Characterization of Particle Size Distributions of Runoff from High Impervious Urban Catchments in the Greater Toronto Area

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Characterization of Particle Size Distributions of Runoff from High Impervious Urban Catchments in the Greater Toronto Area

Final Report

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NOTICE

This report was prepared by Chreyl Goncalves and Tim Van Seters, with field support provided by Christy Graham, Matt Derro, Paul Greck and Amanda Wilson.

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program, led by the Toronto and Region Conservation Authority (TRCA). The program was developed to provide the information, data and analytical tools necessary to support broader implementation of sustainable technologies and practices within a Canadian context. The main program objectives are to:

- monitor and evaluate clean water, air and energy technologies;
- assess barriers and opportunities to implementing technologies ;
- develop supporting tools, guidelines and policies, and
- promote broader use of effective technologies through research, education and advocacy.

Technologies evaluated under STEP are not limited to physical products or devices; they may also include preventative measures, alternative urban site designs, and other innovative practices that help create more sustainable and liveable communities.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Many stormwater best management practices rely, at least in part, on sedimentation for treatment of runoff. The effectiveness of these practices is strongly influenced by the size distribution of particles because smaller particles tend to have lower settling velocities. Thus, accurate data and information on the size distribution of particles in urban runoff is important.

This study assesses the accuracy and reliability of common laboratory particle size distribution (PSD) analytical methods, and identifies a range of PSDs in stormwater runoff that is broadly representative of high impervious drainage areas in the Greater Toronto Area.

To determine the accuracy of laboratory PSD analytical methods, two to three samples of a standard solution of known PSD were submitted for analysis to five laboratories. Three of these laboratories analyzed samples using laser diffraction methods and two used digital micro-imaging. Comparison of PSD results showed good overall correlation among labs, but reported differences were as high as 80% of the standard particle size in certain size ranges.

Samples submitted for PSD analysis were also analyzed for total suspended solids (TSS) at three of the five laboratories. Comparisons revealed only one lab to provide reasonably accurate and repeatable TSS results.

Following the laboratory assessment, untreated stormwater runoff was sampled from six high impervious parking and road drainage areas over the course of six rain events. Grab samples were collected within the storm sewer system, directly from paved surfaces and at storm sewer outfalls. The PSD of samples was analyzed by the two labs that best matched the standard during testing. Comparison of PSD field test results from these two labs showed no statistically significant difference in the average PSDs. However, significant differences were found in the size ranges between 250 and 14.9 µm, and 3.73 to 0.66 µm. There was no significant difference between the reported TSS values from the two labs.

Results from the lab that best matched the standard showed a median particle size range of 4.2 to 31.1 microns across the various source areas and rain events. On average, 50% of particles were finer than 13.7 microns and 90% of particles were finer than 55 microns. Although samples were collected from different source areas and at different locations within the drainage network, the variability among samples collected at a single site was often greater than the variability among samples collected at different sites.

Comparisons to other literature showed that samples collected in the Greater Toronto Area both in the present and previous studies tend to have finer particle PSDs than those collected in many other cold climate jurisdictions. This result is particularly evident in the coarser particle size range above 200 µm, which was almost never found, even in runoff sampled directly from the pavement surface. Further testing is recommended to assess how detection of these coarse particles may be influenced by the sampling methods and laboratory techniques used to analyze samples. This testing should also address the potential discrepancy between the PSD of stormwater as reported by laboratories and the actual or 'effective' PSD of urban runoff draining to stormwater treatment facilities.

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1.0 INTRODUCTION

Insoluble particles and other solid materials that become suspended in water are, in terms of total mass, the largest source of water pollution. Suspended particulate matter clouds the water, reduces the ability of some aquatic organisms to find food, clogs and abrades fish gills, inhibits photosynthesis by aquatic plants, disrupts aquatic food webs, and acts as a transport vector for heavy metals, pesticides, nutrients and other harmful substances. Once deposited, the sediment can destroy the feeding and spawning grounds of fish, and fill lakes, artificial reservoirs and stream channels.

The distance that suspended solids travel, and the type and quantity of pollutants transported, is strongly influenced by the size and shape of the particles in runoff. While large particles settle out rapidly, particles in the smaller size range remain in suspension for long distances. The smaller silt and clay sized particles have greater surface area by mass than larger particles, and thus offer more surface sites for the adsorption of dissolved constituents. In samples of highway runoff, Sansalone and Buchberger (1997) found a strong preferential association of zinc, copper and lead to finer particle sizes. Vase and Chiew (2004) reported a similar association of nutrients (phosphorus and nitrogen) to finer particle sizes in stormwater runoff in Australia.

The effectiveness of stormwater best management practices that rely, at least in part, on sedimentation for treatment of runoff is strongly influenced by the size distribution of particles because smaller particles tend to have lower settling velocities. Thus, accurate data and information on the size distribution of particles in urban runoff are critical to ensuring that these practices are appropriately designed and sized. Existing studies, however, report widely varying distributions making it difficult to select and size stormwater control devices based on the particle size distribution of runoff being treated. In Wisconsin, for instance, Selbig and Bannerman (2011) reported median particle sizes from six urban sources areas ranging from approximately 42 µm in runoff from a mixed use strip mall to 200 µm from runoff samples collected from feeder streets. A considerably smaller median particle size (6 - 9 µm) was found in samples collected through the US National Urban Runoff Program (Driscoll, 1986) and in several studies within the Greater Toronto Area (*e.g.* SWAMP studies, 2003 - 2005; Stantec, 2010). In samples of highway runoff, Sansalone et al (1998) found much coarser distributions (d_{50}=570 um) than has been reported elsewhere.

The wide variation in particle size distribution among studies is influenced by site conditions, including soil type, wind and tree canopy, as well as from human influences, such as vehicular activity and the application of de-icing materials (OMOE, 2003). Some of the variation may also be attributed to differences in sample collection and analysis methods. Studies have shown that transportation and storage of samples can influence the size distribution. Phillip and Walling (1995), for instance, found that storing samples even for an hour substantially increased the mean particle size of fluvial suspended solids due to flocculation. A similar positive correlation between fine particle sizes (2 – 7 µm) and storage time was noted by Li et al (2005), suggesting that extended storage in stormwater treatment systems can enhance settling performance.

This project expands on earlier studies by testing the accuracy and reliability of common laboratory PSD analytical methods, and identifying PSD ranges in stormwater runoff collected from six high impervious drainage areas in the Greater Toronto Area (GTA). Potential sources of variability in field data were reduced by employing a single, repeatable sampling and processing method, selecting similar types of source areas, limiting sampling to a narrow geographic range, and submitting samples to laboratories able to accurately reproduce a solution of known PSD. Field sampling PSD results are compared to other local stormwater runoff studies or studies of similar source areas to provide a context for interpretation of results. Although the sample size in this study is small, the data provide a valuable contribution to the larger body of literature on urban runoff PSDs, and are helpful in characterizing a PSD range that is broadly representative of highly impervious areas within the Greater Toronto Area.

2.0 SITE DESCRIPTIONS

Rain event runoff was sampled from six small, high impervious drainage areas that are representative of where underground sedimentation devices would typically be installed. These sites include a combination of parking lots and small residential and mixed used catchments. Samples were collected within the storm sewer system, from paved surfaces and at storm sewer outfalls (Table 2.1). In all cases, sampled runoff was untreated.

Table 2.1: Stormwater runoff sites

Site	Land Use	Major Land Cover types	Drainage area (m^2)	Sample location
Black Creek	Residential	Grass, Roof and Asphalt	2100	Storm Sewer outfall
Lawrence @ Weston	Mixed use	Roof, Asphalt	1575	Storm Sewer outfall
TRCA head office	Private Parking lot	Asphalt	1600	Runoff leaving parking lot
Bramport	Commercial parking lot	Asphalt	33,500	Storm sewer manhole
Kortright	Private Parking lot	Asphalt	3100	Runoff leaving parking lot
Earth Rangers	Private Parking lot	Asphalt	800	Runoff leaving parking lot

2.1 Parking lot sites

Four locations were selected to represent stormwater runoff originating in parking lots. The Bramport site is a commercial and retail development parking lot near the intersection of Airport Road and Bovaird Drive in Brampton (Figure 2.1). The parking lot area upstream of the sampling location is 33,500 m^2. Samples of runoff were collected from a storm sewer accessed through a manhole. The storm sewer drains to an Oil and Grit Separator unit and underground infiltration chamber system, both of which were downstream of the sampling location. During large rain events, an orifice on the storm sewer downstream of the infiltration chamber system resulted in temporary detention of water in the storm sewer system. Grab samples were taken from the surface using an extendable swing sampling pole. The intake and tubing for an automatic sampler was also installed at the bottom of the manhole to facilitate comparison of the two sampling methods.

