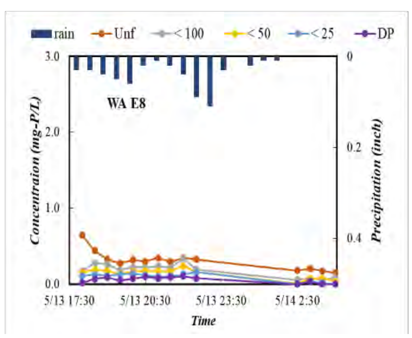
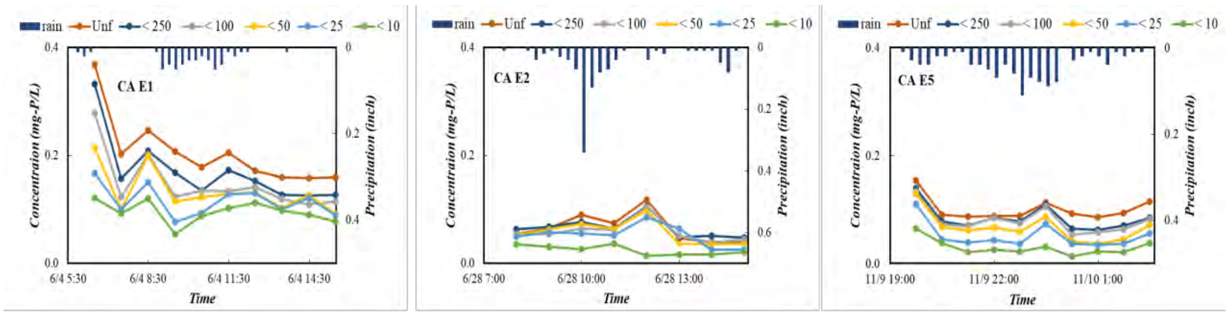


Figure 5: Western Avenue event rainfall and phosphorus concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

For Columbus Avenue, moderately low phosphorus concentrations are associated with different particle size distributions. Figure 6 shows rainfalls and event Phosphorus concentrations for each particle size class of Columbus Avenue.

Sparks Foster storm water samples have low Phosphorus concentrations for events 1 and 2. Due to technical difficulty, samples from that site could not be collected for events 3-8. The high concentration observed in event 9 might be due to the fact that the storm sewer is relatively flat and tends to accumulate pollutants over time. Compared to event 9, event 1 had smaller pollutant



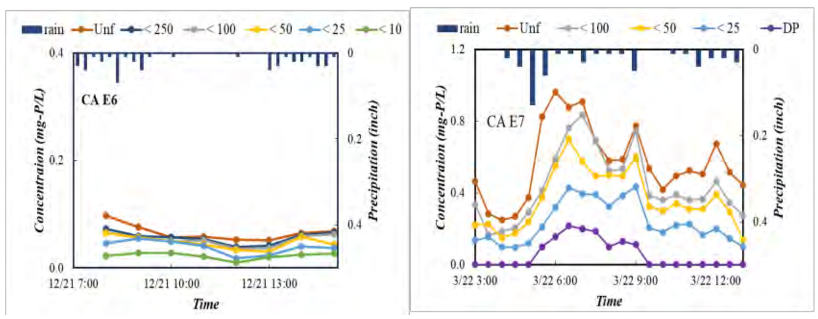


Figure 6: Columbus Avenue event rainfall and phosphorus concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

concentration even though the antecedent dry days were long in both events. This can be explained by the intensity of the rainfall of event 1, that was not strong enough to initiate a high flow condition to dislodge the accumulated debris in the sewer. Figure 7 shows rainfalls and event Phosphorus concentrations for each particle size class of Sparks Foster site.

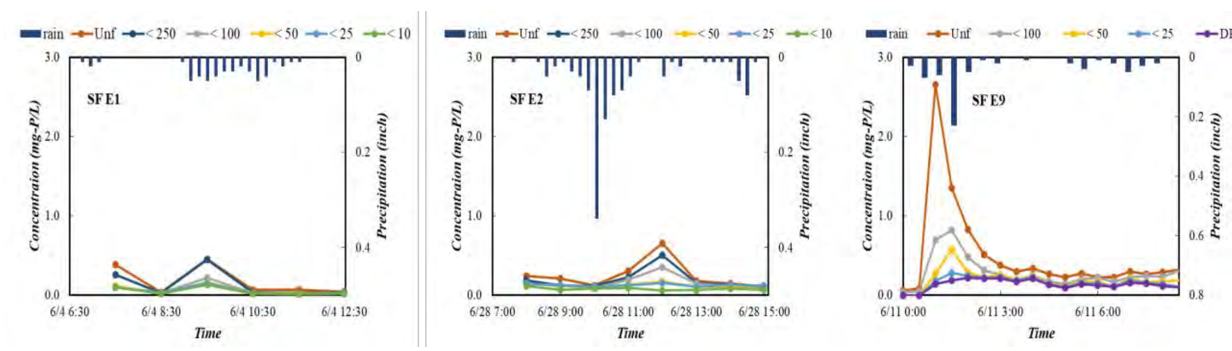


Figure 7: Sparks Foster event rainfall and phosphorus concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters).

Tables 6-9 provide a summary of total phosphorous concentrations for all nine sampled events. In the Tables, event concentration time series are represented as minimum, maximum, mean and median concentrations.

Table 6:Summary of Phosphorus Concentrations for Events 1-6 at Cambridge Park Drive and Western Avenue

		Cambridge Park Drive						Western Avenue					
		Unf.	**< 250 μm**	**< 100 μm**	**< 50 μm**	**< 25 μm**	**< 10 μm**	**Unf.**	**< 250 μm**	**< 100 μm**	**< 50 μm**	**< 25 μm**	**< 10 μm**
	Unit	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
Event 1	Minimum	0.39	0.09	0.07	0.05	0.05	0.04	0.10	0.06	0.03	0.00	0.00	0.00
	Maximum	2.08	0.48	0.47	0.23	0.15	0.13	2.40	1.32	1.03	0.09	0.13	0.00
	Mean	0.80	0.21	0.20	0.12	0.10	0.08	0.71	0.44	0.35	0.03	0.03	0.00
	Median	0.73	0.20	0.19	0.12	0.10	0.09	0.39	0.27	0.21	0.01	0.01	0.00
Event 2	Minimum	0.35	0.10	0.08	0.08	0.06	0.03	0.02	0.07	0.05	0.03	0.04	0.03
	Maximum	1.66	0.51	0.38	0.35	0.26	0.07	0.68	0.53	0.36	0.22	0.18	0.15
	Mean	0.58	0.19	0.16	0.14	0.13	0.04	0.29	0.23	0.18	0.14	0.13	0.08
	Median	0.40	0.13	0.11	0.12	0.11	0.04	0.17	0.17	0.17	0.15	0.16	0.07
Event 3	Minimum	0.06	0.09	0.05	0.05	0.02	0.01	0.13	0.06	0.11	0.09	0.09	0.04
	Maximum	3.00	2.49	2.28	1.02	0.21	0.08	0.39	0.35	0.27	0.17	0.14	0.06
	Mean	0.49	0.46	0.41	0.22	0.05	0.04	0.18	0.14	0.15	0.12	0.11	0.05
	Median	0.10	0.12	0.11	0.07	0.02	0.05	0.14	0.10	0.14	0.12	0.11	0.05
Event 4	Minimum	0.07	0.05	0.04	0.06	0.00	0.02	0.07	0.04	0.04	0.03	0.03	0.02
	Maximum	0.25	0.24	0.24	0.21	0.18	0.09	1.16	0.82	0.49	0.27	0.17	0.05
	Mean	0.15	0.14	0.13	0.13	0.11	0.05	0.27	0.18	0.13	0.11	0.09	0.03
	Median	0.12	0.12	0.12	0.12	0.10	0.04	0.13	0.11	0.10	0.11	0.09	0.03
Event 5	Minimum	0.05	0.03	0.03	0.02	0.01	0.00	0.10	0.09	0.09	0.06	0.04	0.02
	Maximum	0.24	0.22	0.24	0.06	0.04	0.03	0.34	0.25	0.23	0.14	0.13	0.07
	Mean	0.11	0.10	0.09	0.04	0.03	0.02	0.21	0.17	0.16	0.10	0.07	0.03
	Median	0.10	0.10	0.08	0.04	0.03	0.02	0.23	0.21	0.17	0.11	0.07	0.03
Event 6	Minimum	0.13	0.12	0.11	0.10	0.08	0.03	-	-	-	-	-	-
	Maximum	0.25	0.17	0.17	0.15	0.12	0.08	-	-	-	-	-	-
	Mean	0.18	0.14	0.14	0.12	0.10	0.05	-	-	-	-	-	-
	Median	0.18	0.14	0.13	0.12	0.10	0.05	-	-	-	-	-	-

Table 7:Summary of Phosphorus Concentrations for Events 7-9 at Cambridge Park Drive and Western Avenue

		Cambridge Park Drive						Western Avenue					
		Unf.	**< 250 μm**	**< 100 μm**	**< 50 μm**	**< 25 μm**	**< 10 μm**	**Unf.**	**< 250 μm**	**< 100 μm**	**< 50 μm**	**< 25 μm**	**< 10 μm**
	Unit		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
Event 7	Minimum		0.32	0.32	0.21	0.15	0.09		0.34	0.13	0.13	0.08	0.00
	Maximum		4.58	3.42	2.81	1.99	0.52		6.84	3.12	2.02	1.36	0.34
	Mean		1.02	0.90	0.75	0.59	0.17		1.62	0.86	0.62	0.45	0.12
	Median		0.77	0.80	0.63	0.51	0.16		0.75	0.66	0.51	0.41	0.12
Event 8	Minimum		0.09	0.08	0.06	0.05	0.00		0.34	0.13	0.13	0.08	0.00
	Maximum		0.30	0.24	0.23	0.19	0.05		6.84	3.12	2.02	1.36	0.34
	Mean		0.17	0.15	0.14	0.12	0.02		1.62	0.86	0.62	0.45	0.12
	Median		0.16	0.16	0.15	0.11	0.02		0.75	0.66	0.51	0.41	0.12
Event 9	Minimum		0.10	0.08	0.03	0.02	0.00		-	-	-	-	-
	Maximum		1.07	0.37	0.24	0.19	0.14		-	-	-	-	-
	Mean		0.24	0.15	0.10	0.09	0.08		-	-	-	-	-
	Median		0.16	0.13	0.10	0.09	0.08		-	-	-	-	-

Table 8:Summary of Phosphorus Concentrations for Events 1-6 at Columbus Avenue and Sparks Foster Street

		Columbus Avenue						Sparks Foster Street					
		Unf.	**< 250 μm**	**< 100 μm**	**< 50 μm**	**< 25 μm**	**< 10 μm**	**Unf.**	**< 250 μm**	**< 100 μm**	**< 50 μm**	**< 25 μm**	**< 10 μm**
	Unit	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
Event 1	Minimum	0.16	0.13	0.11	0.09	0.08	0.06	0.04	0.03	0.02	0.02	0.01	0.01
	Maximum	0.37	0.33	0.28	0.21	0.17	0.12	0.46	0.45	0.22	0.16	0.16	0.13
	Mean	0.21	0.17	0.15	0.13	0.12	0.10	0.14	0.11	0.06	0.05	0.04	0.04
	Median	0.19	0.16	0.13	0.13	0.11	0.10	0.07	0.04	0.04	0.02	0.02	0.02
Event 2	Minimum	0.04	0.05	0.04	0.04	0.03	0.01	0.11	0.11	0.09	0.09	0.11	0.06
	Maximum	0.12	0.11	0.11	0.10	0.09	0.04	0.66	0.50	0.35	0.17	0.16	0.11
	Mean	0.07	0.07	0.06	0.06	0.05	0.02	0.25	0.19	0.16	0.12	0.13	0.08
	Median	0.06	0.06	0.05	0.06	0.05	0.02	0.19	0.15	0.13	0.11	0.12	0.08
Event 3	Minimum	-	-	-	-	-	-	-	-	-	-	-	-
	Maximum	-	-	-	-	-	-	-	-	-	-	-	-
	Mean	-	-	-	-	-	-	-	-	-	-	-	-
	Median	-	-	-	-	-	-	-	-	-	-	-	-
Event 4	Minimum	-	-	-	-	-	-	-	-	-	-	-	-
	Maximum	-	-	-	-	-	-	-	-	-	-	-	-
	Mean	-	-	-	-	-	-	-	-	-	-	-	-
	Median	-	-	-	-	-	-	-	-	-	-	-	-
Event 5	Minimum	0.09	0.06	0.05	0.04	0.03	0.01	-	-	-	-	-	-
	Maximum	0.15	0.14	0.13	0.13	0.11	0.07	-	-	-	-	-	-
	Mean	0.10	0.08	0.08	0.07	0.05	0.03	-	-	-	-	-	-
	Median	0.09	0.08	0.07	0.06	0.04	0.02	-	-	-	-	-	-
Event 6	Minimum	0.05	0.04	0.04	0.03	0.02	0.01	-	-	-	-	-	-
	Maximum	0.10	0.07	0.07	0.06	0.05	0.03	-	-	-	-	-	-
	Mean	0.07	0.06	0.05	0.05	0.04	0.02	-	-	-	-	-	-
	Median	0.06	0.06	0.05	0.05	0.04	0.02	-	-	-	-	-	-

Table 9:Summary Phosphorus Concentrations for Events 7-9 at Columbus Avenue and Sparks Foster Street

		Columbus Avenue					Sparks Foster Street				
		Unf.	**< 100 μm**	**< 50 μm**	**< 25 μm**	**DP**	**Unf.**	**< 100 μm**	**< 50 μm**	**< 25 μm**	**DP**
	Unit	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
Event 7	Minimum	0.25	0.17	0.14	0.10	0.00	-	-	-	-	-
	Maximum	0.97	0.84	0.70	0.44	0.22	-	-	-	-	-
	Mean	0.57	0.44	0.37	0.24	0.06	-	-	-	-	-
	Median	0.53	0.39	0.33	0.21	0.00	-	-	-	-	-
Event 8	Minimum	-	-	-	-	-	-	-	-	-	-
	Maximum	-	-	-	-	-	-	-	-	-	-
	Mean	-	-	-	-	-	-	-	-	-	-
	Median	-	-	-	-	-	-	-	-	-	-
Event 9	Minimum	-	-	-	-	-	0.06	0.03	0.00	0.00	0.00
	Maximum	-	-	-	-	-	2.65	0.82	0.58	0.28	0.22
	Mean	-	-	-	-	-	0.49	0.28	0.19	0.15	0.14
	Median	-	-	-	-	-	0.29	0.23	0.18	0.15	0.14

4.2 Total Solids Concentrations

Total solids of different particle size fraction (unfiltered, <250 µm, < 100 µm, <50 µm, <25 µm and <10 µm) were measured. Figures 8-11 show the time series data of total solids associated with different particle size fractions at different sites. The maximum value of total solids was observed either at the beginning of an event or just after the maximum intensity rainfall. The higher solids concentration of event 6 can be explained by the rain-on-snow. It rained on the accumulated snow containing lose dirt and atmospheric particulate deposition which got transferred into the storm water by rainfall.

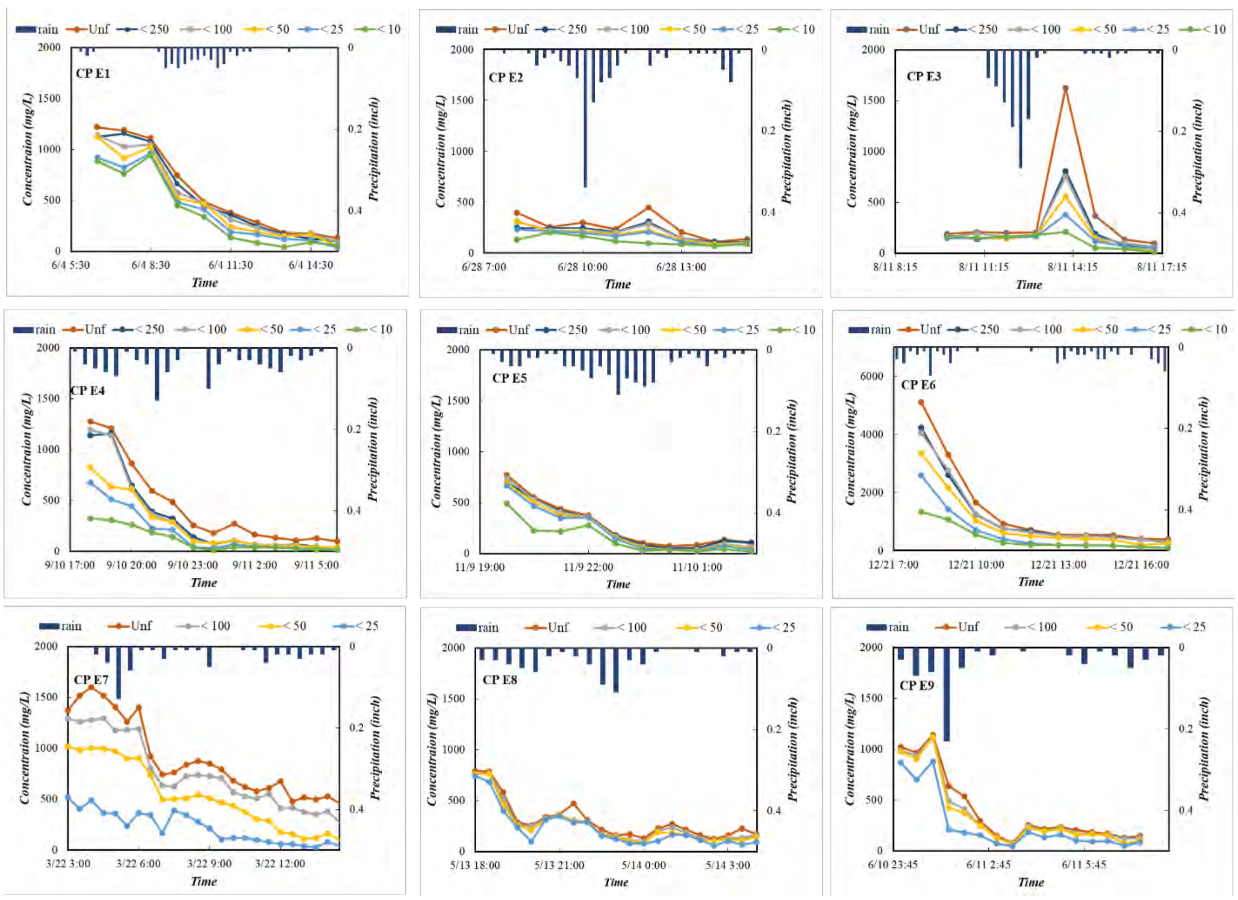


Figure 8: Cambridge Park Drive event total solids concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