Two sites were located within the Kortright Conservation Area near the intersection of Pine Valley Drive and Rutherford Road in Vaughan (Figure 2.2). The north site has a drainage are of approximately 3100 m^2 and is at the north east end of the main Kortright parking lot, where runoff is directed into a ditch. The south has a drainage area of 800 m^2 and is at the south east end of the Earth Rangers parking lot where the runoff flows towards a drainage ditch. Both sites are paved with asphalt. Samples were collected using grab sample bottles directly from the surface as the runoff drained off of the parking lot, and before mixing with surface waters in either of the drainage ditches.

Figure 2.1: Bramport site location

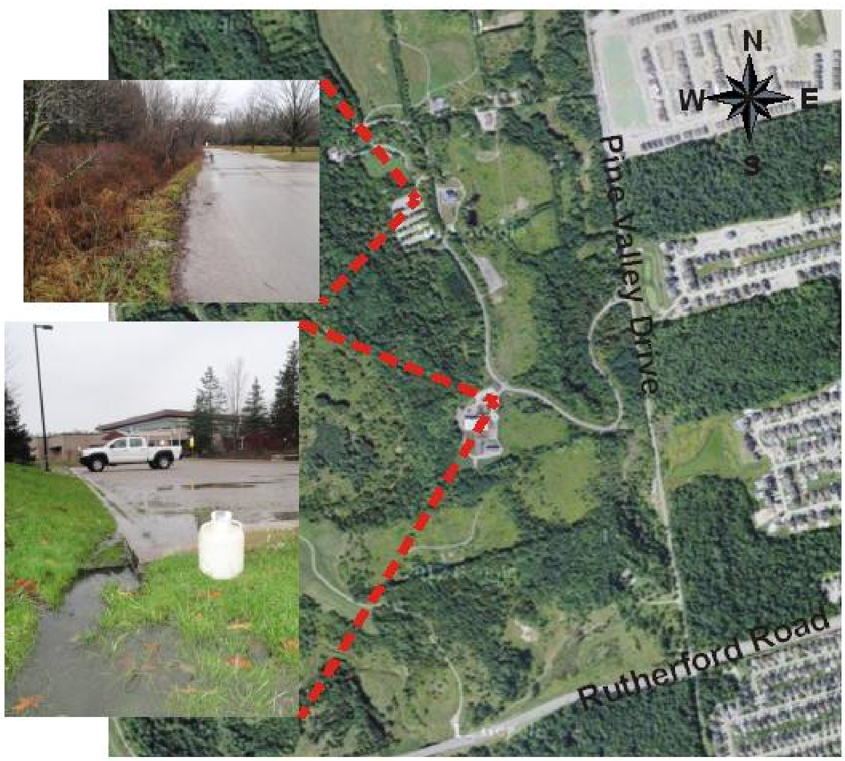

Figure 2.2: Kortright and Earth Rangers parking lots

The fourth parking lot site is located at the TRCA Head office near the intersection of Jane Street and Steeles Avenue West in Toronto (Figure 2.3). This asphalt paved lot has a drainage area of 1600 m^2 and discharges to a small wetland on the north west side of the parking lot. Samples were collected at the edge of the pavement shortly after runoff left the parking lot, prior to mixing with any water in the wetland.

Figure 2.3: TRCA Head Office parking lot. Samples were collected immediately adjacent to the paved parking area as water entered the grass channel shown in the image above.

2.2 Storm sewer outfalls

Two sites were located at storm sewer outfalls draining into Toronto streams. The Black Creek site is located near the intersection of Black Creek Drive and Tretheway Drive in Toronto and has a drainage area of approximately 2100 m^2 (Figure 2.4). The drainage area is residential, with roads, cul-de-sacs and landscaped areas.

The Lawrence at Weston site is located at the intersection of Little Avenue and Lawrence Avenue West, and has an estimated drainage area of 1575 m^2 (Figure 2.5). This site drains both residential areas and commercial plazas. At both sites samples are collected from the storm sewer outfall prior to any mixing with the stream. Samples were not taken when water levels in the stream rose above the invert of the storm sewer outfall, which typically occurred late in a storm event.

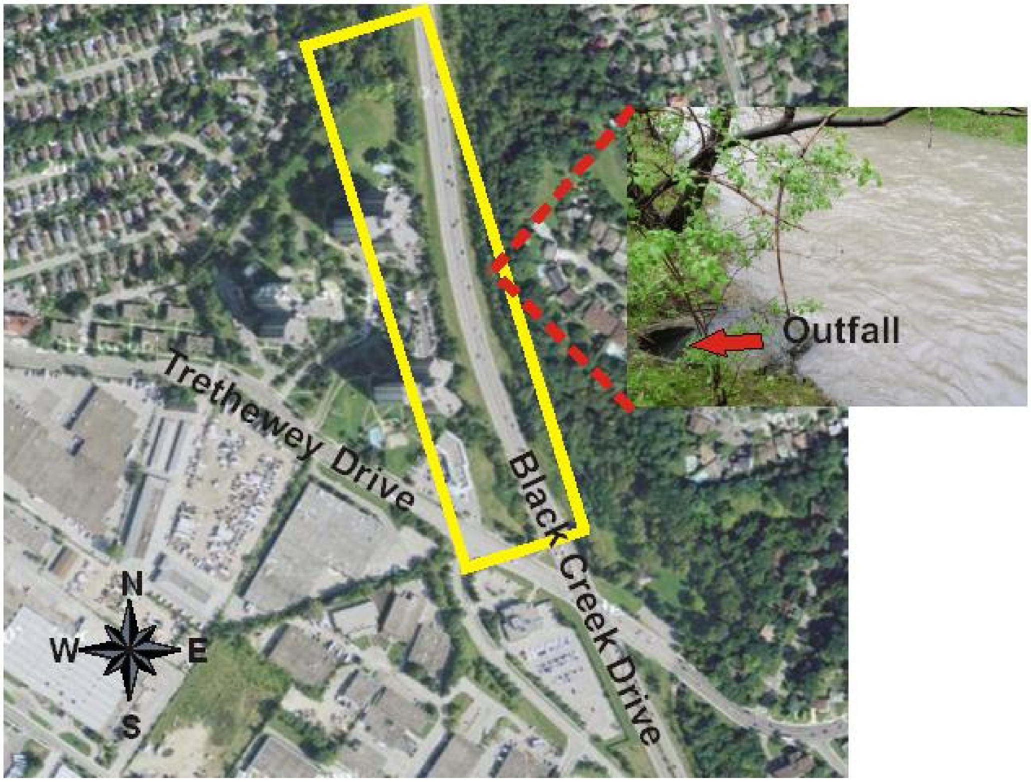

Figure 2.4: Black Creek site location

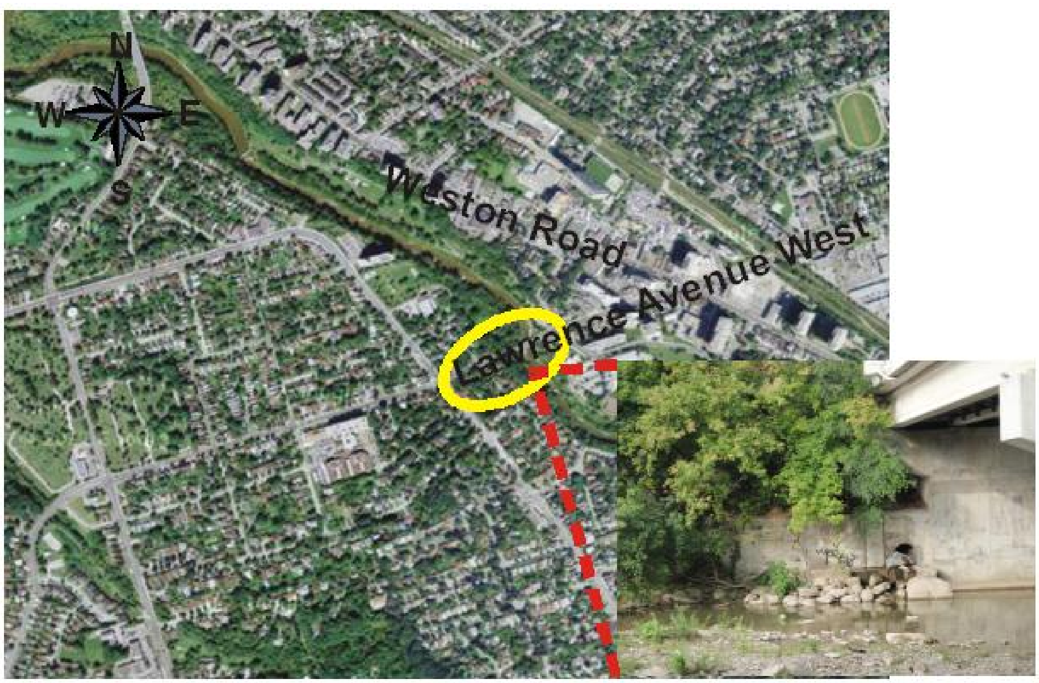

Figure 2.5: Lawrence at Weston site location

3.0 STUDY METHODS

3.1 Lab comparison

In order to determine the accuracy and comparability of laboratory analytical methods, a standard solution of known PSD was submitted to five laboratories. The standard solution was prepared by adding 75 mg of a dry silica mix (Sil-co-sil 52) to 500 mL of distilled water, resulting in a sediment concentration of 150 mg/L. The Sil-co-sil 52 product was selected because the PSD is strictly controlled as part of its manufacturing process and its median particle size (12 µm) and range (1 to 60 µm) compared well with field sample results from other studies in the GTA (*e.g.* SWAMP, 2005).