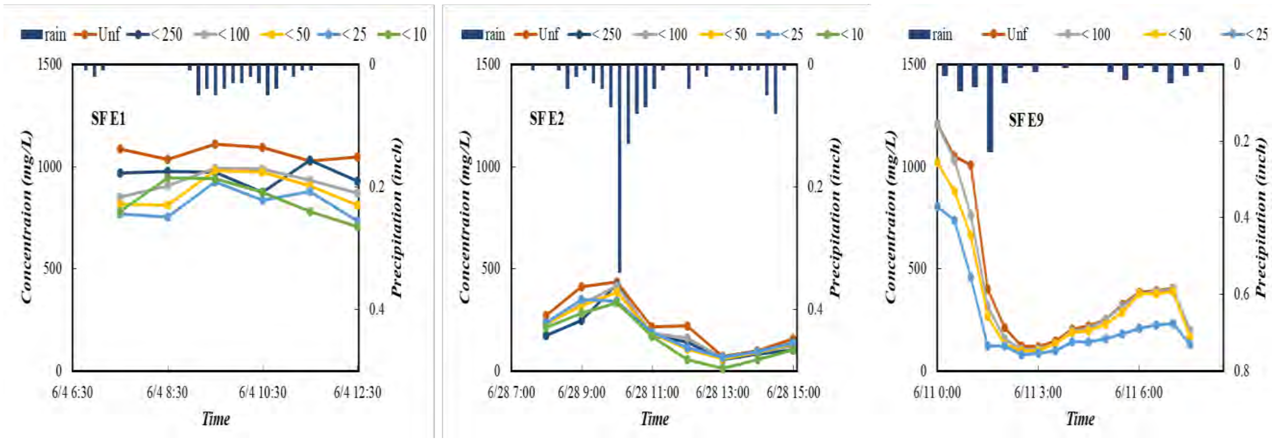


Figure 9: Sparks Street event total solids concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

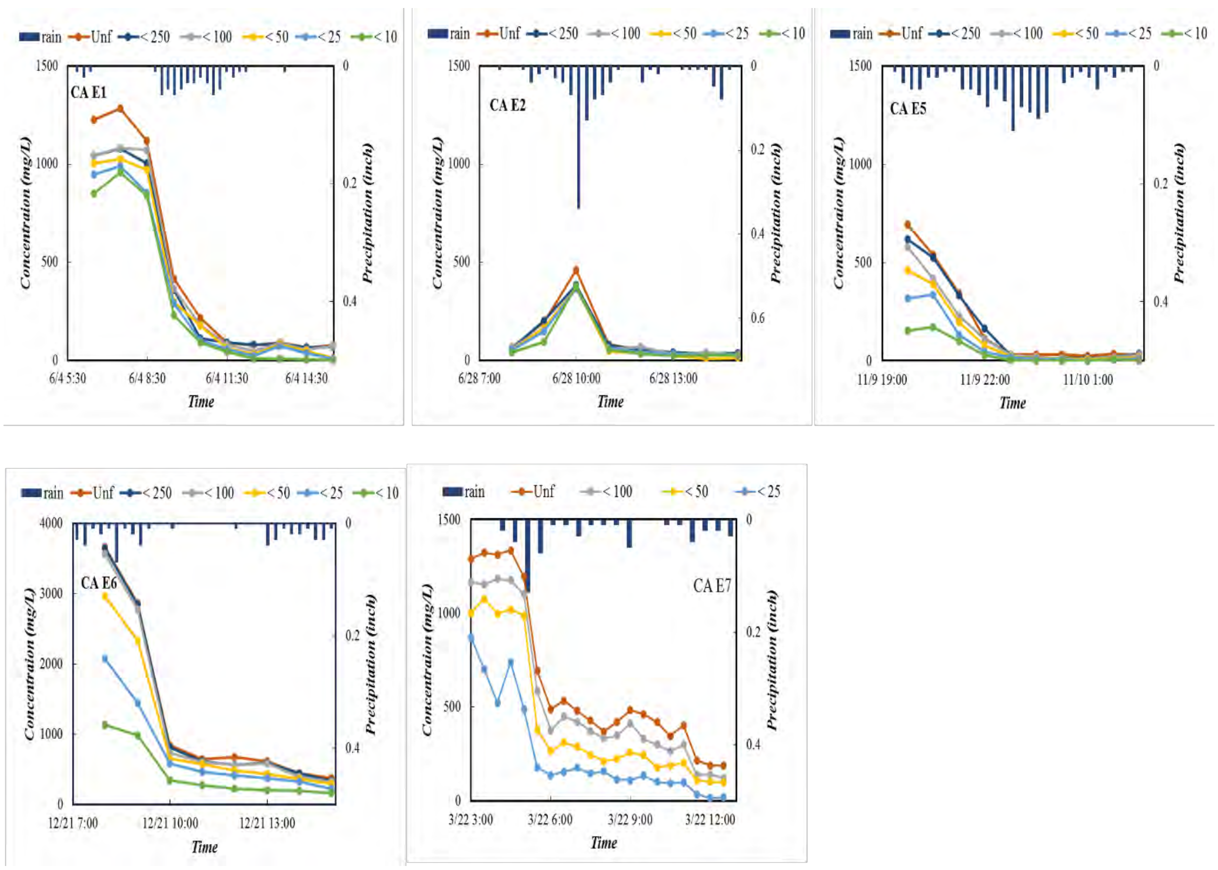


Figure 10: Columbus Avenue event total solids concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

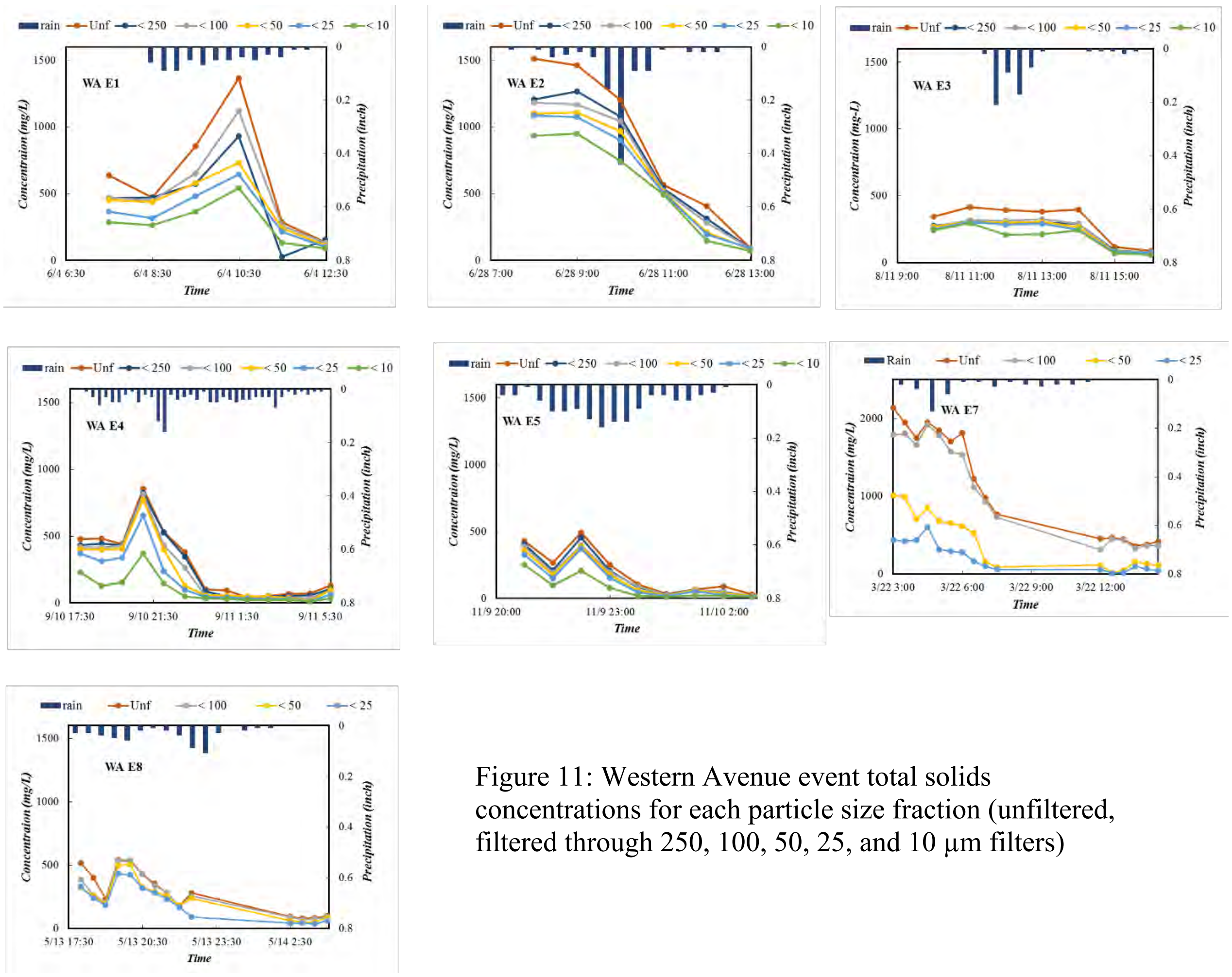


Figure 11: Western Avenue event total solids concentrations for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

4.3 Stormwater phosphorus and total solids loading

The temporal variation of phosphorus and total solids concentration can be expressed in terms of pollutant load. The loading is a function of flow rate over a given time window:

$$\text{Pollutant Load} = C(t) \cdot Q(t) \cdot t$$

where, C(t) is the pollutant concentration [M/L], Q(t) is the average flow rate [L^3/T] and t is the time period [T]. Figure 12-15 show cumulative Phosphorus loading along with flow data of each event and sites. Cumulative total solids loading time series is shown in Figures 16-19. The pollutant loading is highly dependent on site and event characteristics. In the largest drainage area, Cambridge Park, the maximum event Phosphorus load varies from 1-9.2 lb (Figure 12).

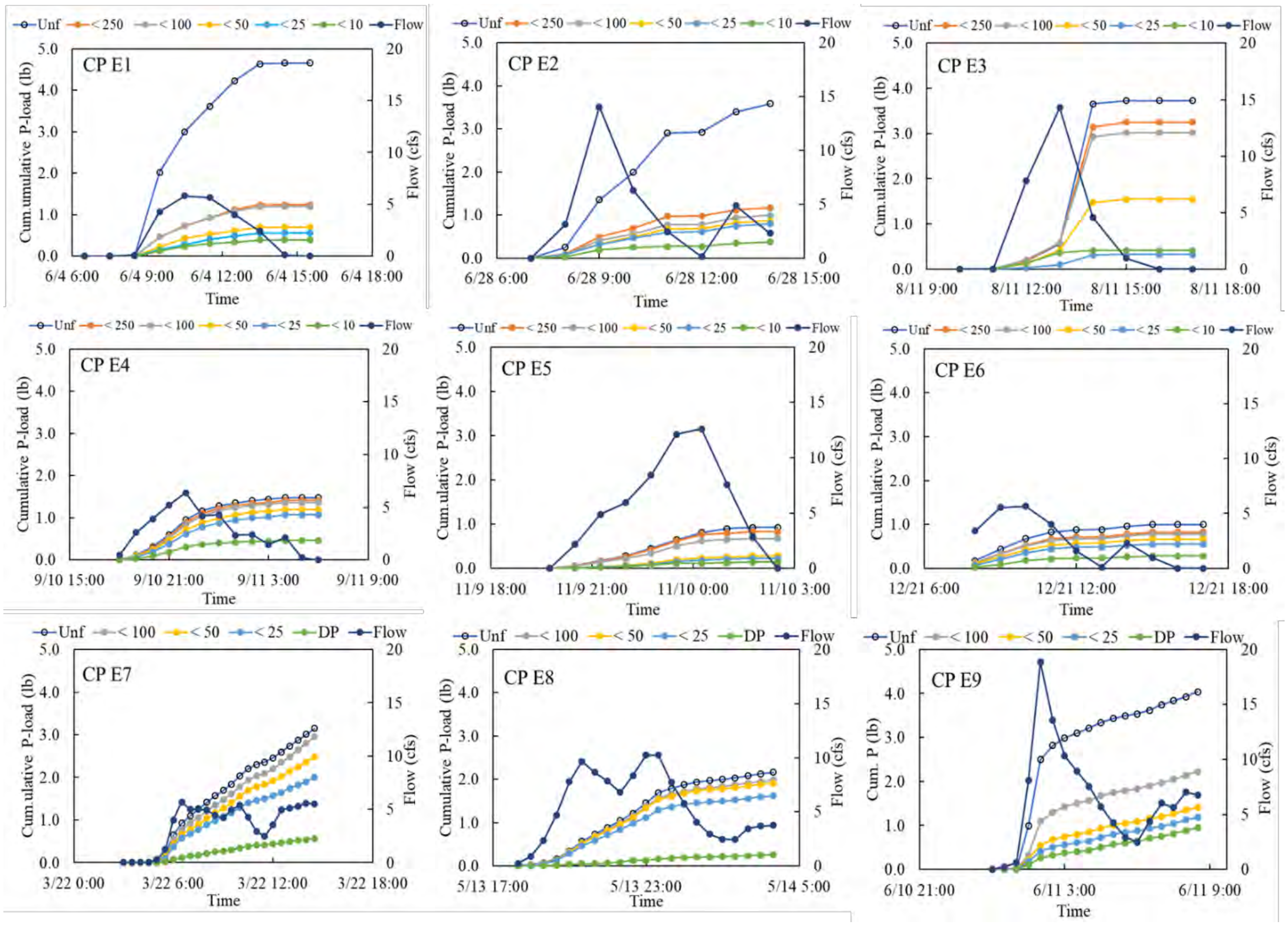


Figure 12: Cambridge Park Drive event Phosphorus loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 μm filters)

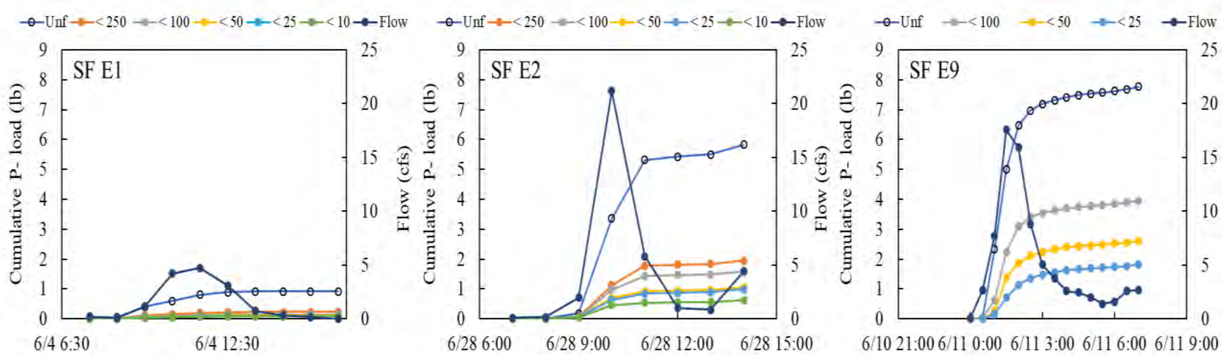


Figure 13: Sparks Street event Phosphorus loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 μm filters)

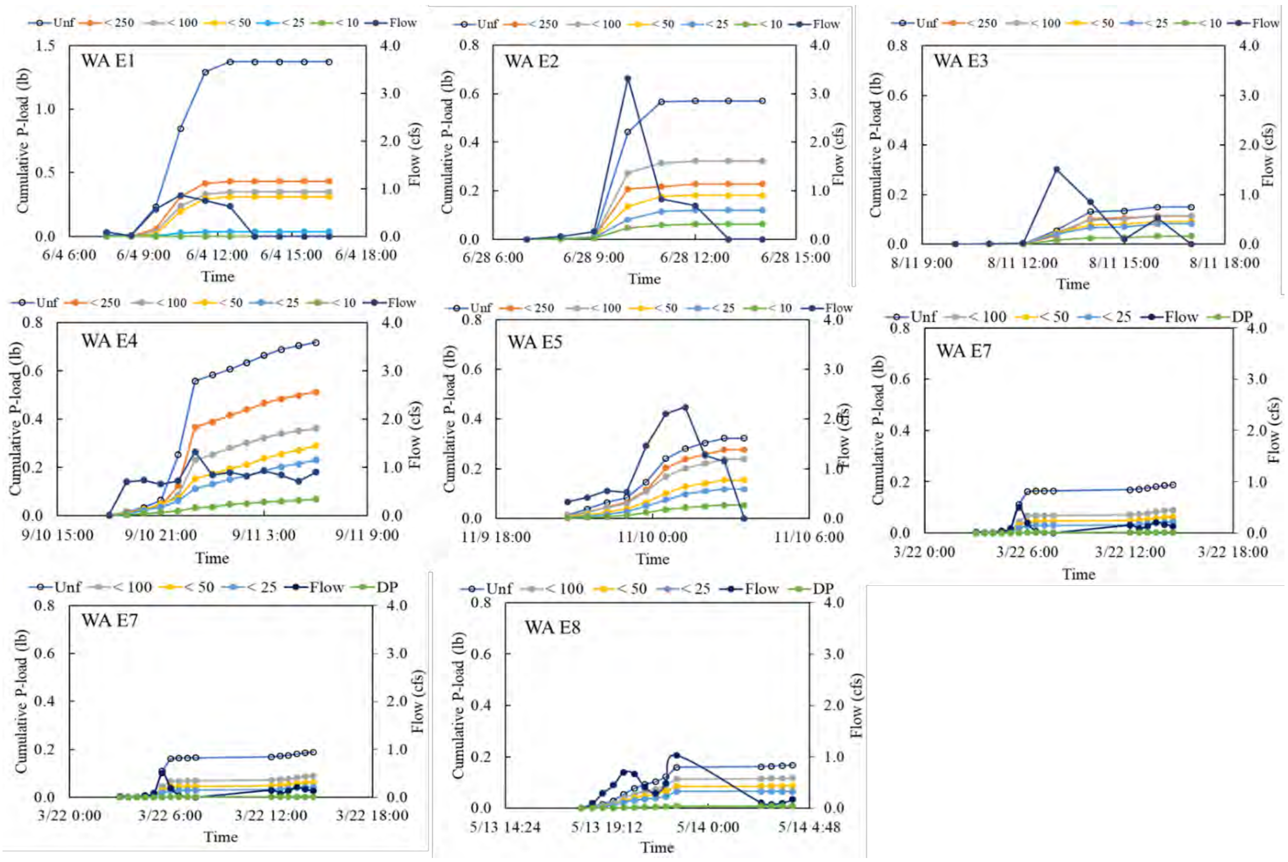


Figure 14: Western Avenue event Phosphorus loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