Labs received 2 or 3 submissions of this standard solution for analysis. The reported PSDs for each lab were compared for accuracy and variability among the samples. The two labs that reported the lowest variability among samples and the most accurate match to the standard were chosen for submission of the field samples.

3.2 Lab methods

Laboratory results of the samples were reported by each lab as the percent of sample volume in each size range. Reported size ranges were not consistent between labs, as there is no standard reporting range.

Each lab followed different procedures, but there were two main methods of particle size determination used. Labs A, B and D used laser diffraction, a method in which a laser beam is passed through the sample. As the beam encounters particles, the light is diffracted at an angle which is directly proportionate to the size of the particle itself. The particle size distribution of the sample is identified by the light intensity distribution pattern resulting from all the particles in the sample. Labs A, B and D referenced ISO 13320:2009 for particle size analysis using laser diffraction. These three labs used a Coulter Counter Particle Size Analyzer to identify the PSD.

Digital micro-imaging was used by Labs C and E. Again, there was no standard method followed by either lab, but the British Standard BS 3406-4 was referenced. In this method the particles in the sample are allowed to settle as the liquid seeps through a filter with a pore size of 0.4 microns. Lab C used sonication to disperse the particles prior to settling on the filter, whereas Lab E did not use sonication, and particles that had agglomerated were not separated. After settling, photomicrographs of the particles retained on the filter are taken using an optical microscope at different magnifications. An Image Processing Software is used to detect the edges of particles, and calculates the number and size of each particle based on the number of pixels it covers in the photo. Results were reported as the number of particles within each size range.

Labs A, B and C also analyzed the samples for Total Suspended Solids (TSS) based on a method similar or equivalent to ASTM D5907-09. By this method, a known aliquot of the sample is filtered through a glass fiber filter, and dried to remove any water. The weight of the remaining residue is the total amount of suspended solids in the aliquot. Results for TSS analysis were reported as the weight of suspended solids (mg) per liter of sample water.

3.3 Field sampling

Samples were collected during six rain events between October 20th and December 15th 2011. During the first three events, runoff samples were collected at three sites: Bramport, Black Creek and Lawrence at Weston. Additional sites were later added to characterize a wider range of runoff conditions. These additional sites were first sampled during the November 29th 2011 rain event. Grab samples were taken to avoid potential particle size bias associated with automated samplers (Clark et al, 2009). Since grab samples are collected at a point in time, the PSDs do not represent the event mean distribution. Rainfall measurements were obtained from tipping bucket rain gauges operated and maintained by TRCA's hydrometrics group.

3.3.1 Sample collection

Prior to sample collection, nalgene sample bottles were rinsed three times using the sample water. At Bramport, an extendable sampling pole was used to reach down into the manhole upstream of the oil grit separator, and collect a sample from a depth of approximately 30 cm below the surface. Grab samples were collected directly from the flow as it left the storm water outlet pipe (prior to entering the stream) at both Black Creek and Lawrence at Weston. At Kortright, Earth Rangers and TRCA Head Office, the samples were taken at the point, or close to the point, where the runoff left the paved surface. Once filled the containers were capped and placed in a cooler.

During the rain event on December 15th, 2011 additional samples were collected using automated sampling pumps installed at the Bramport, Black Creek and the Lawrence and Weston sites. Grab samples were collected using the grab method described above, immediately followed by a sample collected using the autosampler.

The automated samplers were set up with the intake installed inside the outlet pipe (at Black Creek and Lawrence at Weston) and at the bottom of the manhole at Bramport. Sample tubing was Teflon lined and fully purged prior to sampling following a standard procedure. Sample preparation and analysis for both grab and automated samples was the same.

3.3.2 Sample preparation

Every effort was made to submit representative samples to both Lab A and B. Sample nalgenes were inverted several times to thoroughly mix and re-suspend the particles. One bottle for each lab was filled one quarter full. The nalgene was then capped, inverted again several times and the two bottles were filled to another one-quarter (half-full). The process was repeated two more times, inverting the nalgene and filling the bottles to three-quarters full, and then filling them completely.

Samples were delivered to both Lab A and Lab B within 48 hours of rain events for analysis of both PSD and TSS. After each event the nalgenes were filled with de-ionized water for 24 hours, and then rinsed with a 10% hydrogen peroxide and water solution. After air drying, the nalgenes were sealed with the caps to avoid contamination until the next grab sample event.

4.0 LABORATORY COMPARISONS

4.1 Particle size distribution

Standard PSDs submitted to the five labs resulted in slightly different reported PSDs (Figure 4.1). Labs A and B, using laser diffraction, followed the standard test PSD closely, with the largest discrepancies in the finer range, between 1 to 4 microns. Lab D, which also used laser diffraction, reported a PSD that was much more consistent with the reported PSDs of Lab C and E, which used digital microimaging.

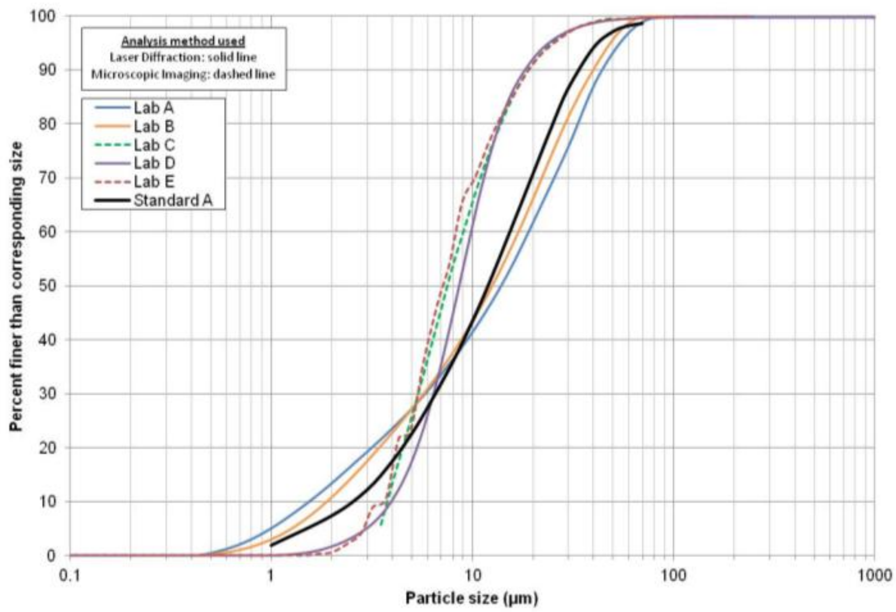

Figure 4.1: PSD for test standard and average PSD reported by Labs A, B, C, D and E.

Due to differences in the size ranges reported by the five labs, results were instead compared based on estimated D values from the plotted PSD distributions (see Appendix A). D-values from each Lab PSD were compared to the corresponding D-values of the test standard using a paired t-test (Table 4.2). Labs C, D and E were found to be significantly different from the test standard in the two-tailed test. Labs A and B, which both used laser diffraction, reported PSDs that were not significantly different from the standard PSD and much closer to the actual size distribution.

Table 4.1: Results from paired t-tests using D-values from each lab, compared to D-values of the test standard.

	Standard	Lab A	Lab B	Lab C	Lab D	Lab E
Mean	14.37	17.43	15.45	8.87	9.47	8.61
Variance	107.15	215.11	162.05	23.93	20.36	24.34
Observations	9	9	9	9	9	9
Pearson Correlation		0.998	0.999	0.997	0.995	0.992
df		8	8	8	8	8
t Stat		2.10	1.35	-3.01	-2.50	-3.15
P(T<=t) two-tail		**0.07**	**0.21**	0.02	0.04	0.01
t Critical two-tail		2.31	2.31	2.31	2.31	2.31

Consistent with the above comparisons, Lab B was best correlated with the standard, followed by A, D, C and E Although not as representative of the standard test PSD, it was interesting to note that Labs C and E, which used microimaging, were highly correlated to each other, ($r = 0.9981$), even though only Lab C used ‘sonication’ to break up conglomerates.

Labs were also evaluated upon the ability to produce PSDs that were comparable between “replicate” samples (Table 4.3). Each lab received 2 or 3 test standard samples, and the results were compared via paired t-tests. Lab A showed the best correlation between the paired replicates, with the lowest correlation being 0.971 between samples 1 and 3, and the highest being 0.993 between samples 1 and 2. Lab B and C also showed good repeatability, having correlations of 0.989 and 0.986 respectively between the two samples. Lab D and E showed the lowest repeat sample correlations among all labs tested.