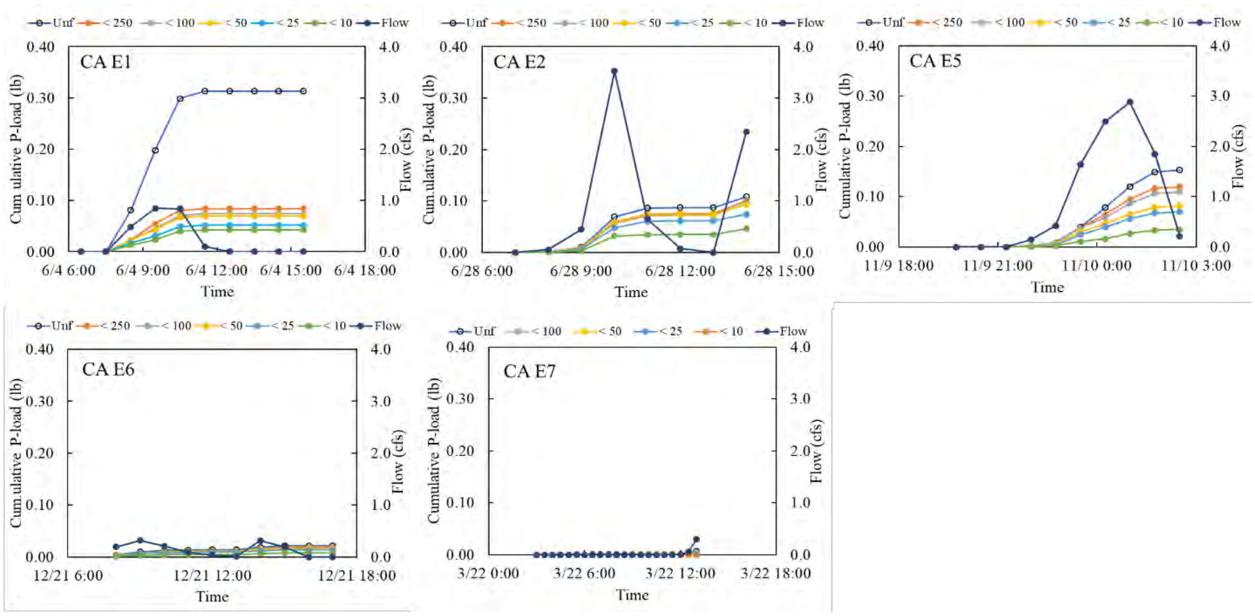


Figure 15: Columbus Avenue event Phosphorus loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

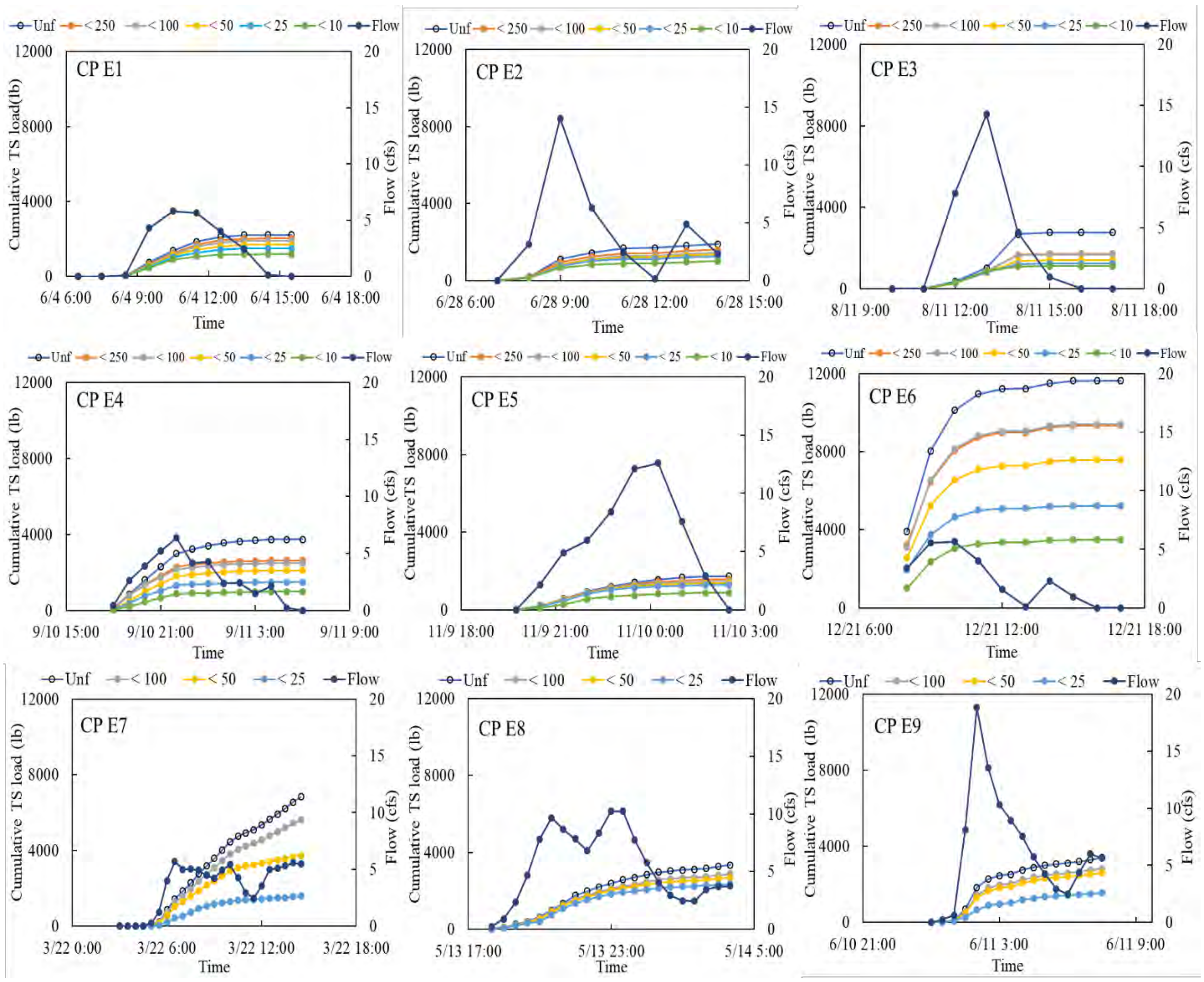


Figure 16: Cambridge Park Drive event total solids loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 μm filters)

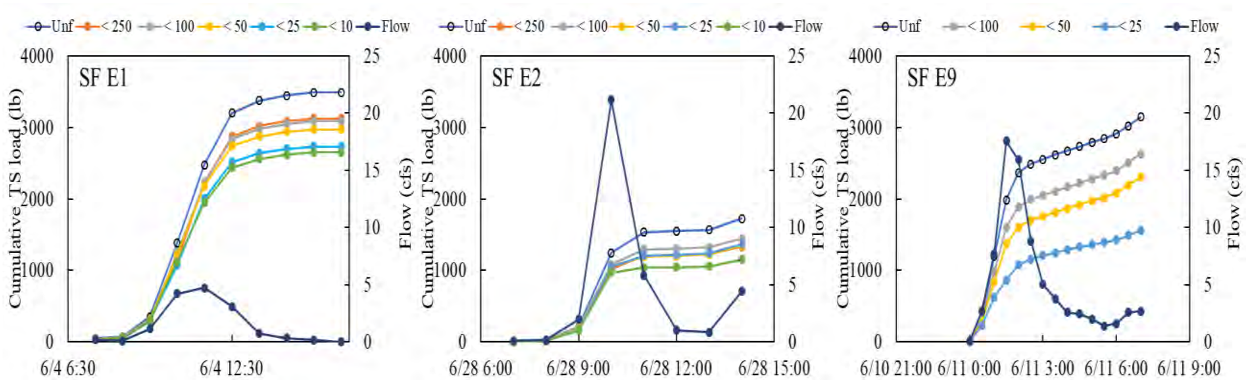


Figure 17: Sparks Street event total solids loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 μm filters)

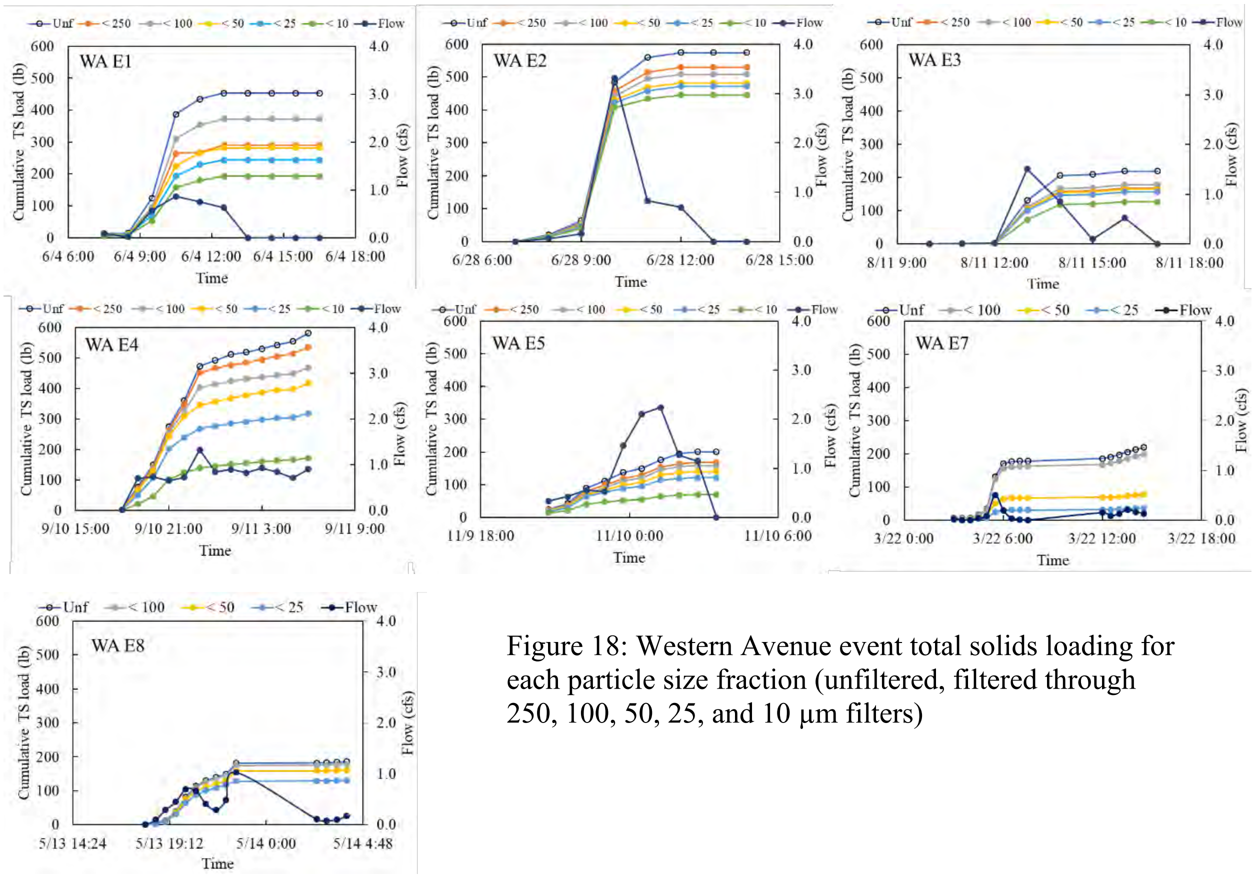


Figure 18: Western Avenue event total solids loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

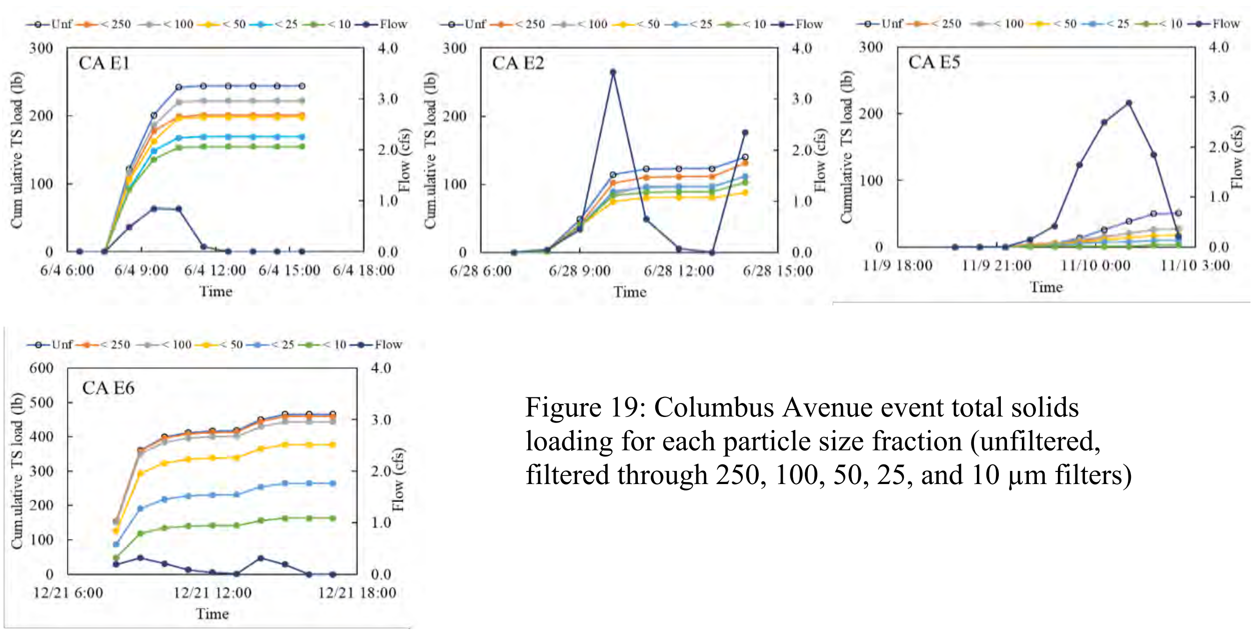


Figure 19: Columbus Avenue event total solids loading for each particle size fraction (unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters)

4.4 Event Mean Concentration

To characterize the concentration of a pollutant in a runoff event, mean concentration (EMC) is used and defined as total pollutant mass (M) discharged during an event divided by the total discharge volume (V) of the event (Sansalone, Koran, Smithson, & Buchberger, 1998). The flow weighted event mean concentration is determined as:

$$\text{EMC} = \frac{M}{V} = \frac{\int Q(t)C(t)dt}{\int Q(t)dt}$$

where, C(t) is time variable pollutant concentration [M/L^3], Q(t) is time variable flow [L^3/T] and t [T] is the duration of the event. Figure 20 shows that the highest EMC for Phosphorus is associated with the particle size fraction greater than 100 μm in Cambridge Park and Western Ave. For Columbus Ave and Sparks Street the highest EMC for TP is associated with the particle size fraction less than 25 μm. However, for TS, all the sites have the highest EMC associated with particle size greater than 100 μm (Figure 21). Tables 10 and 11 show the event mean concentration of the pollutant in between different particle size fractions for TP and TS, respectively.

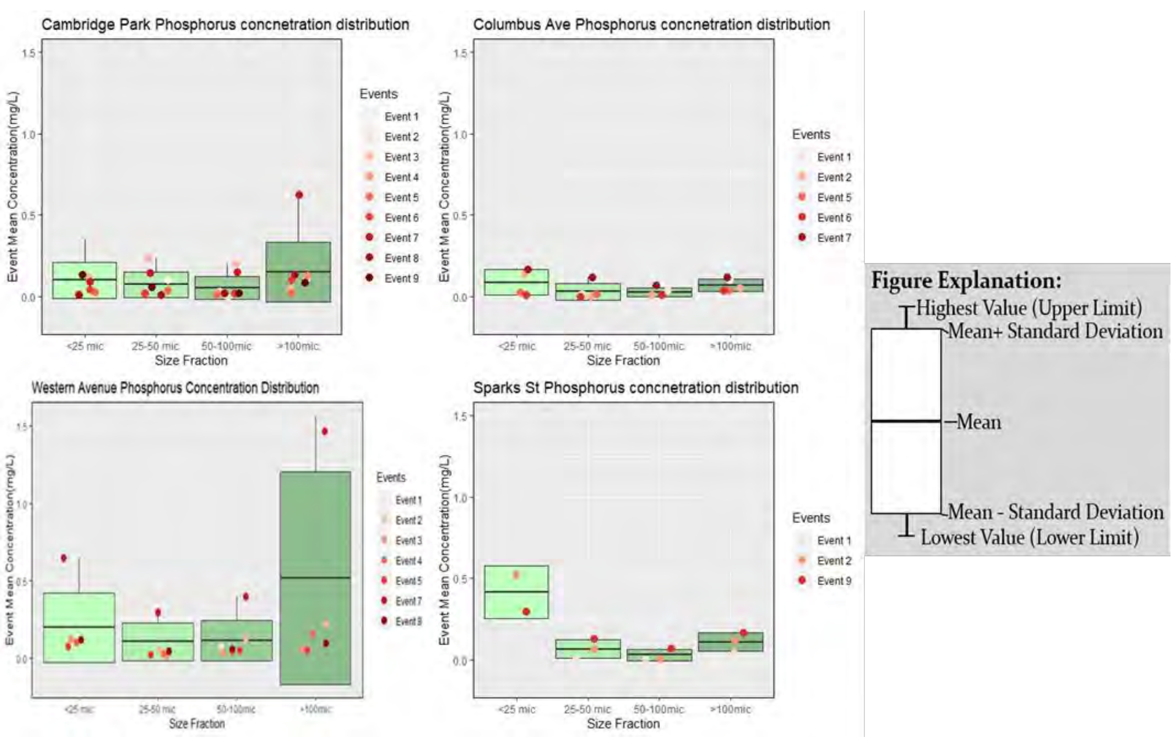


Figure 20: Summary event mean concentrations for Phosphorus

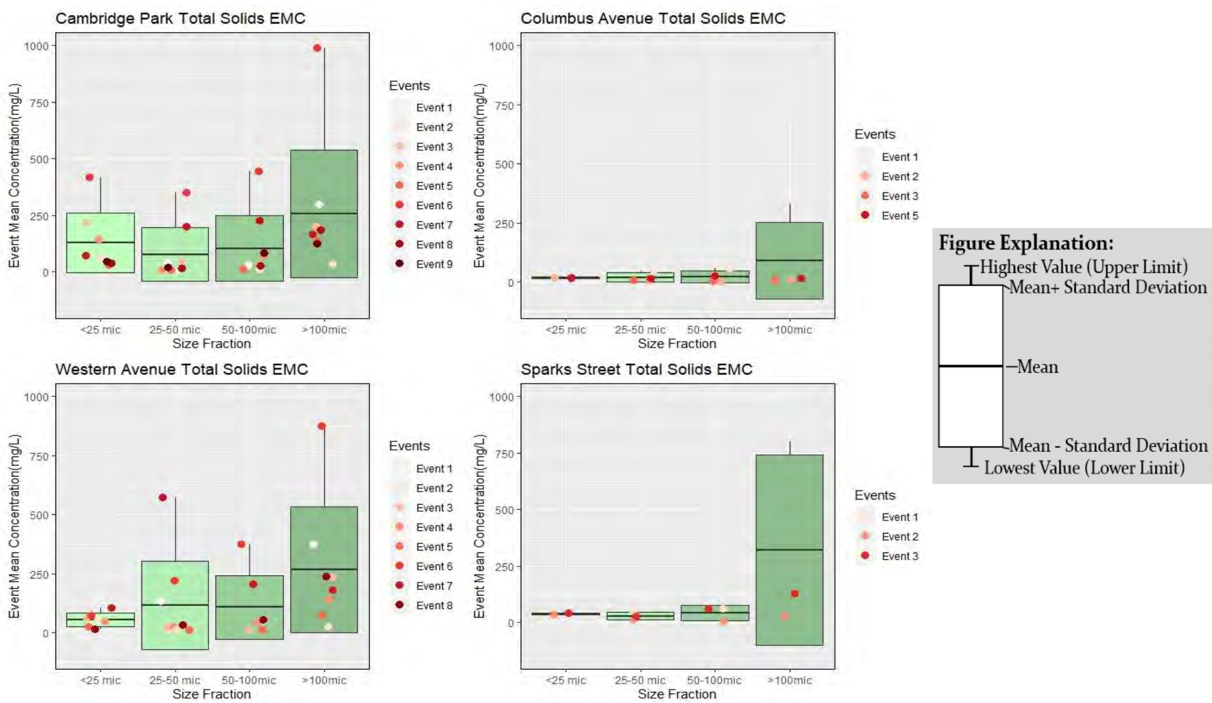


Figure 21: Summary of event mean concentrations for total solids

Table 10:Summary of event mean concentrations for Phosphorus

Site	Particle Size Fraction	Range (mg-P/L)	Standard Deviation	Mean (mg-P/L)	Median (mg-P/L)
Cambridge Park Drive	>100 µm	0.02-0.69	0.25	0.19	0.09
	100-50 µm	0.02-0.24	0.08	0.08	0.04
	50-25 µm	0.00-0.20	0.08	0.06	0.02
	<25 µm	0.02-0.63	0.21	0.17	0.11
Western Avenue	>100 µm	0.05-1.57	0.72	0.59	0.19
	100-50 µm	0.03-0.40	0.14	0.12	0.06
	50-25 µm	0.02-0.30	0.13	0.11	0.04
	<25 µm	0.06-0.65	0.23	0.18	0.10
Columbus Avenue	>100 µm	0.01-0.47	0.18	0.17	0.14
	100-50 µm	0.00-0.12	0.05	0.03	0.01
	50-25 µm	0.01-0.07	0.03	0.03	0.01
	<25 µm	0.04-0.12	0.04	0.07	0.05
Sparks Foster Street	>100 µm	0.34-0.53	0.13	0.44	0.44
	100-50 µm	0.01-0.07	0.04	0.04	0.04
	50-25 µm	0.01-0.01	0.00	0.01	0.01
	<25 µm	0.05-0.12	0.05	0.09	0.09