Table 4.2: Correlations between repeat samples

	1 vs 2	1 vs 3	2 vs 3
Lab A	0.993	0.971	0.992
Lab B	0.989	-	-
Lab C	0.986	-	-
Lab D	0.942	0.991	0.927
Lab E	0.966	0.919	0.977

Based on the results of the standard testing, samples from the field study were submitted to labs A and B. These labs showed both the highest correlation with the test standard, and good repeatability between samples.

4.2 Total suspended solids

Labs A, B and C each evaluated 2 samples of the test standard for Total Suspended Solids. Lab A provided TSS results that had a small variance between the two samples, and was very close to the actual TSS value of 150 mg/L (Table 4.1). However results from Labs B and C showed a large variance, and reported TSS values were much lower than the standard value.

Table 4.3: TSS results from Standard Sample submission[1]

	Lab A	Lab A	Lab B	Lab B	Lab C	Lab C
Reported TSS (mg/L)	145	144	99	127	75	100
Difference from Standard	-5	-6	-51	-23	-75	-50
Variance	0.5		392		312.5	

Note: [1] Although the samples submitted contained 150 mg/L of solids, approximately 5 mg/L may have been lost through the 1.5 to 2 micron glass fibre filter used to determine TSS. Thus the exact TSS concentration of the standard is unknown, but a loss of more than 5 mg/L seems unlikely based on the size distribution presented in Figure 4.1.

5.0 FIELD SAMPLING RESULTS

5.1 Precipitation

A total of six rain events were sampled between October 20th and Dec 31st, 2011. Events ranged in size from a 24 hour cumulative rainfall of 2.4 mm on October 24th to 58 mm on November 29th, 2011 (Table 5.1). The storm on November 23rd 2011 produced the highest intensity rainfall (8 mm/min or 480 mm/h), recorded at 8:00 pm. The majority of rain events were sampled after the first flush of solids washed off the pavement surfaces, but before the rain had stopped. Samples from Earth Rangers, Kortright and TRCA Head Office were collected earlier because these sites were closer. These samples may have included all or a portion of the first flush.

Table 5.1: Rainfall events, 24 hour cumulative amounts and maximum intensity

Event # and Date	1 20-Oct	2 24-Oct	3 23-Nov	4 29-Nov	5 5-Dec	6 15-Dec
24 hour cumulative rainfall (mm)	24.4	2.4	10.2	58	7.8	6.6
Max intensity (mm/h)	8.8	9.6	480	8.8	2.4	14.4

5.2 Total suspended solids

Labs A and B also analyzed each sample for the amount of Total Suspended Solids (TSS). TSS values from Lab A and B were matched by sample date and compared using a paired t-test. Results indicate that there is no significant difference between the reported TSS values from Lab A and Lab B ($p_{two\text{-}tail} = 0.129$). However Figure 5.1 shows that as the TSS increased above 90 mg/L, Lab A reported values higher than Lab B.

Further comparisons indicate that there was no significant difference in reported TSS values when paired samples were compared on a site by site basis. Comparisons of TSS for each rain event revealed a significant difference between Lab A and Lab B values reported for the December 15th event.

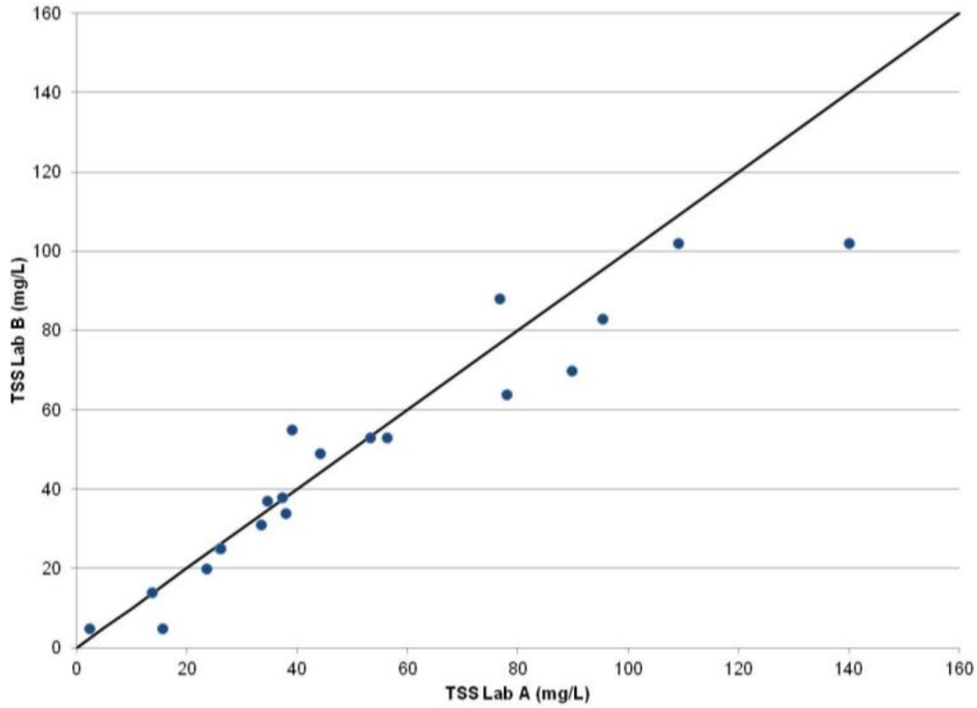

Figure 5.1: Lab A TSS values vs Lab B TSS values

5.3 Particle size distribution

A total of 44 water samples collected at the six sites during the six rain events were submitted for determination of their particle size distribution. However six samples were below the detectable limit for particle size distribution and were not analyzed. In order to compare the analytical results from the field samples, replicate samples were analyzed at Labs A and B, with both labs receiving 17 replicates. Lab A analyzed an additional 4 samples without replicates.

5.3.1 Laboratory comparison using field samples

Duplicate samples identified by Lab A or Lab B were matched by both site and event, and a matched pairs t-test was conducted. This test compared the percentage of particles in each particle range identified by Lab A, to those identified by Lab B. There were no significant differences found in any of the 17 pairs, indicating that there was no significant difference between the paired PSDs reported by Labs A and B. Average PSDs were also calculated for each lab, and compared using a paired t-test. Statistically there was no difference between the Average Lab A PSD and the Average Lab B PSD (P (T<=t) two-tail= 0.999) and the two distributions were highly correlated (r = 0.84). Appendix A shows correlations between labs at each site.

To further test for differences, each size range was tested independently in a matched pairs test. Averages were calculated for each size range, for samples analyzed by Lab A and Lab B. Significant differences between the two labs were found in the size ranges between 250 and 14.9 µm, in which Lab B identified more particles, and 3.73 to 0.66 µm, in which significantly more particles were identified by Lab A (Figure 5.2). When the 95% confidence intervals are plotted along with the average cumulative PSD of both labs, the separation of the confidence intervals confirmed this difference (Figure 5.3). While the average PSDs of Lab

A and Lab B are comparable as a whole particle size distribution, the labs differed in their ability to identify particles in certain size ranges. The cause of these differences is not known, as both labs prepared samples using similar methodologies.

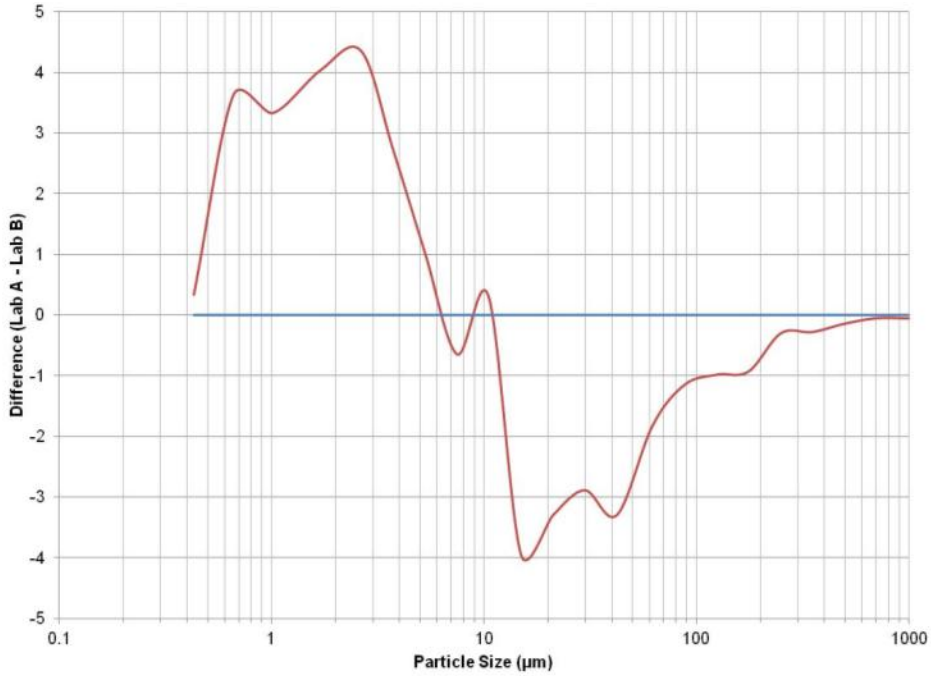

Figure 5.2: Average difference in individual particle size distribution ranges between Lab A and Lab B

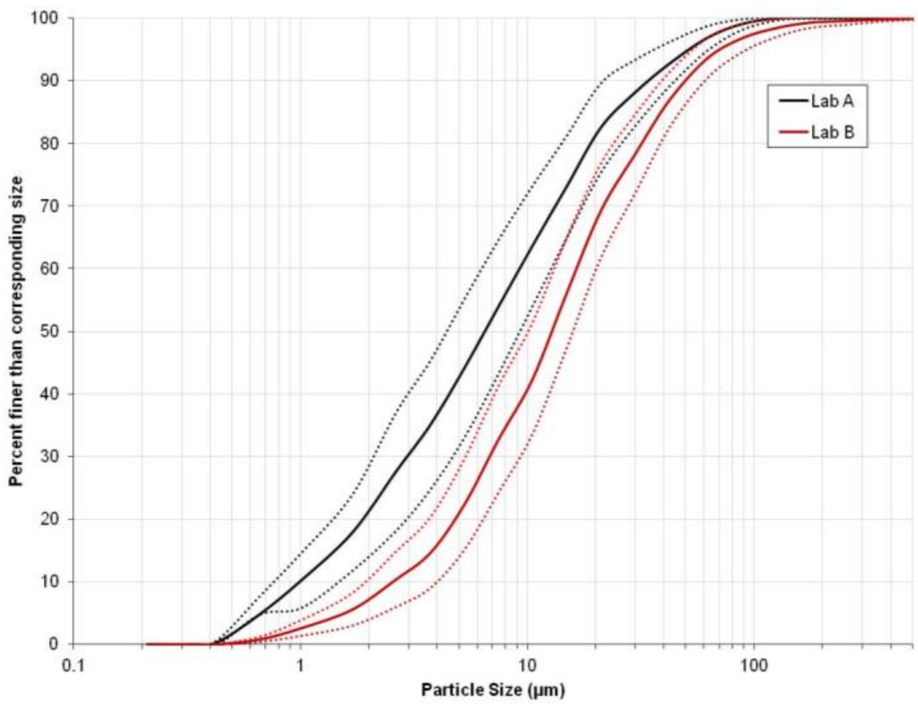

Figure 5.3: Average cumulative PSD for Lab A and B (solid lines) with 95% confidence limits (dotted lines)

5.3.2 Field sample particle size distributions

The average and individual particle size distributions for all field samples are presented in Figure 5.4. PSD and TSS results by site are compared in Table 5.2. Only lab B results are presented as this lab performed marginally better in the standard testing.

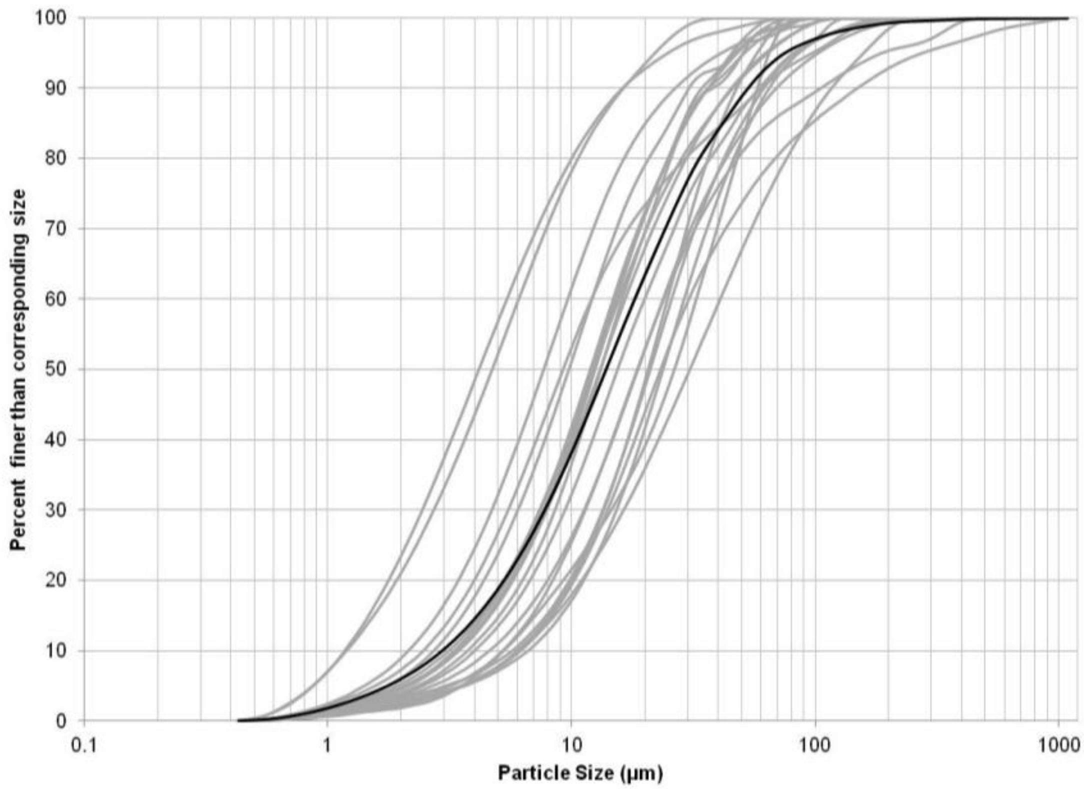

Figure 5.4: Average (black line) and individual sample (grey lines) particle size distributions in the GTA

Sites were grouped according to sample collection location (storm sewer outfall, manhole or direct runoff) and by dominant land use in the catchment (parking lot and mixed use residential/commercial). Median particle sizes varied between 7.8 µm at the Bramport location to 23.7 µm at the Black creek site, with an overall average d_{50} of 13.7 µm. TSS concentrations averaged 73 mg/L and varied from 5 mg/L to 340 mg/L.

- Particle Size Distributions for each of the six sampling locations are presented in Figure 5.5. The largest variation in PSD was found at the Bramport location, where samples were collected from the storm sewer manhole. The d_{50} values varied between 4.2 and 31.1 µm, with an overall median of only 7.8 µm. The finer distribution at this site may have been influenced by orifice control downstream of the sampling location, which would have slowed flows or created backflow conditions resulting in the deposition of larger particles within the sewer.

Table 5.2: Average particle size distributions, TSS concentrations and descriptive statistics for all sites.

Site	**BC**	**LW**	**ER**	**HO**	**KPP**	**BRAM**
Sample Location	Storm outfall		Direct asphalt runoff			storm sewer manhole
Land use	Mixed residential		Parking lot			Parking lot
# of observations	3	4	3	2	3	5
Mean TSS Conc.	52.0	30.6	132.7	48.5	56.7	63.8
Min TSS	5.0	5.0	20.0	14.0	31.0	53.0
Max TSS	102.0	64.0	340.0	83.0	102.0	88.0
Mean	34.0	16.0	20.3	20.5	26.0	16.7
Median	21.0	11.5	14.9	13.6	14.9	7.1
Mode	22.8	10.8	13.0	13.0	13.0	6.2
d_{10}	5.8	3.4	4.1	4.0	4.0	1.7
d_{20}	10.3	5.8	7.0	6.5	7.1	2.8
d_{30}	13.7	7.8	9.4	9.3	9.4	4.4
d_{40}	18.1	10.2	12.5	12.3	12.5	5.8
d_{50}	23.7	12.5	16.0	15.0	16.4	7.8
d_{60}	28.7	16.2	19.8	19.0	21.6	10.3
d_{70}	35.2	19.8	26.1	23.9	28.5	15.0
d_{80}	45.8	26.2	34.5	34.0	38.0	23.9
d_{90}	66.4	46.7	50.3	50.3	60.5	50.3
Min d_{50}	21.1	11.8	12.4	12.7	9.9	4.2
Max d_{50}	27.1	13.0	21.0	19.0	23.8	31.1
SD	18.9	1.2	5.8	8.4	12.5	14.8
CV	55.6	7.4	28.6	41.2	48.0	88.7

Note: D values are interpolated from the PSD graphs and are therefore approximate values

At the other parking lot locations, runoff was collected directly from the surface. These sites - TRCA Head Office, Kortright, and Earth Rangers - showed less variation in the distributions, and their PSDs were very similar, with d_{50} values ranging between 9.9 and 23.8 µm. The average site d_{50} was very similar among sites (15 – 16.4 µm). Stormwater outfall sites at Black Creek and Lawrence and Weston showed more variation between sites than within each site. This result was expected given that the catchment areas contributing to the outfalls are very different. Frequency distributions for each site are presented in Appendix B.