Table 11:Summary of event mean concentrations for total solids

Site	Particle Size Fraction	Range (mg-P/L)	Standard Deviation	Mean (mg-P/L)	Median (mg-P/L)
Cambridge Park Drive	>100	29-417	127	120	63
	100-50 mic	6-348	119	76	18
	50-25 mic	10-443	144	103	31
	<25 mic	32-989	283	256	184
Western Avenue	>100	13-125	37	62	57
	100-50 mic	11-572	194	128	30
	50-25 mic	9-373	129	95	47
	<25 mic	23-874	268	267	207
Columbus Avenue	>100	15-43	13	24	19
	100-50 mic	6-48	20	19	11
	50-25 mic	0-56	25	21	15
	<25 mic	6-332	161	90	11
Sparks Foster Street	>100	35-141	59	72	41
	100-50 mic	11-44	16	27	26
	50-25 mic	2-61	34	41	60
	<25 mic	28-802	421	319	128

4.5 Statistical Analysis

i. Non-uniformity of Phosphorus loading between particle size fractions (Kolmogorov-Smirnov test)

To assess the Phosphorus loading distribution between particle size fractions, the Kolmogorov-Smirnov test (K-S test) is performed using the samples collected between June 2018 to December 2018. K-S test is basically used to decide whether the sample is coming from a specific distribution using an empirical cumulative distribution function (ECDF). Here, a uniform distribution of Phosphorus loading is assumed over all the particle size fractions. A level of significance of 5% ($\alpha = 5\%$) is used to validate the p-value (<0.05). Among 17 events sampled, 8 of the events showed statistically significant non-uniformity in the Phosphorus loading between different particle size fraction (Table 12).

Table 12: Summary of Kolmogorov–Smirnov statistics for cumulative loading distributions fitted to PSDs

Site	Event Date	Interpretation based on KS test p-value (<0.05)
Cambridge Park Drive	E1 (06-04-2018)	Not Uniformly Distributed
	E2 (06-28-2018)	Not Uniformly Distributed
	E3 (08-11-2018)	Uniformly Distributed
	E4 (09-10-2018)	Uniformly Distributed
	E5 (11-09-2018)	Not Uniformly Distributed
	E6 (12-21-2018)	Uniformly Distributed
Western Avenue	E1 (06-04-2018)	Uniformly Distributed
	E2 (06-28-2018)	Not Uniformly Distributed
	E3 (08-11-2018)	Uniformly Distributed
	E4 (09-10-2018)	Uniformly Distributed
	E5 (11-09-2018)	Uniformly Distributed
Columbus Avenue	E1 (06-04-2018)	Not Uniformly Distributed
	E2 (06-28-2018)	Not Uniformly Distributed
	E5 (11-09-2018)	Uniformly Distributed
	E6 (12-21-2018)	Uniformly Distributed
Sparks Street	E1 (06-04-2018)	Not Uniformly Distributed
	E2 (06-28-2018)	Not Uniformly Distributed

ii. Non-uniformity of Phosphorus concentrations between particle size fractions (Paired t-test)

The paired t-test is performed to determine whether the difference in concentrations between particle size fractions is statistically significant. The concentrations associated with different particle size fractions of all sites and events were used to perform paired t-test analysis (all sites). Here, a p-value less than 0.05 means there is a significant difference between the Phosphorus concentrations associated with two different particle size fractions. The results indicated that the greatest mean difference in Phosphorus concentrations is associated with particle sizes less than 25 µm and between 50-25 µm, with particle size class less than 25 µm having the higher phosphorus concentration (Table 13).

Table 13: Statistical Analysis of Phosphorus concentration of all sites (paired t-test)

Size Fraction	100-50 µm	50-25 µm	< 25 µm
> 100 µm	0.07*	0.08*	-0.06
100-50 µm		0.01	-0.12*
50-25 µm			-0.13*

*[The value is the mean phosphorus concentration difference between particle size fraction. * for p-value <0.05. Negative value means the smaller particle size have higher concentration. The value in bracket is the mean concentration of the particle size fraction]*

Considering only individual sites, the paired t-test showed the largest mean difference associated with the particle size fractions less than 25 µm and between 50-25 µm at only Cambridge Park Drive. The largest mean difference in phosphorus concentration was observed for particle sizes greater than 100 µm and between 100-50 µm at the other three sites (Table 14).

Table 14: Statistical analysis of Phosphorus concentration site-wise (paired t-test)

Site	Size Fraction	100-50 µm	50-25 µm	< 25 µm
Cambridge Park Drive	>100 µm (0.13)[a]	0.07*	0.08*	-0.06*
	100-50 µm (0.06)		0.01	-0.12*
	50-25 µm (0.05)			-0.13*
	<25 µm (0.19)			
Western Avenue	>100 µm (0.33)	0.25*	0.26*	0.16*
	100-50 µm (0.09)		0.02	-0.08*
	50-25 µm (0.07)			-0.10*
	<25 µm (0.17)			
Columbus Avenue	>100 µm (0.14)	0.11*	0.09*	0.02
	100-50 µm (0.03)		-0.02*	-0.09*
	50-25 µm (0.05)			-0.07*
	<25 µm (0.12)			
Sparks Street	>100 µm (0.29)	0.24*	0.27*	0.17*
	100-50 µm (0.05)		0.03*	-0.07*
	50-25 µm (0.02)			-0.10*
	<25 µm (0.12)			

[The value is the mean total solids concentration difference between particle size.
** for p-value <0.05. Negative value means the smaller particle size have higher concentration.*
[a] - the mean concentration of the particle size fraction within bracket]

The largest significant difference in total solids concentration is observed between particle sizes less than 25 µm and between 50-25 µm when considering all sites and events (Table 15).

Table 15: Statistical analysis of total solids of all sites and events (paired t-test)

Size Fraction	100-50 µm	50-25 µm	<25 µm
>100 µm	-16	-27*	-176*
100-50 µm		-1	-128*
50-25 µm			-127*

For total solids, all sites had a greater concentration associated with particle sizes less than 25 µm. The highest total solids concentration difference is in between particle size less than 25 µm and between 50-25 µm (Table 16).

Table 16:Statistical analysis of total solids of site wise (paired t-test)

Site	Size Fraction	100-50 µm	50-25 µm	< 25 µm
Cambridge Park Drive	>100 µm (88)[a]	15	-33*	-160*
	100-50 µm (73)		-47*	-174*
	50-25 µm (121)			-127*
	<25 µm (247)			
Western Avenue	>100 µm (60)	-91*	-13	-133*
	100-50 µm (150)		78*	-42
	50-25 µm (72)			-120*
	<25 µm (193)			
Columbus Avenue	>100 µm (62)	-11	-39*	-176*
	100-50 µm (74)		-28*	-165*
	50-25 µm (106)			-137*
	<25 µm (263)			
Sparks Street	>100 µm (63)	29*	-4	-290*
	100-50 µm (34)		-32*	-319*
	50-25 µm (67)			-287*
	<25 µm (353)			

[The value is the mean total solids concentration difference between particle size.
** for p-value <0.05. Negative value means the smaller particle size have higher concentration.*
[a] - the mean concentration of the particle size fraction within bracket]

4.6 Effect of rainfall characteristics on pollutant load

The relationships between storm event characteristics and Phosphorus and solids loadings are explored using the Pearson correlation coefficient (Tables 17 and 18). Two different rainfall gauges were used in this study to assess loading from a high to medium density urban watershed (Cambridge Park Drive) and a road segment with a high fraction of impervious surface area (Western Avenue). Differences in the effect of site and rainfall characteristics on pollutant loading can be observed at these two sites. Phosphorus loading are divided into four different size fractions (greater than 100µm, 100-50 µm, 50-25 µm and less than 25 µm). These loadings are normalized by area of watershed and rainfall per event. For Cambridge Park Drive, a weak correlation is observed between event characteristics and different particle sizes. Phosphorus associated with particles greater than 100 µm showed a negative correlation with duration and positive correlation with antecedent dry period. Western Avenue has a strong positive correlation with peak rainfall intensity and Phosphorus within the 100-50 µm particle size fraction. Similar to Cambridge Park

Drive, Western Avenue has a positive correlation between antecedent dry period and Phosphorus associated with particle sizes greater than 100 µm (Table 17).

Table 17: Correlation between Phosphorus loading and rainfall event characteristics (Pearson correlation coefficient)

Cambridge Park Drive	**>100 µm**	**100-50 µm**	**50-25 µm**	**<25µm**
Total Rainfall	-0.43	-0.38	-0.32	-0.49
Mean Rainfall intensity	-0.38	-0.41	-0.40	-0.55
Peak rainfall Intensity	-0.09	-0.09	-0.08	-0.33
Duration	**-0.60**	-0.23	0.12	0.35
Antecedent dry period	**0.39**	0.09	-0.14	0.00

Western Avenue	**>100 µm**	**100-50 µm**	**50-25 µm**	**<25µm**
Total Rainfall	-0.48	0.27	-0.50	0.22
Mean Rainfall intensity	-0.73	0.33	-0.68	-0.10
Peak rainfall Intensity	-0.45	**0.89**	-0.45	0.19
Duration	0.03	-0.01	-0.04	0.47
Antecedent dry period	**0.53**	-0.40	0.47	0.22

For total solids, Cambridge park drive showed weak correlation between rainfall characteristics and total solids load associated with different particle size fractions. However, at Western avenue, total solids for particle sizes greater than 100 µm has strong correlation with mean rainfall intensity (negative), antecedent dry period (positive) and total rainfall (negative). Moreover, total solids associated with 50-25 µm particles showed very strong correlation with antecedent dry period and duration of rainfall that might be associated with the break down or weathering of solid particle with longer dry period and rainfall duration (Table 18).

Table 18: Correlation between total solids loading and rainfall event characteristics (Pearson correlation coefficient)

Cambridge Park Drive	**>100 µm**	**100-50 µm**	**50-25 µm**	**<25µm**
Total Rainfall	-0.42	-0.51	-0.58	-0.49
Mean Rainfall intensity	-0.47	-0.57	-0.61	-0.55
Peak rainfall Intensity	-0.34	-0.39	-0.44	-0.33
Duration	0.27	0.25	0.29	0.35
Antecedent dry period	0.02	-0.06	0.03	0.00

Western Avenue	>100 µm	100-50 µm	50-25 µm	<25µm
Total Rainfall	**-0.61**	-0.53	0.04	0.22
Mean Rainfall intensity	**-0.98**	-0.79	-0.78	-0.10
Peak rainfall Intensity	-0.40	-0.50	-0.58	0.19
Duration	0.18	0.04	**0.78**	0.47
Antecedent dry period	**0.69**	0.57	**1.00**	0.22

4.7 Summary of annual Phosphorus-loading by particle size fraction

The percentage distribution of Phosphorus load in lb/ac between particle size fractions for all the events are grouped by site in Figure 22. The annual Phosphorus export is calculated based on loading (lb/ac/in of rainfall) and scaled to annual loading using 43 in/yr rainfall (Figure 23). For Sparks Street and Western Avenue, the largest size fraction of annual Phosphorus export is associated with particle greater than 100 µm. However, in Columbus Avenue, the highest Phosphorus loading is associated with particle sizes less than 25 µm and Western Avenue has the highest Phosphorus loading associated with particle size greater than 100 µm. Table 19 shows the TMDL requirement from Cambridge and the normalized annual loading (mean and median) observed in this study.

Table 19: Annual Phosphorus loading comparison

Land Cover and Land Use	**TMDL requirement (lb/acre/yr)**	**Cambridge Park**		**Western Avenue**		**Columbus Avenue**		**Sparks Street**	
		Mean (lb/acre/yr)	Median (lb/acre/yr)	Mean (lb/acre/yr)	Median (lb/acre/yr)	Mean (lb/acre/yr)	Median (lb/acre/yr)	Mean (lb/acre/yr)	Median (lb/acre/yr)
Commercial	0.53	1.01	0.67	5.23	3.28	0.50	0.23	2.29	1.98
Industrial	0.45	0.86	0.57	4.44	2.78	0.42	0.20	1.94	1.68
High Density Residential	0.35	0.67	0.44	3.45	2.16	0.33	0.15	1.51	1.31
Medium Density Residential	0.17	0.32	0.22	1.68	1.05	0.16	0.07	0.73	0.63
Low Density Residential	0.02	0.04	0.03	0.00	0.00	0.00	0.00	0.09	0.07
Agriculture	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Forest	0.13	0.25	0.16	1.28	0.80	0.12	0.06	0.56	0.49
Open land	0.02	0.04	0.03	0.20	0.12	0.02	0.01	0.09	0.07

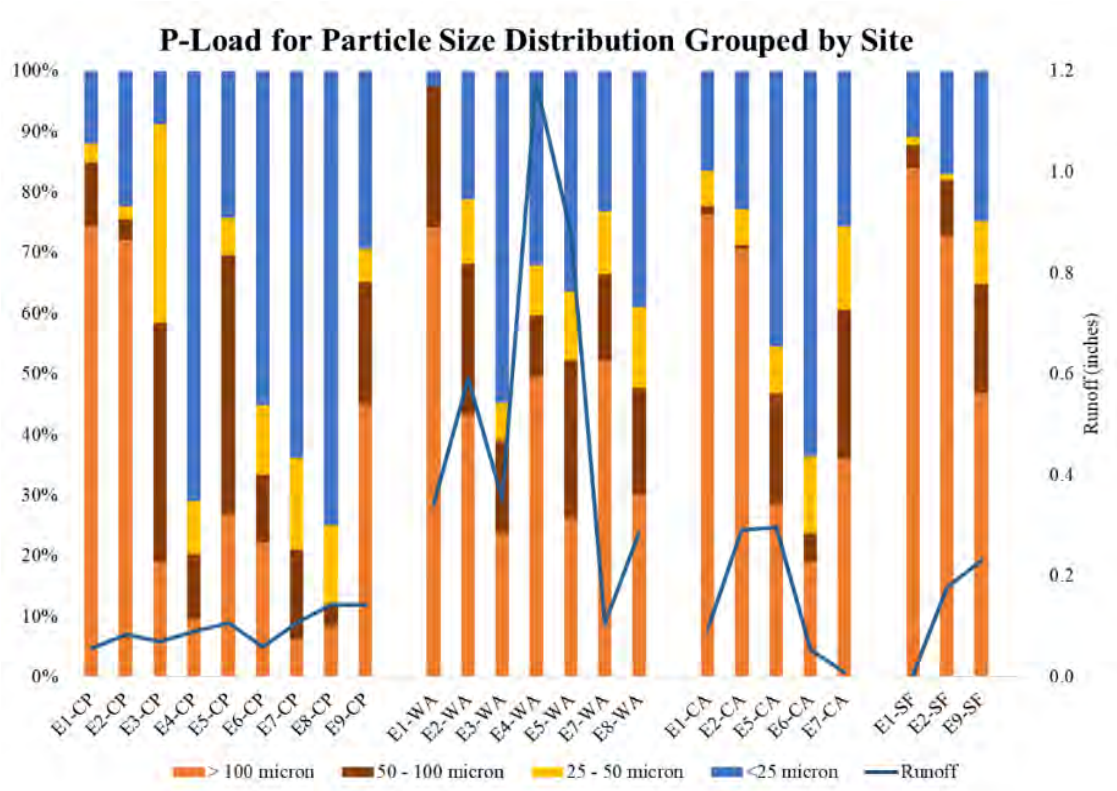


Figure 22: Phosphorus load distributions based on particle size for each event (grouped by site)

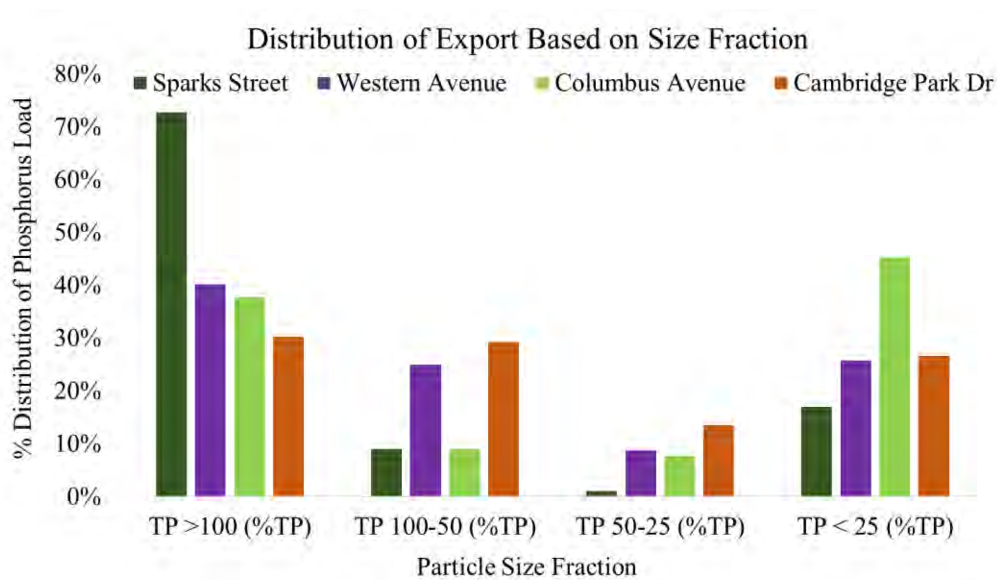


Figure 23: Distribution of annual Phosphorus export based on size fraction

4.8 Relationship between Total Phosphorus and Total solids

Design criteria for structural best management practices (BMPs) often include flowrate and the suspended solids concentration corresponding to that flowrate. To design a BMP to divert Phosphorus, it is important to understand how this nutrient loading is associated with total solids loading. Therefore, cumulative mass fraction of Phosphorus load is compared to the cumulative total solids mass fraction (Figure 24). The relationship tends to be linear but varies from event to event. Note that, for the December 2018 event (Event 6) at Cambridge park drive and Columbus Avenue, Phosphorus loading was very low. This might be related to the source of Phosphorus that contributes to the loading being limited in December.