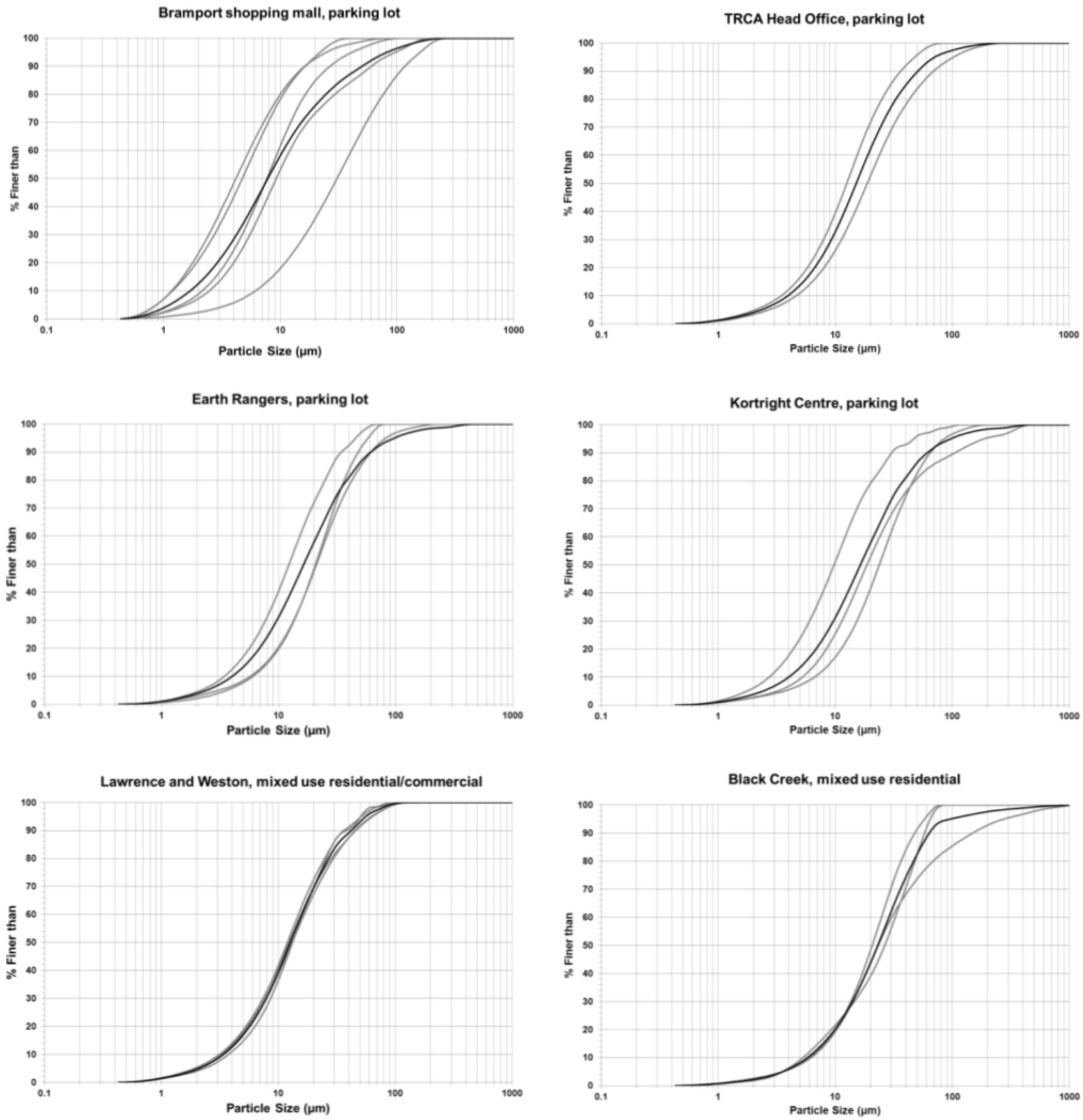

Figure 5.5: Average (black) and individual sample (grey) particle size distributions by sampling location

5.3.3 Site comparative analysis

Sites were compared using d_{10}, d_{50} and d_{90} values reported by Lab B. d_{10} values ranged from 1.19 to 6.80 µm, d_{50} from 4.15 to 31.1 µm and d_{90} from 16.39 to 153.0 µm. Comparisons were made between sites that were sampled during the same rain event. An Analysis of Variance (ANOVA) was used to compare d_{10}, d_{50} and d_{90} particle sizes. As sampling did not occur at every site during every rain event, comparisons between all the sites was not possible.

Table 5.3 presents the results of the ANOVA comparisons. D-values for the Black Creek and Lawrence-Weston sites were compared for events 2, 5 and 6. At the d_{10} and d_{50} levels, these two sites were statistically different. As mentioned previously, there was more variation in the d_{10} and d_{50} levels between these sites than within the sites.

Kortright and Earth Rangers sites were compared for events 4, 5 and 7. Statistically there was no significant difference between these sites in terms of d_{10}, d_{50} or d_{90} values. There was more variation among events sampled at these sites than between sites. Similarity between these sites was expected, as the sites are close to one another, have similar drainage areas and land uses, and were sampled at approximately the same time.

The Lawrence-Weston mixed use site was also compared to the Bramport parking lot site for events 4, 5 and 6. These two sites were statistically different for the d_{10} and d_{50} values.

Five sites were sampled during both rain events 4 and 5. The d_{10}, d_{50} and d_{90} values were compared for these two events and found no significant difference between the events. The temporal variation in the D-values at each individual site was greater than the spatial variation at different sampling sites.

Table 5.3: Results of ANOVA comparing d_{10}, d_{50} and d_{90} values

ANOVA	Sites	Sample Location	Events	$p(d_{10})$	$p(d_{50})$	$p(d_{90})$
1	BC LW	Storm outfall Storm outfall	2,5,6	0.0019[1]	0.0033[1]	0.2657
2	ER KPP	Direct surface runoff Direct surface runoff	4,5,7	0.7372	0.8270	0.5468
3	LW BRAM	Storm outfall Parking lot manhole	4,5,6	0.027[2]	0.024[2]	0.5812
4	BRAM ER THO KPP LW	Parking lot manhole Direct surface runoff Direct surface runoff Direct surface runoff Storm outfall	4,5	0.4518	0.4964	0.3233

Notes: [1]Significant at $p<0.01$, [2]significant at $p<0.05$

Average PSDs for all samples collected were calculated for parking lot runoff sites (Earth Rangers, TRCA Head Office, Kortright, and Bramport), and for mixed use sites (Lawrence-Weston and Black Creek). The average PSDs were compared using an ANOVA, and no significant difference between the two types of runoff was found ($p = 0.632$).

5.3.4 Sampling method comparative analysis

Samples collected by an automated sampler were compared to samples collected using the grab method (Figure 5.6). At the Black Creek and Lawrence-Weston sites the two methods produce similar PSDs, which are highly correlated ($r = 0.977$ and 0.981 respectively). However, the PSDs produced from the Bramport location are different. The PSD captured by the auto sampler had a much coarser distribution, and the correlation between the two methods is low (r = 0.542273) compared to the other two sites.

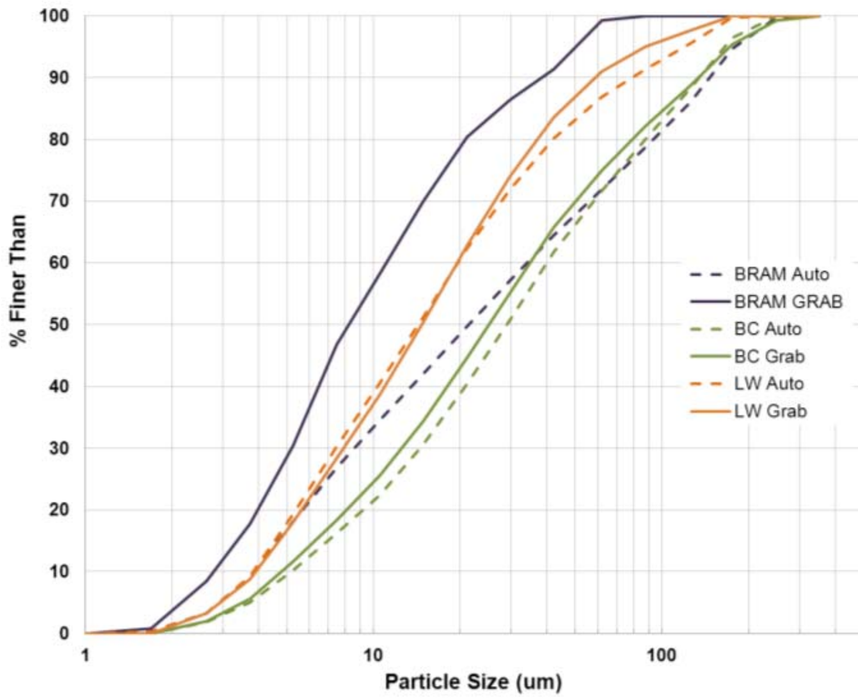

Figure 5.6: PSDs of samples collected using an auto sampler or grab method. Samples at the BRAM site were collected at different depths in the water column

The low correlation at Bramport is likely related to differences in the location of the auto sample and grab sample collected at this site. The intake for the automated sampler was located at the bottom of a manhole, and the sampling rod was not long enough to collect the grab sample at the same location. Hence, the sample was collected higher up in the column of water within the manhole, and as a result some of the coarser and heavier particles that had settled may not have been captured by the grab sample resulting in the finer grab PSD shown in Figure 5.5. This may also explain why this particular site had the finest PSD and highest coefficient of variation (see Table 5.2) among sites, and highlights the importance of integrated depth sampling where the flow stream well exceeds the diameter of the grab sampling container.

Other researchers have also evaluated the effect of auto samplers on the distribution of particle sizes. Fowler et al (2009) did not find a statistically significant difference between median particle sizes and sediment event mean concentrations in parking lot runoff collected using auto samplers and whole volume samples, but noted that some bias was evident in particle sizes greater than 160 microns. A study of highway runoff water quality in California also found no difference is PSDs between samples collected by the grab or automated samplers (Caltrans, 2001). Clark et al (2009) reported that peristaltic pump auto samplers could not effectively capture particles above 250 microns. In our study, over 95% of particles were below 200 microns, which may explain why the two types of samples were well correlated at the sites where samples were taken at the same location and depth.

5.3.5 Comparison to other studies

Table 5.4 compares results from the present study to those from studies in the GTA and other cold climate jurisdictions. Median particle sizes ranged from 5.9 µm in Toronto to 55 µm in Wisconsin. Differences in source areas, laboratory techniques and sampling methods likely explain much of the variation among studies. Researchers reporting coarser distributions (Selbig and Bannerman, 2011; Horwatich and Bannerman, 2010) tended to have a much larger number of samples with particles above 200 µm.

Table 5.4: Comparison of particle size distributions from previous studies in cold climates

Land use	# of Obs.	Location	Sample location	Sample Method	Lab Analytical Method	d_{10} (µm)	d_{50} (µm)	d_{90} (µm)	Source
Mixed residential	66	GTA	storm sewer	auto sampler	Coulter counter particle analyzer	0.9	5.9	44	SWAMP studies[1]
Parking lot	44	Markham, Toronto	storm sewer	auto sampler	Coulter counter particle analyzer	2.0	9.0	92	SWAMP studies[1]
Commercial parking lot	1	Calgary, Alberta	Storm sewer	n/a	Coulter counter particle analyzer	2.1	8.5	25.9	Lab report, 2010
Public bus yard	11	Toronto	storm sewer	auto sampler	microimaging	4.0	19.2	154.1	Stantec, 2008
Commercial parking lot	45	Madison, WI	storm sewer	auto sampler	wet sieve (>32 µm); particle analyzer (<32 µm)	< 2	55	500	Horwatich and Bannerman, 2010[1]
Mixed use	20	Madison, WI	storm sewer	auto sampler	wet sieve (>32 um); particle analyzer (<32 µm)	--	42	--	Selbig and Bannerman, 2011[1]
Parking lot	94	Madison, WI	storm sewer	auto sampler	wet sieve (>32 µm); particle analyzer (<32 µm)	--	54	--	Selbig and Bannerman, 2011[1]
Parking lot	18	New Hampshire	storm sewer	auto sampler	particle analyzer	--	46	--	Fowler et al, 2009
Mixed use	7	Toronto	storm outfall	grab	Coulter counter particle analyzer	4.0	16.4	55.1	present study[1]
Parking lot	12	Toronto, Vaughan, Brampton	direct runoff, manhole	grab	Coulter counter particle analyzer	2.6	12.4	55.2	present study[1]

Notes:[1] Approximate values based on average or median particle size distributions interpolated from graphs

The particle size distribution reported in this study is on the lower end of the range reported in the literature, and is considerably finer than the distribution reported in the 1994 version of the Ontario *Stormwater Management Practices, Planning and Design Manual* (MOEE, 1994), which is based on data from the National Urban Runoff Program in the United States (1983). This distribution, with a median particle size of

95 µm, is currently recommended by the City of Toronto for use in sizing hydrodynamic separators when site specific particle size data are not available.

6.0 CONCLUSIONS

This study characterizes the PSD of stormwater and TSS in runoff from six highly impervious urban drainage areas in the GTA and offers insights into some of the factors that may influence results. The major study findings include the following:

- Testing the reported PSD results of five laboratories against a standard of known PSD showed good overall correlation among labs but only Labs A and B reported PSDs that were statistically comparable to the standard
- TSS results from standard testing conducted at three laboratories revealed only one lab to provide reasonably accurate and repeatable results.
- The two labs that best matched the standard during lab testing were used to analyze field samples. Field test results from these labs showed the PSDs to be statistically different for particle sizes between 250 to 14.9 µm, and 3.73 to 0.66 µm.
- Field sampling results from the lab that best matched the standard showed a median particle size range of 4.2 to 31.1 µm across the various source areas and rain events. On average, 50% of particles were finer than 13.7 µm and 90% of particles were finer than 55 µm.
- Although samples were collected from different source areas and at different locations within the drainage network (e.g. direct road runoff, storm sewer, storm outfall), there was more variability among samples collected at a single site than there was among samples collected at different sites.
- Comparisons to other literature showed that samples collected in the Greater Toronto Area both in the present and previous studies tend to have finer particle PSDs than those collected in other cold climate jurisdictions. This result is particularly evident in the coarser particle sizes above 200 µm, which were almost never found, even in runoff sampled directly from the pavement surface.
- Comparisons between auto samplers and manual grab samples showed good comparability over the full range of particle sizes reported by the laboratory. The only set of samples that showed a difference was collected at different depths in the flow stream.

While this study has helped to characterize the PSD of urban runoff using a specific sampling and analytical method, questions remain about the factors influencing the wide variability of PSD results reported by different researchers. The large variation at the site level indicates that stormwater PSD is strongly influenced by local conditions and land use. However, the literature review also indicates a clear difference among studies in the presence of coarser size particles greater than 150 to 200 microns, which in this study were rarely found in samples collected either from the sewer, at the outfall or in direct runoff from the surface. Testing the five laboratories against a standard with a coarser distribution would help to determine whether these particles are effectively characterized by common laboratory PSD analysis methods. Further investigations into intra-event variability, and the role of sample collection timing and method on PSD should also be conducted.

Laboratories typically use chemical dispersants and other physical treatments to break up agglomerated particles prior to analysis. These procedures are an important part of the standard PSD analysis procedure that reduces variability associated with agglomeration caused by storage and/or mixing during transport to laboratories. However, breaking up agglomerates renders the PSD results less representative of actual field conditions. The actual field or 'effective' PSD is subject to a variety of physical, chemical and biologically mediated flocculation processes. These processes are neither well understood nor easy to simulate, but would typically produce a coarser PSD than is reported by laboratories (Phillips and Walling, 1995). Further research is needed to assess the relationship between the PSD of stormwater as reported by laboratories and the 'effective' field PSD in urban runoff, as well as the factors that may influence this relationship. Once the 'effective' PSD is better understood, additional monitoring is needed to assess the capacity of stormwater sedimentation devices to alter this PSD through treatment.