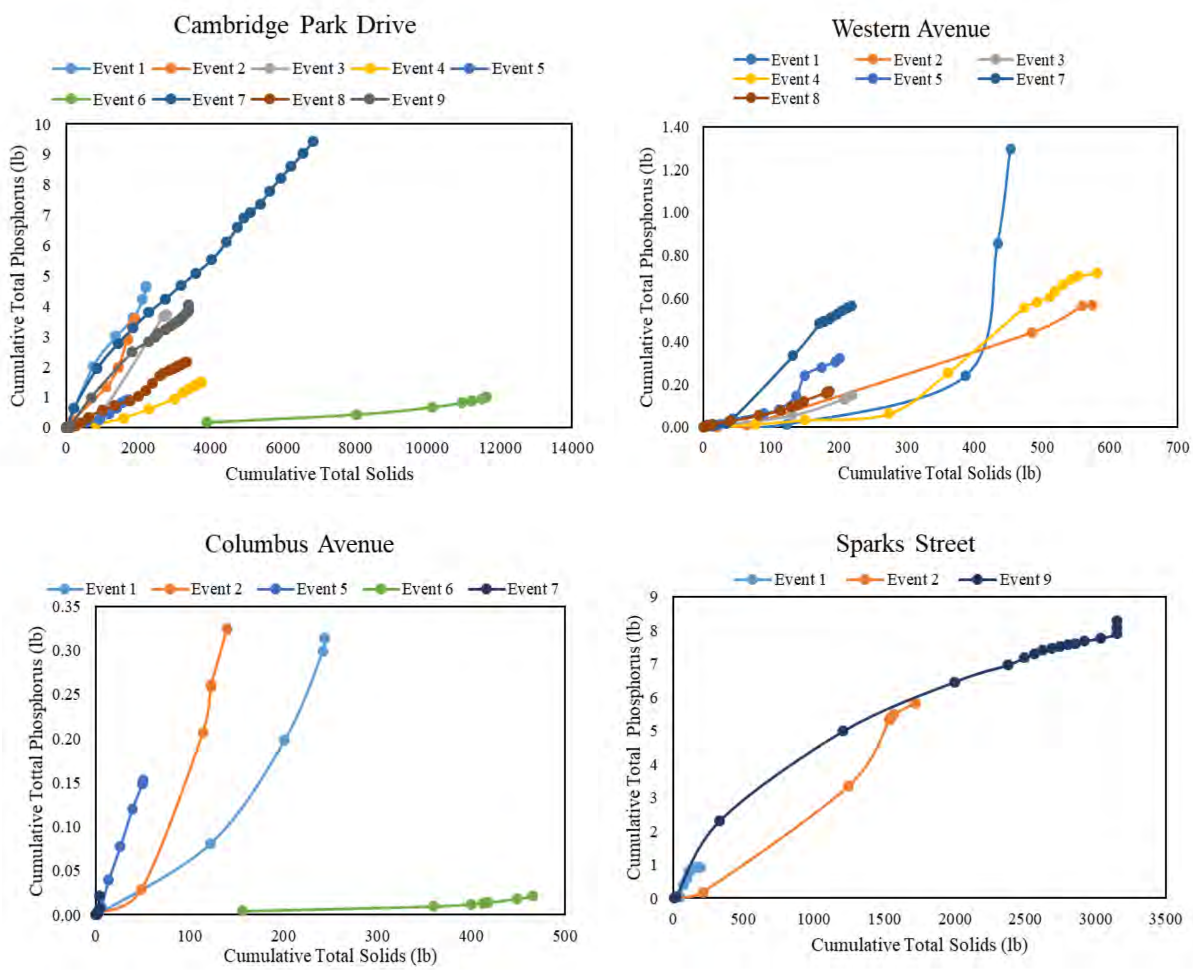
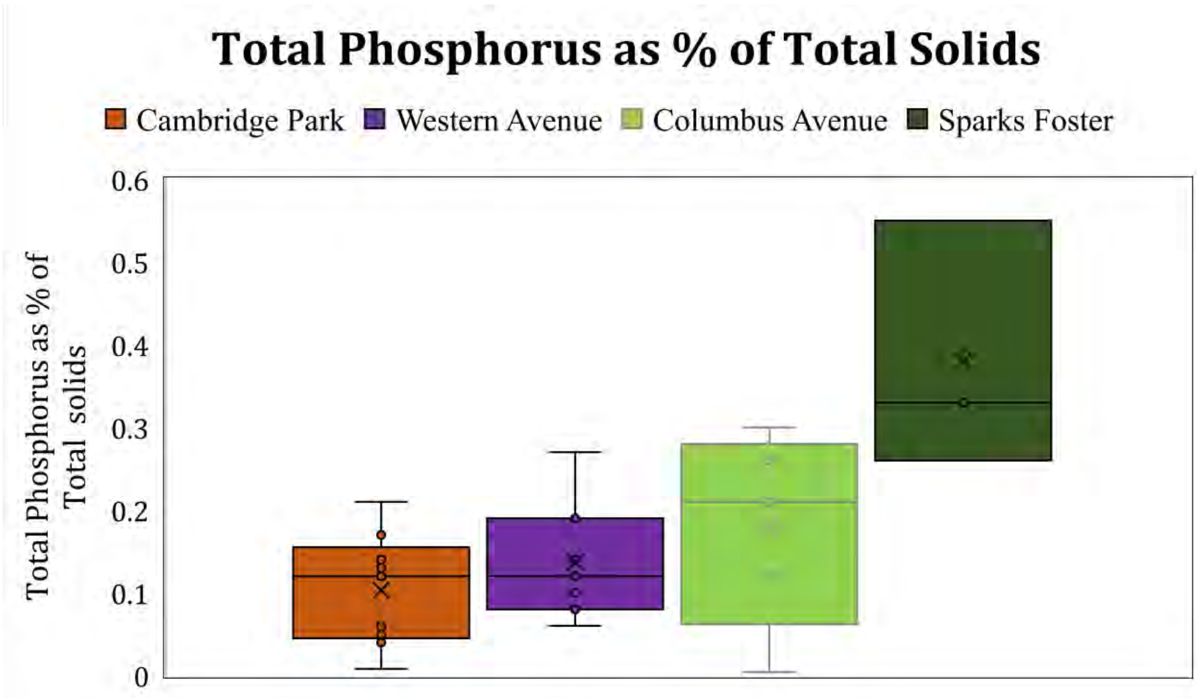


Figure 24: Cumulative mass fraction of Phosphorus as a function of cumulative total solids mass fraction

For the data shown in Figure 24, linear regression models were fit to each event forcing a zero intercept. The slope of the linear models of the loading expressed as the percentage of total Phosphorus loading per a percentage of total solids loading is shown in Figure 25.



Sites	Cambridge Park		Western Avenue		Columbus Avenue		Sparks Foster	
Events	Slope (%)	R^2	Slope (%)	R^2	Slope (%)	R^2	Slope (%)	R^2
Event 1	0.21	0.99	0.19	0.67	0.12	0.94	0.55	0.87
Event 2	0.17	0.95	0.1	0.99	0.21	0.94	0.33	0.98
Event 3	0.13	0.97	0.06	0.74	-	-	-	-
Event 4	0.04	0.93	0.12	0.88	-	-	-	-
Event 5	0.05	0.93	0.14	0.86	0.3	1.00	-	-
Event 6	0.008	0.86	-	-	0.004	0.74	-	-
Event 7	0.14	0.99	0.27	0.99	0.26	0.48	-	-
Event 8	0.06	0.98	0.08	0.97	-	-	-	-
Event 9	0.12	0.99	-	-	-	-	0.26	0.98
%Impervious area	69		88		69		48	

Figure 25: Total Phosphorus loading as a percentage of total solids load.

4.9 Effect of land cover and land use

To observe the effect of land use and land cover on pollutant loading, pollutant export (load per unit area per inch of rainfall) from different sites is related to the percentage impervious area from that site (Figure 26). A clear increasing total solids export pattern can be observed with an increase in the percentage of impervious area. However, this pattern is not distinct in case of Phosphorus. Note that, two of the sites (Cambridge Park Drive and Columbus Avenue) have the same percentage imperviousness, which is highlighted by more points grouped at 69% percent imperviousness.

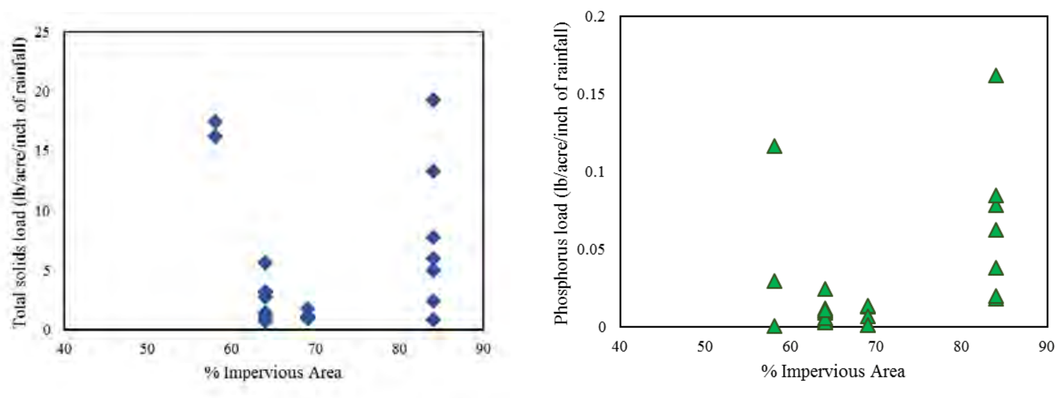


Figure 26: Variability in pollutant load export with imperviousness (Total solids-left, total Phosphorus- right)

4.10 Water Quality Parameters

Continuous water quality variables were monitored during the summer events at Cambridge Park using a Sonde multiprobe. Water quality variables included - pH, temperature, salinity, specific conductivity, dissolved oxygen, turbidity. With an increase in flowrate, an increase in dissolved oxygen and turbidity and sharp depletion in specific conductivity was observed in Events 1 and 2 (Figure 27). The idea is to explore using these variables or various combinations of each to predict the onset of relatively high Phosphorus loading. However, limited Sonde data were collected due to some technical difficulty.

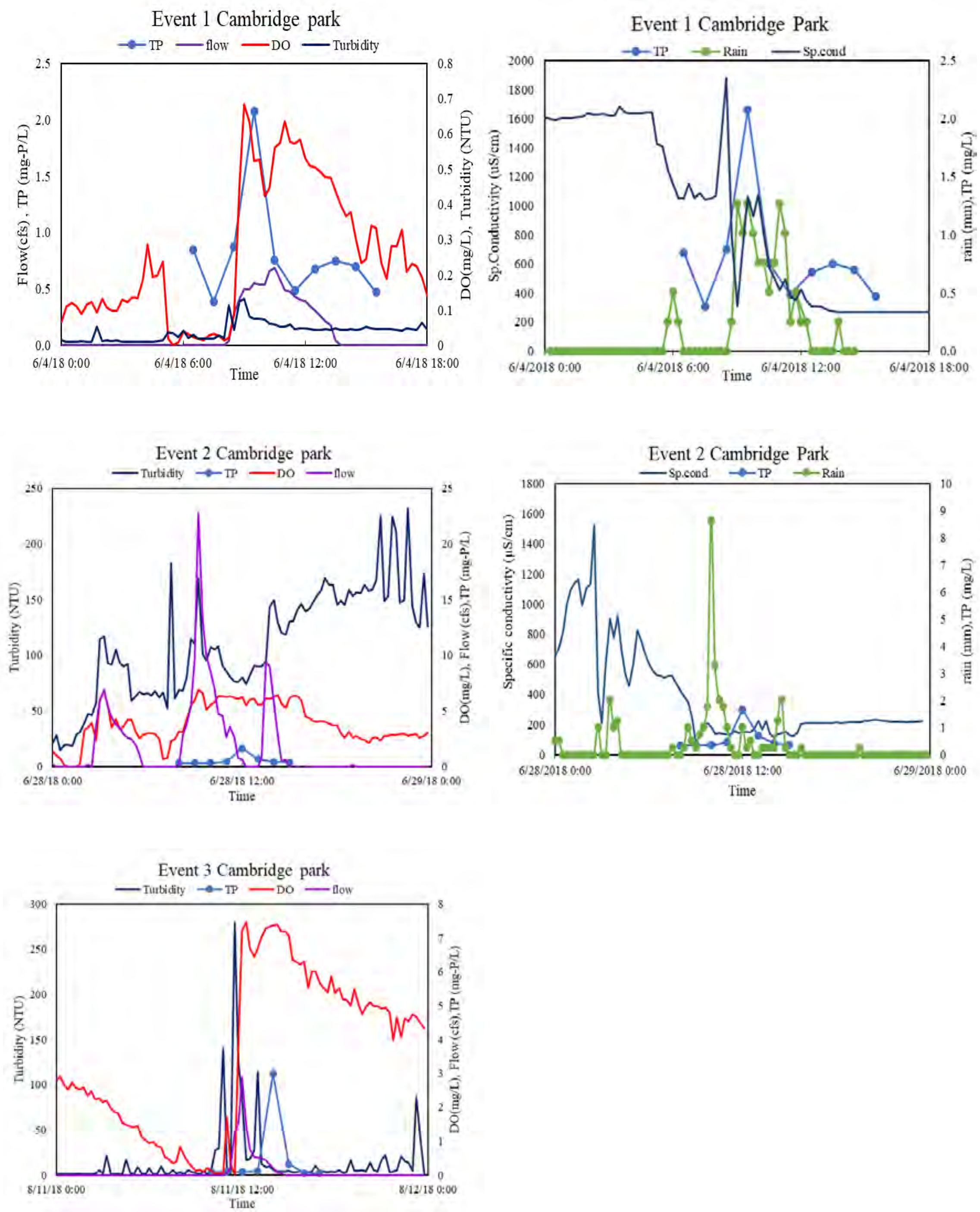


Figure 27: Water quality variables measured with sensor probe

4.11 Alewife Wetland

Water samples were also collected during the first three events from the Alewife constructed wetland outlet to observe the performance of the wetland. Note that, Cambridge park drive is located at the upstream end of the inlet of wetland. Therefore, the performance of the wetland can be assessed by comparing Cambridge park drive and wetland outlet results. As expected, the wetland showed a relatively flat Phosphorus concentration pattern and with smaller concentrations as compare to the inflows (i.e., Cambridge park drive). On average, the wetland concentrations are roughly 75% of the inflow concentrations (Figure 28).

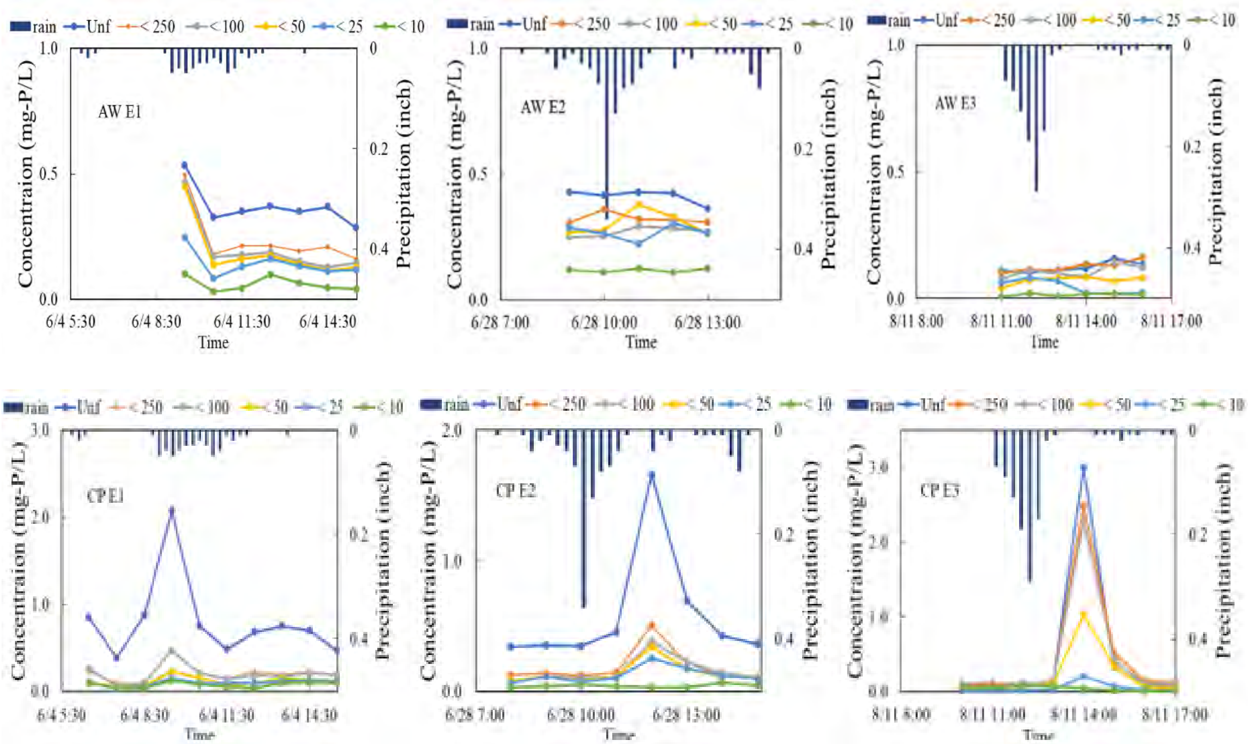


Figure 28: Alewife constructed wetland outflow (top) and inflow (bottom) event Phosphorus concentrations

4.12 Effect of Street Sweeping

Previous studies have shown physical removal of particulate nutrients and soluble nutrients from leaf litter and dirt can be achieved by effective street sweeping (Duan, Delaney-Newcomb, Kaushal, Findlay, & Belt, 2014; Selbig, 2016). The monthly sweeping schedule maintained by the City of Cambridge impacts Western Avenue, Columbus Avenue and Sparks Street watersheds.

The time period between sample collection and the days since last sweeping is compared against normalized Phosphorus loading from Western Avenue. With the increase in the time gap between sweeping and sampling. Figure 29 (Western Avenue) suggests that there was a buildup of phosphorus on the roadway, thus contributing to the high Phosphorus loading. In other words, street sweeping appears to be effectively decreasing the Phosphorus load. Columbus Avenue did not show any significant relationship (R^2 = 0.24) between Phosphorus loading and pollutant buildup duration (the approximate days between sample collection and street sweeping). However, only three events' samples were collected for Sparks street, which is not enough to observe the efficiency of street sweeping.

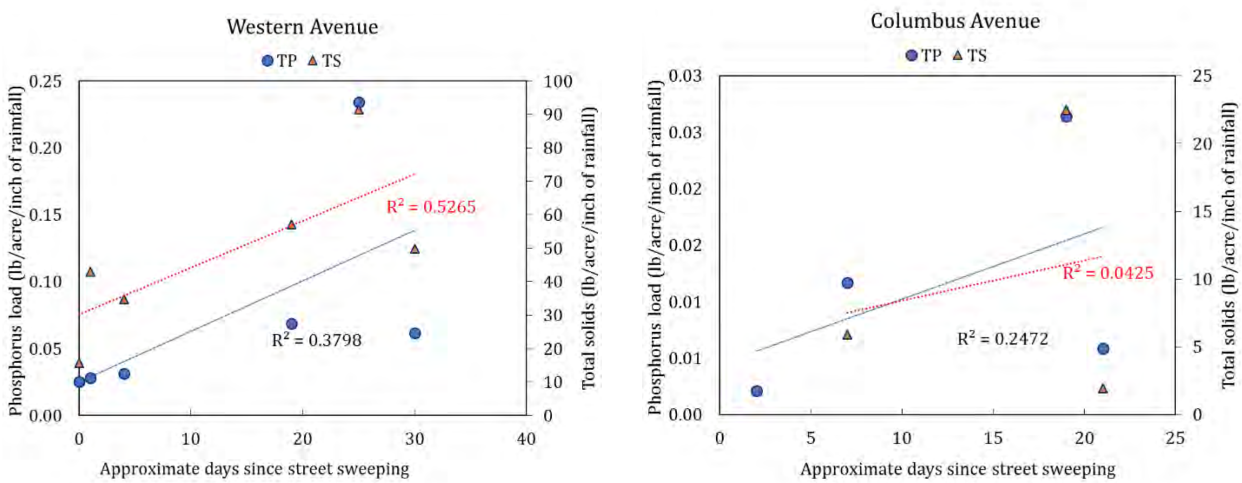


Figure 29: Effect of street sweeping on Phosphorus loading (Western Avenue- left, Columbus Avenue - right)

5. Implications

A typical BMP design assumption is that the phosphorus load distribution is dominated by single size fraction. This assumption is applied to determine when a particle of a specific size will start moving within a stormwater pipe. For example, a flow deflection mechanism can be triggered by pipe flow velocity based on the shear stress to suspend solid particles of a specific size (Bedoya et al., 2014).

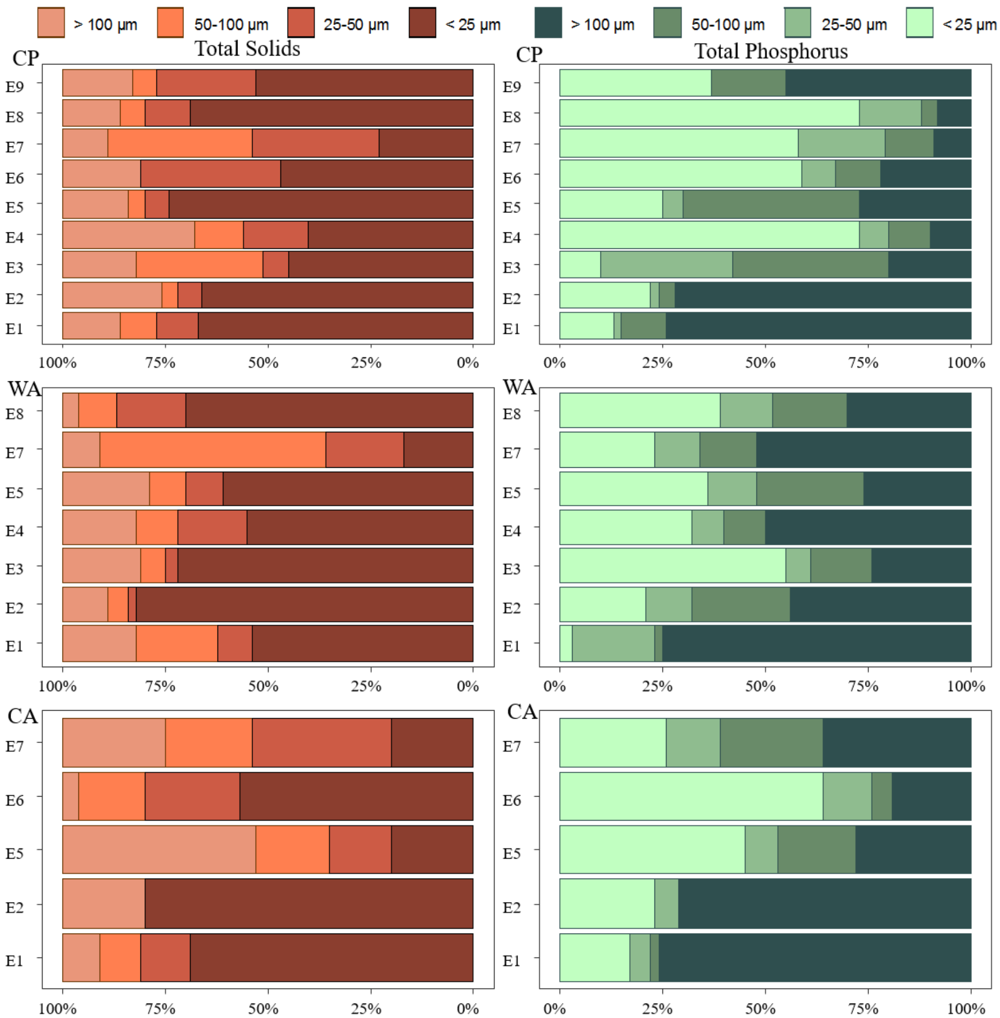


Figure 30: Total Solids and Total Phosphorus percentage load distribution according to particle size fraction.

Figure 30 shows that roughly 50% of the total solids load is associated with particle sizes less than 25 µm. However, there exists no evidence of phosphorus loading being dominated by one specific particle size fraction since the load distribution is relatively even for small and large particles. Therefore, while calculating the pollutant removal capacity for a structural BMP (for example- stormwater ponds), assumptions for the particulate phosphorus distribution can be challenging to estimate (MPCA, 2005). A BMP designed to remove one particle-size fraction may fail to capture a significant Phosphorus loads associated with larger or small particle sizes. However, capturing and diverting all runoff to a treatment facility is not economically feasible. Thus, novel BMPs utilizing continuous real-time monitoring of phosphorous are needed to optimize flow diversions strategies. The ability to characterize real-time nutrient fluxes and divert unique fractions of event stormwater to treatment facilities would further provide water quality managers with flexibility to separately quantify nutrient export to receiving waters and reductions (i.e., loads diverted to treatment facilities).

6. Summary

In this study, stormwater runoff sampling and analysis is performed to characterize Phosphorus and Total Solids concentrations and loadings association with different particle size fractions. A combination of instantaneous and composite sampling for nine storm events during the period June 2018 – June 2019 were collected from four different catchments (Cambridge Park Drive, Columbus Avenue, Sparks Street, and Western Avenue) within the City of Cambridge, MA. The stormwater samples were collected using ISCO 6712c autosamplers. Each sample was divided into six or five subsamples based on particle size: unfiltered, filtered through 250, 100, 50, 25, and 10 µm filters or unfiltered, filtered through 100, 50, 25µm filters and dissolved Phosphorus. The subsamples were then analyzed for total phosphorus and total solids using standard methods. In total 302, samples were collected, and 1661 sub-samples were analyzed.

The analysis of these high-resolution stormwater samples shows that the phosphorus is not uniformly distributed between different particle sizes and that the distribution of phosphorus loading differs from total solids loading distributions. Thus, these findings support potential diversion and treatment approaches targeting unique portions of event stormwater (e.g., velocity based). Depending on the rainfall and drainage characteristics, the observed phosphorus distributions vary. In general, the largest site, Cambridge Park Drive, has higher total phosphorus and total solids concentrations associated with particle sizes less than 25 µm. However, the smallest watershed, Western Avenue, has larger phosphorus concentrations associated with particle sizes greater than 100 µm even though its highest total solids concentrations are associated with particle sizes less than 25 µm. Columbus Avenue and Sparks Street show similar concentration patterns as from Western Avenue. Future research is needed to better understand the mechanism leading to the particle size distributions for total phosphorus and total solids loadings being different. These new insights can ultimately be used to develop new BMP diversion strategies specifically targeting phosphorus removal.

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Appendix A: Total Phosphorus Concentrations

Event 1 (6/4/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
5:30AM- 6:30 AM	6:30 AM	0.845	0.229	0.262	0.114	0.103	0.098						
6:30AM- 7:30 AM	7:30 AM	0.385	0.099	0.065	0.053	0.045	0.039	0.365	0.103	0.050	0.048	0.038	< 0.02
7:30AM- 8:30 AM	8:30 AM	0.875	0.091	0.097	0.062	0.055	0.042	0.3	0.061	0.050	0.045	0.019	< 0.02
8:30AM- 9:30 AM	9:30 AM	2.075	0.479	0.475	0.234	0.154	0.131	1.755	0.439	0.285	0.121	0.020	< 0.02
9:30AM- 10:30 AM	10:30 AM	0.755	0.203	0.213	0.162	0.100	0.079	3.195	1.320	1.027	0.923	0.127	< 0.02
10:30AM- 11:30 AM	11:30 AM	0.485	0.153	0.146	0.073	0.098	0.056	2.635	0.620	0.558	0.603	0.037	< 0.02
11:30AM- 12:30 PM	12:30 PM	0.680	0.230	0.192	0.099	0.097	0.043	0.58	0.105	0.145	0.098	0.017	< 0.02
12:30PM- 1:30 PM	1:30 PM	0.750	0.199	0.177	0.148	0.123	0.099						
1:30PM- 2:30 PM	2:30 PM	0.700	0.220	0.214	0.139	0.125	0.101						
2:30PM- 3:30 PM	3:30 PM	0.470	0.196	0.192	0.120	0.110	0.098						

Event 2 (6/28/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
7:00AM- 8:00 AM	7:00 AM	0.345	0.127	0.079	0.078	0.064	0.032	0.161	0.171	0.168	0.147	0.174	0.146
8:00AM- 9:00 AM	8:00 AM	0.355	0.137	0.118	0.114	0.116	0.040	0.136	0.166	0.141	0.132	0.169	0.113
9:00AM- 10:00 AM	9:00 AM	0.350	0.126	0.104	0.079	0.076	0.053	0.174	0.169	0.167	0.143	0.143	0.088
10:00AM- 11:00 AM	10:00 AM	0.455	0.145	0.109	0.118	0.104	0.042	0.582	0.267	0.357	0.172	0.100	0.058
11:00AM- 12:00 PM	11:00 AM	1.660	0.506	0.384	0.345	0.255	0.031	0.676	0.053	0.22	0.223	0.175	0.057
12:00PM- 1:00 PM	12:00 PM	0.695	0.223	0.229	0.173	0.181	0.033	0.019	0.071	0.051	0.032	0.039	0.026
2:00PM- 3:00 PM	1:00 PM	0.425	0.125	0.143	0.116	0.123	0.070						
1:00PM- 2:00 PM	2:00 PM	0.365	0.095	0.111	0.108	0.098	0.048						

Event 3 (8/11/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
9:00AM- 10:00 AM	10:00 AM	0.096	0.086	0.076	0.052	0.016	0.069	0.152	0.157	0.136	0.131	0.112	0.05
10:00AM- 11:00 AM	11:00 AM	0.104	0.103	0.053	0.045	0.015	0.051	0.125	0.103	0.114	0.114	0.109	0.05
11:00AM- 12:00 PM	12:00 PM	0.096	0.095	0.119	0.066	0.017	0.076	0.14	0.097	0.121	0.121	0.093	0.047
12:00PM- 1:00 PM	1:00 PM	0.123	0.13	0.116	0.095	0.022	0.072	0.162	0.103	0.136	0.135	0.118	0.049
1:00PM- 2:00 PM	2:00 PM	3.000	2.485	2.281	1.024	0.205	0.046	0.394	0.354	0.269	0.166	0.142	0.044
2:00PM- 3:00 PM	3:00 PM	0.328	0.515	0.416	0.336	0.069	0.017	0.139	0.131	0.135	0.089	0.095	0.039
3:00PM- 4:00 PM	4:00 PM	0.069	0.138	0.102	0.064	0.023	0.01	0.132	0.063	0.111	0.095	0.102	0.055
4:00PM- 5:00 PM	5:00 PM	0.064	0.113	0.098	0.052	0.017	0.016						

Event 4 (9/10/2018-9/11/2018)		**Cambridge Park Drive**						**Western Avenue**					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
5:00PM- 6:00 PM	6:00 PM	0.098	0.105	0.099	0.118	0.106	0.054	0.082	0.041	0.041	0.034	0.033	0.020
6:00PM- 7:00 PM	7:00 PM	0.173	0.149	0.141	0.148	0.087	0.039	0.092	0.073	0.052	0.049	0.040	0.020
7:00PM- 8:00 PM	8:00 PM	0.227	0.206	0.175	0.155	0.148	0.081	0.114	0.092	0.105	0.106	0.089	0.030
8:00PM- 9:00 PM	9:00 PM	0.251	0.243	0.242	0.206	0.163	0.077	0.204	0.108	0.094	0.166	0.096	0.033
9:00PM- 10:00 PM	10:00 PM	0.244	0.232	0.221	0.175	0.162	0.085	1.164	0.494	0.285	0.137	0.157	0.040
10:00PM- 11:00 PM	11:00 PM	0.230	0.225	0.215	0.172	0.179	0.057	1.027	0.821	0.487	0.272	0.174	0.042
11:00PM- 12:00 AM	12:00 AM	0.124	0.122	0.125	0.116	0.099	0.037	0.136	0.120	0.120	0.109	0.093	0.022
12:00AM- 1:00 AM	1:00 AM	0.152	0.151	0.149	0.143	0.131	0.043	0.119	0.132	0.132	0.105	0.104	0.051
1:00AM- 2:00 AM	2:00 AM	0.102	0.094	0.090	0.101	0.095	0.029	0.146	0.130	0.117	0.089	0.075	0.023
2:00AM- 3:00 AM	3:00 AM	0.101	0.086	0.088	0.080	0.083	0.026	0.146	0.128	0.097	0.126	0.110	0.025
3:00AM- 4:00 AM	4:00 AM	0.098	0.097	0.084	0.094	0.092	0.031	0.132	0.095	0.094	0.096	0.081	0.020
5:00AM- 6:00 AM	5:00 AM	0.065	0.045	0.039	0.059	0.000	0.020	0.098	0.091	0.080	0.103	0.078	0.027
4:00AM- 5:00 AM	6:00 AM	0.088	0.062	0.040	0.113	0.095	0.022	0.065	0.069	0.048	0.090	0.073	0.023

Event 5 (11/9/2018-11/10/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
Composite Sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
7:00 PM - 7:45 PM	7:45 PM	0.237	0.217	0.236	0.055	0.027	0.020	0.233	0.208	0.227	0.120	0.071	0.029
7:45 PM - 8:30 PM	8:30 PM	0.177	0.171	0.146	0.038	0.036	0.029	0.344	0.182	0.168	0.110	0.067	0.027
8:30 PM - 9:15 PM	9:15 PM	0.130	0.126	0.120	0.032	0.031	0.022	0.293	0.224	0.199	0.124	0.073	0.033
9:15 PM - 10:00 PM	10:00 PM	0.110	0.101	0.071	0.029	0.017	0.013	0.213	0.210	0.189	0.136	0.130	0.065
10:00 PM - 10:45 PM	10:45 PM	0.121	0.113	0.083	0.032	0.026	0.024	0.256	0.205	0.199	0.107	0.096	0.044
10:45 PM - 11:30 PM	11:30 PM	0.096	0.094	0.080	0.039	0.032	0.020	0.265	0.250	0.169	0.102	0.067	0.035
11:30 PM - 12:15 AM	12:15 AM	0.078	0.070	0.056	0.019	0.012	0.000	0.107	0.094	0.088	0.074	0.062	0.02
12:15 AM - 1:00 AM	1:00 AM	0.066	0.026	0.025	0.020	0.019	0.011	0.110	0.094	0.088	0.061	0.056	0.029
1:00 AM - 1:45 AM	1:45 AM	0.060	0.057	0.050	0.045	0.037	0.021	0.096	0.093	0.091	0.066	0.041	0.02
1:45 AM - 2:30 AM	2:30 AM	0.047	0.038	0.036	0.063	0.042	0.024						

Event 6 (12/21/2018-12/22/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
7:00PM- 8:00 PM	8:00 PM	0.232	0.170	0.168	0.136	0.092	0.032						
8:00PM- 9:00 PM	9:00 PM	0.207	0.165	0.162	0.121	0.108	0.048						
9:00PM- 10:00 PM	10:00 PM	0.189	0.151	0.145	0.134	0.118	0.074						
10:00PM- 11:00 PM	11:00 PM	0.169	0.157	0.125	0.112	0.100	0.043						
11:00PM- 12:00 AM	12:00 AM	0.143	0.134	0.136	0.131	0.102	0.055						
12:00AM- 1:00 AM	1:00 AM	0.246	0.127	0.115	0.105	0.098	0.033						
1:00AM- 2:00 AM	2:00 AM	0.138	0.125	0.119	0.112	0.079	0.051						
2:00AM- 3:00 AM	3:00 AM	0.191	0.174	0.162	0.147	0.118	0.079						
3:00AM- 4:00 AM	4:00 AM	0.141	0.127	0.121	0.119	0.103	0.067						
4:00AM- 5:00 AM	5:00 AM	0.125	0.115	0.106	0.096	0.089	0.039						
5:00AM- 6:00 AM	6:00 AM	0.139	0.132	0.128	0.115	0.077	0.033						
6:00AM- 7:00 AM	7:00 AM	0.102	0.100	0.103	0.090	0.082	0.037						
7:00AM- 8:00 AM	8:00 AM	0.089	0.064	0.061	0.058	0.052	0.033						
8:00AM- 9:00 AM	9:00 AM	0.077	0.073	0.070	0.057	0.050	0.021						
9:00AM- 10:00 AM	10:00 AM	0.061	0.060	0.051	0.057	0.048	0.020						

Event 7 (3/22/2019)		Cambridge Park Drive					Western Avenue				
Sampling Period	Time	Unf.	<100 µm	<50 µm	<25 µm	DP	Unfiltered	<100 µm	<50 µm	<25 µm	DP
Non-composite Sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
3:00:00 AM	3:00:00 AM	0.695	0.340	0.245	0.225	0.099	2.965	1.640	0.900	0.810	0.280
3:30:00 AM	3:30:00 AM	0.725	0.475	0.295	0.200	0.089	0.375	0.200	0.130	0.075	0.000
4:00:00 AM	4:00:00 AM	0.425	0.320	0.205	0.145	0.099	0.380	0.190	0.140	0.081	0.000
4:30:00 AM	4:30:00 AM	0.320	0.325	0.390	0.240	0.117	0.335	0.130	0.160	0.100	0.000
5:00:00 AM	5:00:00 AM	0.500	0.405	0.305	0.220	0.106	0.565	0.210	0.175	0.110	0.000
5:30:00 AM	5:30:00 AM	4.580	3.420	2.810	1.990	0.520	5.550	2.205	1.485	0.945	0.300
6:00:00 AM	6:00:00 AM	2.890	2.505	2.040	1.860	0.335	6.843	3.120	2.015	1.360	0.335
6:30:00 AM	6:30:00 AM	1.305	1.160	1.070	0.960	0.215	2.365	0.820	0.795	0.415	0.190
7:00:00 AM	7:00:00 AM	0.905	0.805	0.620	0.560	0.200	1.035	0.490	0.430	0.305	0.105
7:30:00 AM	7:30:00 AM	0.905	0.685	0.610	0.535	0.110	1.200	0.950	0.515	0.440	0.155
8:00:00 AM	8:00:00 AM	0.805	0.810	0.790	0.605	0.205					
8:30:00 AM	8:30:00 AM	0.920	0.800	0.740	0.585	0.210					
9:00:00 AM	9:00:00 AM	0.820	0.825	0.725	0.550	0.160					
9:30:00 AM	9:30:00 AM	0.790	0.765	0.655	0.500	0.105					
10:00:00 AM	10:00:00 AM	0.960	0.845	0.805	0.615	0.235					
10:30:00 AM	10:30:00 AM	1.020	0.935	0.885	0.660	0.265					
11:00:00 AM	11:00:00 AM	0.940	0.895	0.740	0.600	0.185					
11:30:00 AM	11:30:00 AM	0.655	0.640	0.520	0.455	0.105					
12:00:00 PM	12:00:00 PM	0.730	0.800	0.630	0.485	0.125	0.775	0.600	0.513	0.474	0.132
12:30:00 PM	12:30:00 PM	0.750	0.815	0.535	0.395	0.150	0.755	0.580	0.505	0.460	0.125
1:00:00 PM	1:00:00 PM	0.735	0.710	0.670	0.505	0.185	0.740	0.680	0.605	0.490	0.135
1:30:00 PM	1:30:00 PM	0.660	0.815	0.530	0.390	0.110	0.725	0.650	0.550	0.405	0.120
2:00:00 PM	2:00:00 PM	0.685	0.755	0.530	0.395	0.100	0.685	0.680	0.580	0.385	0.105
2:30:00 PM	2:30:00 PM	0.660	0.715	0.630	0.520	0.165	0.645	0.670	0.375	0.280	0.000

Event 8 (5/13/2019-5/14/2019)		Cambridge Park Drive					Western Avenue				
Sampling Period	Time	Unf.	<100 µm	<50 µm	<25 µm	DP	Unfiltered	<100 µm	<50 µm	<25 µm	DP
Non-composite Sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
6:00:00 PM	6:00:00 PM	0.297	0.238	0.231	0.191	0.029	0.651	0.174	0.154	0.111	0.020
6:30:00 PM	6:30:00 PM	0.242	0.183	0.181	0.177	0.006	0.441	0.282	0.193	0.129	0.069
7:00:00 PM	7:00:00 PM	0.164	0.138	0.127	0.102	0.018	0.328	0.263	0.178	0.110	0.093
7:30:00 PM	7:30:00 PM	0.166	0.155	0.153	0.149	0.022	0.274	0.183	0.131	0.129	0.051
8:00:00 PM	8:00:00 PM	0.212	0.208	0.201	0.178	0.029	0.321	0.224	0.167	0.138	0.076
8:30:00 PM	8:30:00 PM	0.206	0.196	0.189	0.164	0.009	0.300	0.216	0.171	0.119	0.099
9:00:00 PM	9:00:00 PM	0.164	0.161	0.157	0.133	0.000	0.347	0.236	0.173	0.101	0.081
9:30:00 PM	9:30:00 PM	0.182	0.165	0.163	0.148	0.017	0.296	0.218	0.170	0.109	0.090
10:00:00 PM	10:00:00 PM	0.202	0.199	0.192	0.157	0.024	0.348	0.338	0.240	0.130	0.106
10:30:00 PM	10:30:00 PM	0.185	0.170	0.166	0.157	0.047	0.326	0.196	0.161	0.159	0.078
11:00:00 PM	11:00:00 PM	0.204	0.195	0.193	0.115	0.000	-	-	-	-	-
11:30:00 PM	11:30:00 PM	0.209	0.176	0.173	0.152	0.028	-	-	-	-	-
12:00:00 AM	12:00:00 AM	0.112	0.095	0.091	0.087	0.023	-	-	-	-	-
12:30:00 AM	12:30:00 AM	0.137	0.103	0.093	0.079	0.022	-	-	-	-	-
1:00:00 AM	1:00:00 AM	0.130	0.127	0.123	0.083	0.011	-	-	-	-	-
1:30:00 AM	1:30:00 AM	0.110	0.095	0.103	0.081	0.027	-	-	-	-	-
2:00:00 AM	2:00:00 AM	0.101	0.094	0.062	0.046	0.025	-	-	-	-	-
2:30:00 AM	2:30:00 AM	0.128	0.110	0.103	0.090	0.029	0.179	0.061	0.008	0.000	0.000
3:00:00 AM	3:00:00 AM	0.114	0.109	0.106	0.092	0.029	0.205	0.078	0.076	0.042	0.036
3:30:00 AM	3:30:00 AM	0.110	0.098	0.078	0.101	0.030	0.178	0.060	0.078	0.016	0.000
4:00:00 AM	4:00:00 AM	0.091	0.076	0.059	0.053	0.021	0.150	0.092	0.040	0.004	0.000

Event 9 (6/11/2019)		Cambridge Park Drive					Western Avenue				
Sampling Period	Time	Unf.	<100 µm	<50 µm	<25 µm	DP	Unfiltered	<100 µm	<50 µm	<25 µm	DP
Non-composite Sample		mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
12:00 AM	12:00 AM	0.120	0.112	0.039	0.027	0.016	-	-	-	-	-
12:30 AM	12:30 AM	0.114	0.098	0.033	0.022	0.000	-	-	-	-	-
1:00 AM	1:00 AM	0.213	0.135	0.080	0.071	0.063	-	-	-	-	-
1:30 AM	1:30 AM	1.072	0.347	0.244	0.188	0.108	-	-	-	-	-
2:00 AM	2:00 AM	0.714	0.365	0.153	0.112	0.076	-	-	-	-	-
2:30 AM	2:30 AM	0.211	0.132	0.085	0.064	0.037	-	-	-	-	-
3:00 AM	3:00 AM	0.146	0.111	0.053	0.049	0.047	-	-	-	-	-
3:30 AM	3:30 AM	0.104	0.080	0.059	0.045	0.031	-	-	-	-	-
4:00 AM	4:00 AM	0.144	0.075	0.053	0.042	0.035	-	-	-	-	-
4:30 AM	4:30 AM	0.191	0.159	0.142	0.133	0.112	-	-	-	-	-
5:00 AM	5:00 AM	0.194	0.161	0.149	0.141	0.136	-	-	-	-	-
5:30 AM	5:30 AM	0.192	0.136	0.129	0.126	0.112	-	-	-	-	-
6:00 AM	6:00 AM	0.160	0.132	0.125	0.124	0.124	-	-	-	-	-
6:30 AM	6:30 AM	0.163	0.153	0.143	0.125	0.136	-	-	-	-	-
7:00 AM	7:00 AM	0.191	0.096	0.067	0.065	0.063	-	-	-	-	-
7:30 AM	7:30 AM	0.141	0.121	0.105	0.101	0.098	-	-	-	-	-
8:00 AM	8:00 AM	0.120	0.118	0.108	0.104	0.094	-	-	-	-	-
8:30 AM	8:30 AM	0.147	0.109	0.076	0.082	0.078	-	-	-	-	-

Event 1 (6/4/2018)	Columbus Avenue						Sparks Street				
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm
1-hour composite sample	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
5:30AM- 6:30 AM	1.105	0.332	0.279	0.214	0.167	0.122					
6:30AM- 7:30 AM	0.610	0.157	0.123	0.100	0.100	0.092	1.145	0.254	0.117	0.114	0.103
7:30AM- 8:30 AM	0.740	0.209	0.202	0.200	0.151	0.120	0.110	0.028	0.025	0.023	0.025
8:30AM- 9:30 AM	0.620	0.169	0.123	0.115	0.077	0.055	1.365	0.449	0.215	0.162	0.155
9:30AM- 10:30 AM	0.535	0.135	0.135	0.123	0.094	0.088	0.210	0.034	0.029	0.023	0.020
10:30AM- 11:30 AM	0.615	0.173	0.134	0.129	0.128	0.102	0.195	0.028	0.024	0.016	0.015
11:30AM- 12:30 PM	0.515	0.153	0.142	0.132	0.130	0.112	0.125	0.038	0.028	0.023	0.018
12:30PM- 1:30 PM	0.480	0.128	0.119	0.103	0.100	0.098	0.145	0.072	0.060	0.049	0.040
1:30PM- 2:30 PM	0.475	0.126	0.110	0.127	0.122	0.090	0.040	0.042	0.039	0.015	0.012
2:30PM- 3:30 PM	0.480	0.128	0.115	0.091	0.089	0.078	0.055	0.047	0.035	0.031	0.013

Event 2 (6/28/2018)	Columbus Avenue						Sparks Street				
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm
1-hour composite sample	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
7:00AM- 8:00 AM	0.165	0.063	0.055	0.052	0.050	0.036	0.570	0.190	0.137	0.145	0.149
8:00AM- 9:00 AM	0.195	0.068	0.054	0.063	0.058	0.031	0.360	0.120	0.126	0.112	0.126
9:00AM- 10:00 AM	0.270	0.077	0.065	0.073	0.056	0.027	0.350	0.117	0.091	0.105	0.105
10:00AM- 11:00 AM	0.225	0.064	0.062	0.064	0.052	0.037	0.670	0.223	0.195	0.135	0.122
11:00AM- 12:00 PM	0.355	0.106	0.105	0.098	0.086	0.014	1.505	0.502	0.351	0.171	0.158
12:00PM- 1:00 PM	0.140	0.049	0.051	0.037	0.064	0.016	0.470	0.157	0.145	0.107	0.105
2:00PM- 3:00 PM	0.120	0.051	0.039	0.035	0.025	0.016	0.400	0.133	0.113	0.105	0.133
1:00PM- 2:00 PM	0.120	0.048	0.044	0.037	0.025	0.021	0.335	0.112	0.101	0.093	0.105

Event 5(11/9/2018-11/10/2018)	Columbus Avenue						Sparks Street				
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm
1-hour Composite Sample	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
7:00 PM - 7:45 PM	0.154	0.139	0.133	0.129	0.110	0.065	-	-	-	-	-
7:45 PM - 8:30 PM	0.090	0.078	0.072	0.068	0.045	0.038	-	-	-	-	-
8:30 PM - 9:15 PM	0.087	0.070	0.069	0.061	0.039	0.021	-	-	-	-	-
9:15 PM - 10:00 PM	0.088	0.085	0.085	0.067	0.043	0.026	-	-	-	-	-
10:00 PM - 10:45 PM	0.088	0.078	0.075	0.059	0.037	0.022	-	-	-	-	-
10:45 PM - 11:30 PM	0.113	0.109	0.106	0.087	0.074	0.031	-	-	-	-	-
11:30 PM - 12:15 AM	0.092	0.065	0.053	0.041	0.037	0.013	-	-	-	-	-
12:15 AM - 1:00 AM	0.086	0.062	0.058	0.037	0.034	0.022	-	-	-	-	-
1:00 AM - 1:45 AM	0.094	0.070	0.063	0.045	0.037	0.021	-	-	-	-	-
1:45 AM - 2:30 AM	0.115	0.085	0.083	0.071	0.056	0.038	-	-	-	-	-

Event 6 (12/21/2018-12/22/2018)	Columbus Avenue						Sparks Street				
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm
1-hour composite sample	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
7:00PM- 8:00 PM	0.097	0.072	0.066	0.065	0.046	0.022	-	-	-	-	-
8:00PM- 9:00 PM	0.076	0.060	0.056	0.057	0.055	0.028	-	-	-	-	-
9:00PM- 10:00 PM	0.057	0.056	0.049	0.050	0.049	0.028	-	-	-	-	-
10:00PM- 11:00 PM	0.058	0.054	0.052	0.044	0.041	0.021	-	-	-	-	-
11:00PM- 12:00 AM	0.052	0.039	0.036	0.034	0.018	0.010	-	-	-	-	-
12:00AM- 1:00 AM	0.051	0.041	0.037	0.030	0.023	0.020	-	-	-	-	-
1:00AM- 2:00 AM	0.065	0.061	0.059	0.058	0.040	0.025	-	-	-	-	-
2:00AM- 3:00 AM	0.068	0.066	0.063	0.043	0.037	0.027	-	-	-	-	-
3:00AM- 4:00 AM	0.052	0.044	0.040	0.020	0.019	0.016	-	-	-	-	-
4:00AM- 5:00 AM	0.055	0.050	0.048	0.028	0.027	0.018	-	-	-	-	-
5:00AM- 6:00 AM	0.108	0.099	0.092	0.060	0.046	0.018	-	-	-	-	-
6:00AM- 7:00 AM	0.059	0.040	0.028	0.022	0.020	0.011	-	-	-	-	-
7:00AM- 8:00 AM	0.050	0.035	0.030	0.031	0.028	0.016	-	-	-	-	-
8:00AM- 9:00 AM	0.070	0.056	0.053	0.048	0.026	0.015	-	-	-	-	-
9:00AM- 10:00 AM	0.098	0.073	0.068	0.055	0.049	0.014	-	-	-	-	-

Event 7 (3/22/2018)			Columbus Avenue					Sparks Street		
Sampling Period	Unf.	<100 µm	<50 µm	<25 µm	DP	Unfiltered	<100 µm	<50 µm	<25 µm	DP
Non-composite Sample	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
3:00:00 AM	0.465	0.335	0.22	0.135	0	-	-	-	-	-
3:30:00 AM	0.285	0.165	0.225	0.155	0	-	-	-	-	-
4:00:00 AM	0.25	0.185	0.15	0.0985	0	-	-	-	-	-
4:30:00 AM	0.27	0.205	0.175	0.0965	0	-	-	-	-	-
5:00:00 AM	0.375	0.295	0.24	0.12	0	-	-	-	-	-
5:30:00 AM	0.825	0.415	0.375	0.21	0.1	-	-	-	-	-
6:00:00 AM	0.965	0.595	0.55	0.32	0.155	-	-	-	-	-
6:30:00 AM	0.88	0.765	0.7	0.43	0.215	-	-	-	-	-
7:00:00 AM	0.91	0.835	0.575	0.395	0.2	-	-	-	-	-
7:30:00 AM	0.69	0.695	0.495	0.39	0.185	-	-	-	-	-
8:00:00 AM	0.58	0.525	0.5	0.325	0.1	-	-	-	-	-
8:30:00 AM	0.585	0.535	0.495	0.385	0.13	-	-	-	-	-
9:00:00 AM	0.775	0.745	0.6	0.435	0.111	-	-	-	-	-
9:30:00 AM	0.535	0.385	0.325	0.205	0	-	-	-	-	-
10:00:00 AM	0.42	0.36	0.3	0.18	0	-	-	-	-	-
10:30:00 AM	0.495	0.39	0.34	0.22	0	-	-	-	-	-
11:00:00 AM	0.525	0.36	0.31	0.225	0	-	-	-	-	-
11:30:00 AM	0.505	0.365	0.31	0.165	0	-	-	-	-	-
12:00:00 PM	0.675	0.465	0.39	0.2	0	-	-	-	-	-
12:30:00 PM	0.515	0.345	0.295	0.145	0	-	-	-	-	-
1:00:00 PM	0.445	0.275	0.138	0.101	0	-	-	-	-	-

Event 9 (6/11/2019)	Columbus Avenue					Sparks Street				
Sampling Period	Unf.	<100 µm	<50 µm	<25 µm	DP	Unfiltered	<100 µm	<50 µm	<25 µm	DP
Non-composite Sample	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L	mg-P/L
12:00 AM	-	-	-	-	-	0.062	0.033	0.000	0.000	0.000
12:30 AM	-	-	-	-	-	0.086	0.052	0.000	0.000	0.000
1:00 AM	-	-	-	-	-	2.653	0.696	0.275	0.177	0.135
1:30 AM	-	-	-	-	-	1.353	0.820	0.578	0.281	0.186
2:00 AM	-	-	-	-	-	0.825	0.480	0.279	0.241	0.215
2:30 AM	-	-	-	-	-	0.515	0.312	0.228	0.220	0.210
3:00 AM	-	-	-	-	-	0.380	0.255	0.254	0.226	0.212
3:30 AM	-	-	-	-	-	0.294	0.195	0.192	0.184	0.172
4:00 AM	-	-	-	-	-	0.334	0.247	0.243	0.228	0.212
4:30 AM	-	-	-	-	-	0.264	0.172	0.148	0.139	0.130
5:00 AM	-	-	-	-	-	0.228	0.135	0.105	0.098	0.093
5:30 AM	-	-	-	-	-	0.271	0.201	0.168	0.151	0.142
6:00 AM	-	-	-	-	-	0.229	0.216	0.167	0.144	0.121
6:30 AM	-	-	-	-	-	0.229	0.170	0.111	0.107	0.105
7:00 AM	-	-	-	-	-	0.299	0.224	0.207	0.186	0.154
7:30 AM	-	-	-	-	-	0.269	0.240	0.161	0.151	0.146
8:00 AM	-	-	-	-	-	0.289	0.231	0.168	0.138	0.118
8:30 AM	-	-	-	-	-	0.324	0.302	0.189	0.111	0.099

Appendix B: Total Solids Concentrations

Event 1 (6/4/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5:30AM- 6:30 AM	6:30 AM	1218	1124	1141	1124	919	885	-	-	-	-	-	-
6:30AM- 7:30 AM	7:30 AM	1187	1157	1029	917	826	764	635	468	471	451	363	286
7:30AM- 8:30 AM	8:30 AM	1111	1077	1048	1021	963	941	470	472	450	435	317	264
8:30AM- 9:30 AM	9:30 AM	744	661	574	522	483	453	855	573	652	579	480	363
9:30AM- 10:30 AM	10:30AM	487	448	478	468	411	339	1365	932	1119	731	644	541
10:30AM- 11:30 AM	11:30AM	380	359	313	242	193	138	285	24	261	241	213	133
11:30AM- 12:30 PM	12:30 PM	282	248	234	190	167	85	135	153	130	112	101	91
12:30PM- 1:30 PM	1:30 PM	180	168	155	146	119	46	-	-	-	-	-	-
1:30PM- 2:30 PM	2:30 PM	176	125	170	168	113	91	-	-	-	-	-	-
2:30PM- 3:30 PM	3:30 PM	131	103	97	57	41	61	-	-	-	-	-	-

Event 2 (6/28/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
7:00AM- 8:00 AM	8:00 AM	395	248	309	311	234	134	1511	1204	1184	1100	1085	935
8:00AM- 9:00 AM	9:00 AM	253	246	224	216	213	205	1461	1265	1168	1108	1072	949
9:00AM- 10:00 AM	10:00AM	298	245	215	214	198	168	1200	1079	1044	969	899	746
10:00AM- 11:00 AM	11:00AM	234	212	206	185	167	117	566	539	522	510	504	493
11:00AM- 12:00 PM	12:00 PM	449	310	287	223	207	98	407	311	283	210	194	147
12:00PM- 1:00 PM	1:00 PM	208	148	146	129	111	85	94	92	89	81	90	73
2:00PM- 3:00 PM	2:00 PM	113	109	93	88	73	69	-	-	-	-	-	-
1:00PM- 2:00 PM	3:00 PM	136	109	100	95	91	84	-	-	-	-	-	-

Event 3(8/11/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
9:00AM- 10:00 AM	10:00 AM	190	175	160	152	152	169	342	276	269	269	250	242
10:00AM- 11:00 AM	11:00 AM	214	141	195	158	152	152	414	301	318	307	306	295
11:00AM- 12:00 PM	12:00 PM	202	168	166	148	160	167	390	291	314	299	284	209
12:00PM- 1:00 PM	1:00 PM	205	168	180	169	166	181	380	298	324	304	291	210
1:00PM- 2:00 PM	2:00 PM	1624	807	752	557	382	213	396	291	292	262	245	240
2:00PM- 3:00 PM	3:00 PM	369	190	161	146	122	56	118	91	84	82	78	68
3:00PM- 4:00 PM	4:00 PM	133	80	99	57	70	45	89	73	80	71	72	55
4:00PM- 5:00 PM	5:00 PM	97	67	65	23	47	12	-	-	-	-	-	-

Event 4(9/10/2018-9/11/2018)		**Cambridge Park Drive**						**Western Avenue**					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5:00PM- 6:00 PM	6:00 PM	1279	1138	1196	824	674	323	477	435	417	404	367	231
6:00PM- 7:00 PM	7:00 PM	1212	1159	1141	635	513	309	482	443	413	397	311	129
7:00PM- 8:00 PM	8:00 PM	867	650	620	612	447	264	440	434	430	405	339	156
8:00PM- 9:00 PM	9:00 PM	596	392	366	338	226	187	853	824	811	772	653	370
9:00PM- 10:00 PM	10:00 PM	489	326	291	290	212	143	532	526	433	399	236	145
10:00PM- 11:00 PM	11:00PM	258	139	105	99	45	38	380	348	263	128	97	49
11:00PM- 12:00 AM	12:00 AM	179	73	82	80	34	12	100	85	54	58	46	32
12:00AM- 1:00 AM	1:00 AM	275	107	108	106	67	43	95	49	53	57	42	29
1:00AM- 2:00 AM	2:00 AM	167	67	68	65	49	38	42	42	36	50	33	24
2:00AM- 3:00 AM	3:00 AM	134	59	59	55	41	37	54	50	26	48	30	22
3:00AM- 4:00 AM	4:00 AM	111	67	60	56	34	29	69	54	40	39	29	21
5:00AM- 6:00 AM	5:00 AM	132	50	45	45	21	16	73	57	33	17	12	10
4:00AM- 5:00 AM	6:00 AM	97	24	23	46	18	11	131	103	94	97	64	32

Event 5(11/9/2018-11/10/2018)		Cambridge Park Drive						Western Avenue					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
Composite Sample		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
7:00 PM - 7:45 PM	7:45 PM	773	699	743	691	665	492	427	408	387	359	327	251
7:45 PM - 8:30 PM	8:30 PM	554	538	536	502	469	229	269	212	193	178	152	98
8:30 PM - 9:15 PM	9:15 PM	435	416	408	376	349	217	494	456	400	387	371	207
9:15 PM - 10:00 PM	10:00 PM	374	362	361	359	357	279	252	206	196	177	154	79
10:00 PM - 10:45 PM	10:45 PM	179	176	168	159	148	98	105	83	89	59	44	17
10:45 PM - 11:30 PM	11:30 PM	103	83	71	64	47	29	35	30	26	23	18	10
11:30 PM - 12:15 AM	12:15 AM	73	54	35	38	39	38	68	64	65	59	51	24
12:15 AM - 1:00 AM	1:00 AM	84	53	37	33	28	21	92	47	46	37	24	18
1:00 AM - 1:45 AM	1:45 AM	133	126	96	83	76	43	30	20	16	17	14	9
1:45 AM - 2:30 AM	2:30 AM	110	106	66	52	39	19	28	48	47	33	30	17
Event 6(12/21/2108-12/22/2018)		**Cambridge Park Drive**						**Western Avenue**					
Sampling Period	Time	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1- hour composite sample		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
6:00PM-7:00 PM	7:00 PM	652	624	591	503	380	247	-	-	-	-	-	-
7:00PM- 8:00 PM	8:00 PM	5108	4224	4056	3354	2578	1328	-	-	-	-	-	-
8:00PM- 9:00 PM	9:00 PM	3308	2602	2761	2154	1429	1077	-	-	-	-	-	-
9:00PM- 10:00 PM	10:00 PM	1656	1248	1261	1029	705	546	-	-	-	-	-	-
10:00PM- 11:00 PM	11:00 PM	924	751	763	602	389	262	-	-	-	-	-	-
11:00PM- 12:00 AM	12:00 AM	720	671	618	499	256	203	-	-	-	-	-	-
12:00AM- 1:00 AM	1:00 AM	548	524	522	441	202	189	-	-	-	-	-	-
1:00AM- 2:00 AM	2:00 AM	540	498	497	408	198	176	-	-	-	-	-	-
2:00AM- 3:00 AM	3:00 AM	536	485	468	369	177	169	-	-	-	-	-	-
3:00AM- 4:00 AM	4:00 AM	404	368	370	193	130	119	-	-	-	-	-	-
4:00AM- 5:00 AM	5:00 AM	384	303	296	250	104	97	-	-	-	-	-	-
5:00AM- 6:00 AM	6:00 AM	324	286	286	241	99	89	-	-	-	-	-	-
6:00AM- 7:00 AM	7:00 AM	204	207	206	146	78	68	-	-	-	-	-	-
7:00AM- 8:00 AM	8:00 AM	252	218	207	125	54	47	-	-	-	-	-	-
8:00AM- 9:00 AM	9:00 AM	464	172	179	126	32	28	-	-	-	-	-	-
9:00AM- 10:00 AM	10:00 AM	244	184	203	199	20	14	-	-	-	-	-	-

Event 7(3/22/2019)		Cambridge Park Drive				Western Avenue			
Sampling Period	Time	Unf. mg/L	<100 µm mg/L	<50 µm mg/L	<25 µm mg/L	Unfiltered mg/L	<100 micron mg/L	<50 micron mg/L	<25 micron mg/L
3:00:00 AM	3:00:00 AM	1371	1292	1019	519	2139	1793	1009	432
3:30:00 AM	3:30:00 AM	1517	1261	981	405	1947	1807	989	426
4:00:00 AM	4:00:00 AM	1601	1278	1002	489	1750	1659	708	434
4:30:00 AM	4:30:00 AM	1518	1294	998	366	1950	1920	847	607
5:00:00 AM	5:00:00 AM	1406	1175	970	358	1845	1784	680	314
5:30:00 AM	5:30:00 AM	1264	1180	900	237	1706	1573	654	291
6:00:00 AM	6:00:00 AM	1401	1192	898	365	1813	1533	611	278
6:30:00 AM	6:30:00 AM	920	805	739	344	1224	1117	523	166
7:00:00 AM	7:00:00 AM	742	635	498	168	978	928	156	99
7:30:00 AM	7:30:00 AM	761	627	503	390	766	732	87	58
8:00:00 AM	8:00:00 AM	839	728	510	345	-	-	-	-
8:30:00 AM	8:30:00 AM	873	738	541	277	-	-	-	-
9:00:00 AM	9:00:00 AM	849	726	506	212	-	-	-	-
9:30:00 AM	9:30:00 AM	793	707	465	104	-	-	-	-
10:00:00 AM	10:00:00 AM	682	571	438	119	-	-	-	-
10:30:00 AM	10:30:00 AM	622	530	376	121	-	-	-	-
11:00:00 AM	11:00:00 AM	577	507	302	98	-	-	-	-
11:30:00 AM	11:30:00 AM	607	553	289	77	-	-	-	-
12:00:00 PM	12:00:00 PM	675	410	176	59	454	312	114	55
12:30:00 PM	12:30:00 PM	479	415	155	61	465	450	13	9
1:00:00 PM	1:00:00 PM	518	375	110	39	446	433	48	17
1:30:00 PM	1:30:00 PM	495	349	121	28	361	323	158	97
2:00:00 PM	2:00:00 PM	526	381	159	78	380	367	129	66
2:30:00 PM	2:30:00 PM	461	275	101	41	417	363	115	43

Event 8(5/13/2019-5/14/2019)	Cambridge Park Drive	Western Avenue

Sampling Period	Time	Unf. mg/L	<100 µm mg/L	<50 µm mg/L	<25 µm mg/L	Unf. mg/L	<100 µm mg/L	<50 µm mg/L	<25 µm mg/L
6:00:00 PM	6:00:00 PM	790	760	760	744	516	386	326	329
6:30:00 PM	6:30:00 PM	788	773	764	686	404	264	259	240
7:00:00 PM	7:00:00 PM	582	516	460	397	232	209	194	183
7:30:00 PM	7:30:00 PM	288	266	256	236	540	533	496	433
8:00:00 PM	8:00:00 PM	256	246	210	99	538	533	507	426
8:30:00 PM	8:30:00 PM	338	323	314	314	432	430	326	321
9:00:00 PM	9:00:00 PM	366	360	359	351	354	341	293	282
9:30:00 PM	9:30:00 PM	472	306	292	284	282	281	259	232
10:00:00 PM	10:00:00 PM	306	294	288	288	178	174	183	170
10:30:00 PM	10:30:00 PM	214	170	166	155	280	257	239	93
11:00:00 PM	11:00:00 PM	162	150	140	122	-	-	-	-
11:30:00 PM	11:30:00 PM	172	114	104	80	-	-	-	-
12:00:00 AM	12:00:00 AM	128	94	84	77	-	-	-	-
12:30:00 AM	12:30:00 AM	228	206	191	106	-	-	-	-
1:00:00 AM	1:00:00 AM	272	239	182	164	-	-	-	-
1:30:00 AM	1:30:00 AM	214	186	164	163	-	-	-	-
2:00:00 AM	2:00:00 AM	158	130	119	113	-	-	-	-
2:30:00 AM	2:30:00 AM	124	110	103	60	96	90	63	43
3:00:00 AM	3:00:00 AM	160	134	126	106	80	70	53	45
3:30:00 AM	3:30:00 AM	226	133	111	68	86	76	50	37
4:00:00 AM	4:00:00 AM	172	160	146	95	100	93	87	62

Event 9(6/11/2019)	Cambridge Park Drive					Western Avenue			
Sampling Period	Time	Unf.	<100 µm	<50 µm	<25 µm	Unf.	<100 µm	<50 µm	<25 µm
		mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
12:00 AM	12:00 AM	1021	987.14	975.71	869.00	-	-	-	-
12:30 AM	12:30 AM	966	941.43	907.14	701.00	-	-	-	-
1:00 AM	1:00 AM	1141	1127.14	1118.57	883.00	-	-	-	-
1:30 AM	1:30 AM	643	494.29	427.14	211.00	-	-	-	-
2:00 AM	2:00 AM	541	412.86	374.29	180.00	-	-	-	-
2:30 AM	2:30 AM	294	252.86	248.57	155.00	-	-	-	-
3:00 AM	3:00 AM	150	132.86	131.43	77.54	-	-	-	-
3:30 AM	3:30 AM	81	74.29	71.43	48.00	-	-	-	-
4:00 AM	4:00 AM	260	242.86	230.00	189.00	-	-	-	-
4:30 AM	4:30 AM	216	202.86	200.00	137.00	-	-	-	-
5:00 AM	5:00 AM	239	228.57	215.71	163.00	-	-	-	-
5:30 AM	5:30 AM	210	170.00	160.00	105.00	-	-	-	-
6:00 AM	6:00 AM	186	171.43	168.57	98.00	-	-	-	-
6:30 AM	6:30 AM	173	164.29	157.14	101.00	-	-	-	-
7:00 AM	7:00 AM	130	122.86	77.14	56.00	-	-	-	-
7:30 AM	7:30 AM	150	130.00	104.29	84.00	-	-	-	-

Event 1 (6/4/2018)	Columbus Avenue						Sparks Street					
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5:30AM- 6:30 AM	1226	1044	1042	1006	947	851	-	-	-	-	-	-
6:30AM- 7:30 AM	1282	1078	1084	1026	988	958	1088	969	853	816	768	779
7:30AM- 8:30 AM	1118	1005	1070	970	854	841	1037	979	908	813	755	946
8:30AM- 9:30 AM	418	360	368	301	292	232	1111	973	993	981	925	941
9:30AM- 10:30 AM	217	113	180	178	102	93	1094	875	991	972	834	875
10:30AM- 11:30 AM	92	91	80	63	58	44	1029	1032	933	907	880	781
11:30AM- 12:30 PM	77	82	48	32	25	11	1046	929	869	813	733	707
12:30PM- 1:30 PM	91	86	89	82	76	10	1053	892	856	792	763	720
1:30PM- 2:30 PM	69	66	55	49	40	7	945	837	932	851	782	787
2:30PM- 3:30 PM	78	72	73	14	10	3	1070	1019	900	816	779	759

Event 2(6/28/2018)	Columbus Avenue						Sparks Street					
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
7:00AM- 8:00 AM	68	63	62	52	51	43	271	174	229	231	236	213
8:00AM- 9:00 AM	197	205	167	169	151	97	411	249	326	319	349	282
9:00AM- 10:00 AM	460	386	374	368	366	379	436	424	416	386	342	333
10:00AM- 11:00 AM	83	77	59	45	65	56	218	173	186	183	187	170
11:00AM- 12:00 PM	57	57	71	40	41	33	219	140	160	105	114	56
12:00PM- 1:00 PM	34	43	32	24	35	24	71	55	64	59	66	14
2:00PM- 3:00 PM	28	35	41	9	28	29	99	81	90	90	95	54
1:00PM- 2:00 PM	32	39	27	13	30	27	156	101	121	134	136	101

Event 5(11/9/2018-11/10/2018)	Columbus Avenue					
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
Composite Sample	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
7:00 PM - 7:45 PM	692	619	578	461	319	154
7:45 PM - 8:30 PM	539	523	419	389	336	171
8:30 PM - 9:15 PM	344	331	228	198	132	98
9:15 PM - 10:00 PM	113	166	109	78	45	27
10:00 PM - 10:45 PM	33	30	28	21	16	3
10:45 PM - 11:30 PM	30	6	22	13	10	0
11:30 PM - 12:15 AM	30	15	12	9	5	0
12:15 AM - 1:00 AM	26	13	10	6	0	0
1:00 AM - 1:45 AM	36	19	17	11	8	8
1:45 AM - 2:30 AM	28	34	27	16	11	0

Event 6(12/21/2018-12/22/2018)	Columbus Avenue					
Sampling Period	Unf.	<250 µm	<100 µm	<50 µm	<25 µm	<10 µm
1-hour composite sample	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
6:00PM-7:00 PM	601	589	576	488	397	202
7:00PM- 8:00 PM	3662	3648	3568	2965	2071	1132
8:00PM- 9:00 PM	2866	2848	2776	2339	1443	989
9:00PM- 10:00 PM	842	811	740	654	588	344
10:00PM- 11:00 PM	642	612	604	575	469	276
11:00PM- 12:00 AM	672	569	566	487	411	224
12:00AM- 1:00 AM	618	593	585	436	378	201
1:00AM- 2:00 AM	445	442	400	362	329	199
2:00AM- 3:00 AM	373	334	322	293	228	167
3:00AM- 4:00 AM	261	258	233	179	133	92
4:00AM- 5:00 AM	290	223	216	198	139	87
5:00AM- 6:00 AM	247	232	177	129	92	79
6:00AM- 7:00 AM	305	299	283	210	145	93
7:00AM- 8:00 AM	376	353	325	256	169	101
8:00AM- 9:00 AM	433	414	391	336	229	182
9:00AM- 10:00 AM	473	441	429	419	378	195

Event 7 (3/21/2019-3/22/2019)	Columbus Avenue			
Sampling Period	Unf. mg/L	<100 µm mg/L	<50 µm mg/L	<25 µm mg/L
3:00:00 AM	1291	1168	1003	871
3:30:00 AM	1323	1155	1078	702
4:00:00 AM	1314	1185	998	522
4:30:00 AM	1337	1176	1022	739
5:00:00 AM	1196	1102	987	489
5:30:00 AM	693	584	379	178
6:00:00 AM	488	376	266	137
6:30:00 AM	534	448	310	155
7:00:00 AM	480	421	289	176
7:30:00 AM	426	372	245	145
8:00:00 AM	368	333	211	156
8:30:00 AM	420	349	224	111
9:00:00 AM	483	413	257	110
9:30:00 AM	463	330	244	134
10:00:00 AM	419	299	177	101
10:30:00 AM	347	265	189	92
11:00:00 AM	401	300	201	99
11:30:00 AM	215	137	109	35
12:00:00 PM	188	139	100	15
12:30:00 PM	187	121	99	19

Event 9 (6/11/2019)	Columbus Avenue			
Sampling Period	Unf.	<100 µm	<50 µm	<25 µm
	mg/L	mg/L	mg/L	mg/L
12:00 AM	1207	1203	1020	803
12:30 AM	1051	1031	880	737
1:00 AM	1009	766	662	459
1:30 AM	401	317	269	123
2:00 AM	213	159	130	120
2:30 AM	123	107	99	79
3:00 AM	117	106	100	88
3:30 AM	146	133	133	99
4:00 AM	204	196	190	140
4:30 AM	219	207	197	141
5:00 AM	253	253	229	157
5:30 AM	327	317	287	178
6:00 AM	383	377	376	209
6:30 AM	393	390	377	222
7:00 AM	403	401	387	233
7:30 AM		200	164	129