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APPENDIX A

Mean PSD Correlations

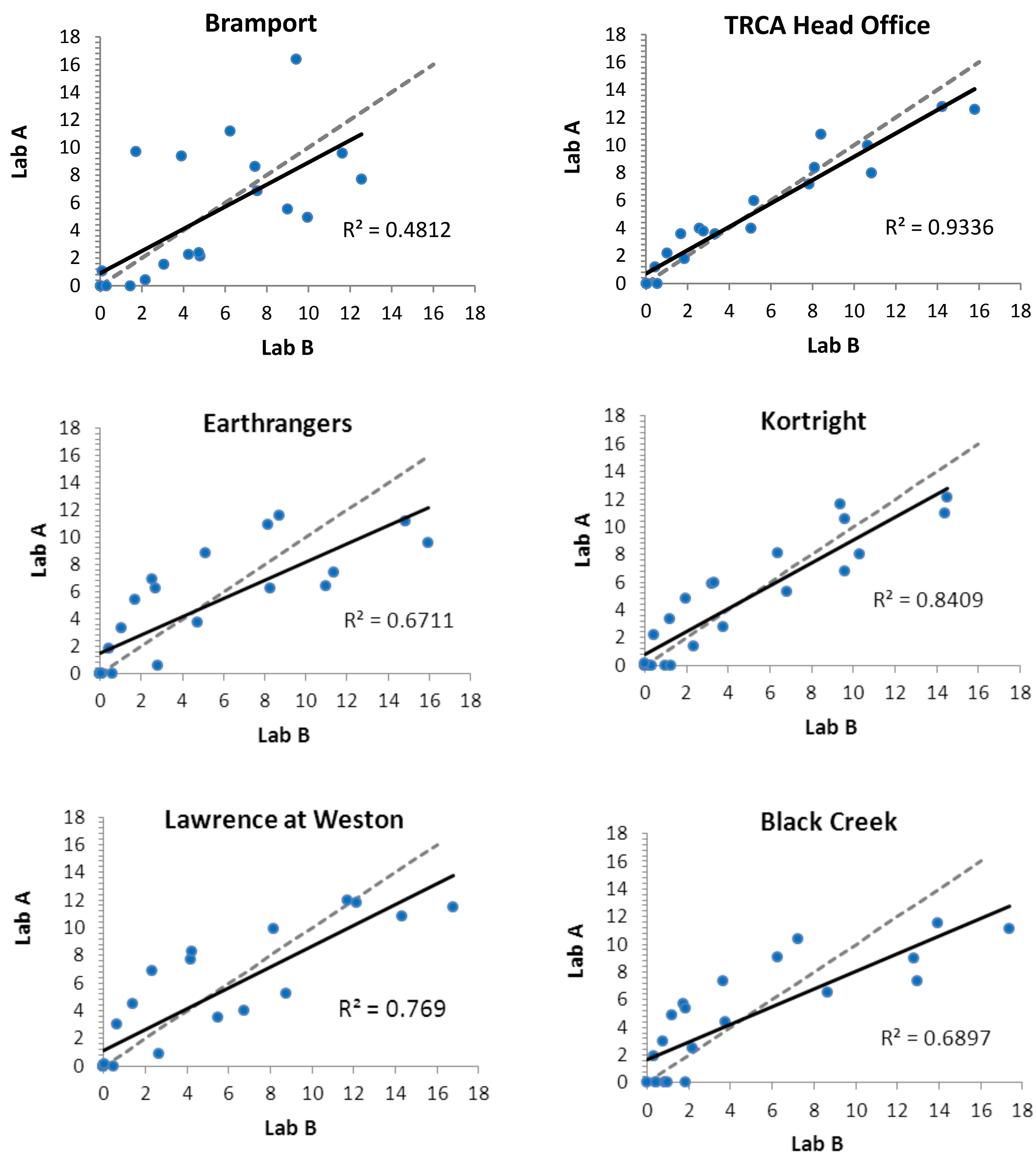

Figure A1: Correlation between mean PSD reported by Lab A and Lab B

APPENDIX B

Frequency Distribution and Average PSD for Mixed Use and Parking Lot Sites

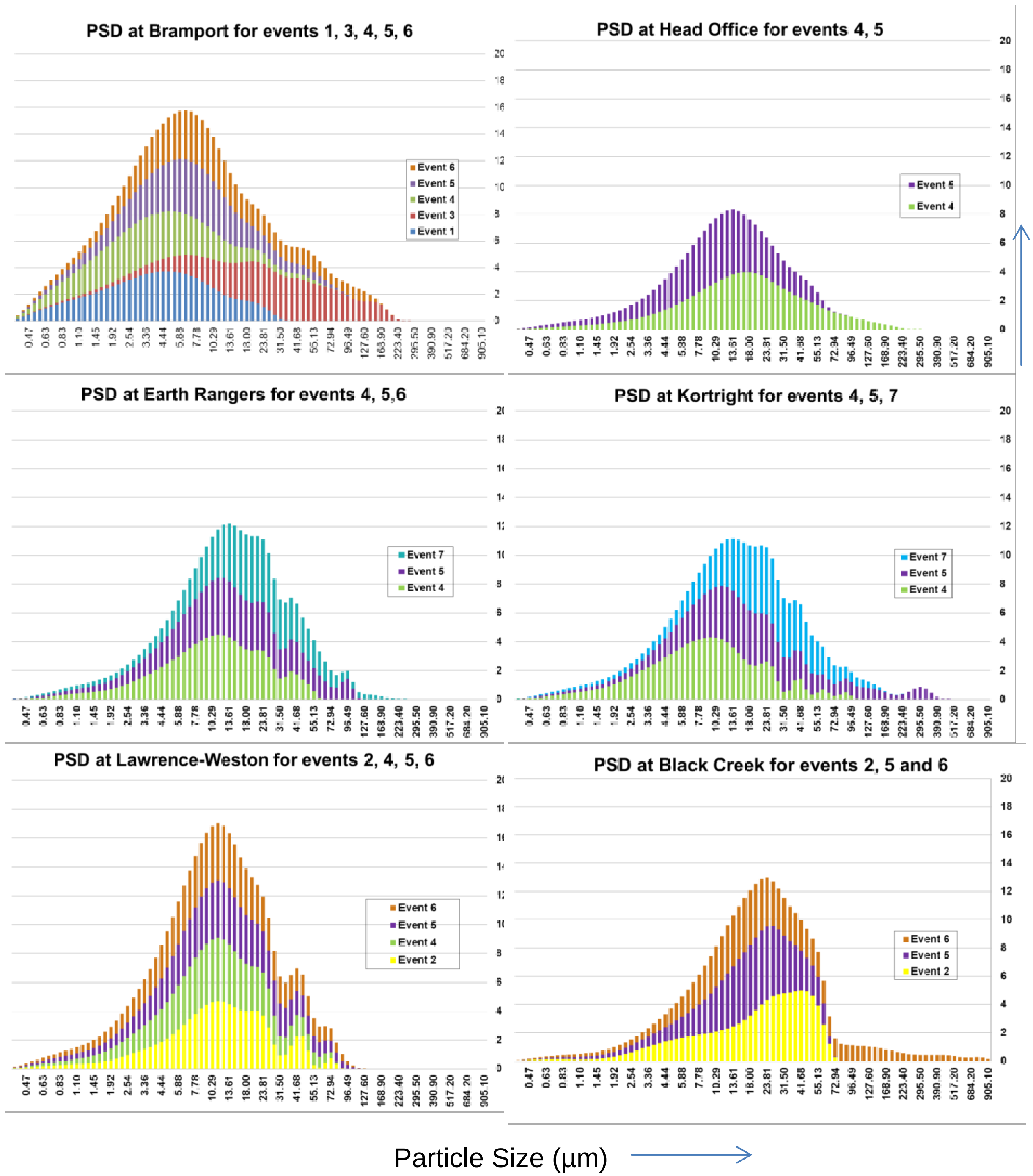

Figure B1: Frequency distribution of particle sizes by site

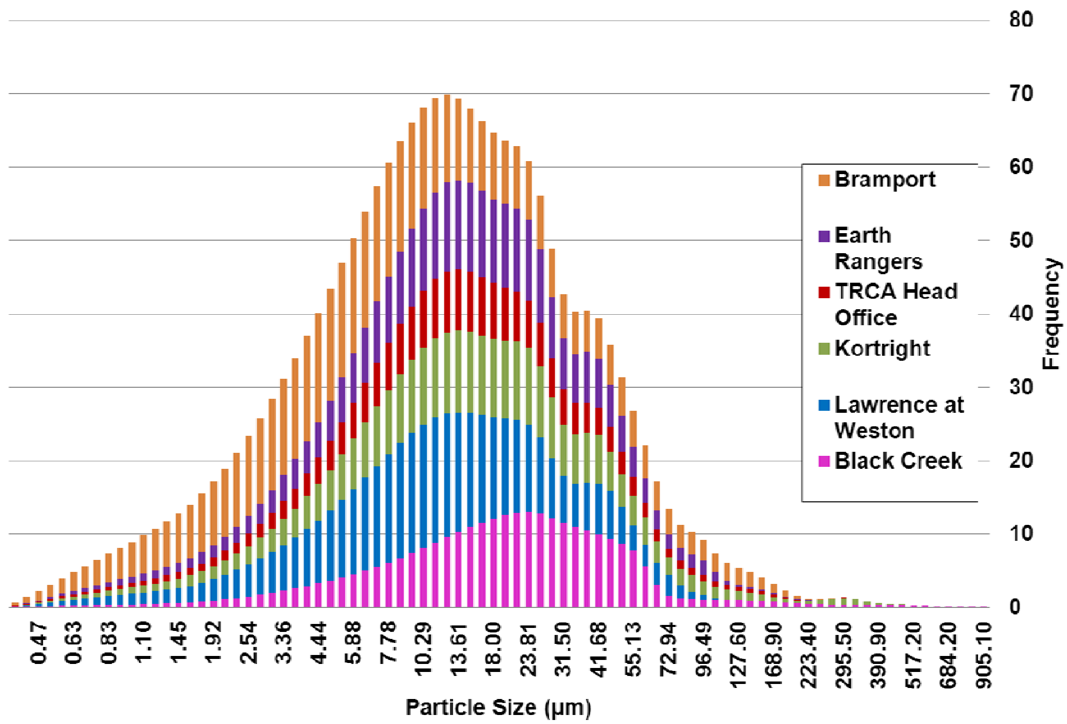

Figure B2: Average PSD for six urban runoff sites in the GTA

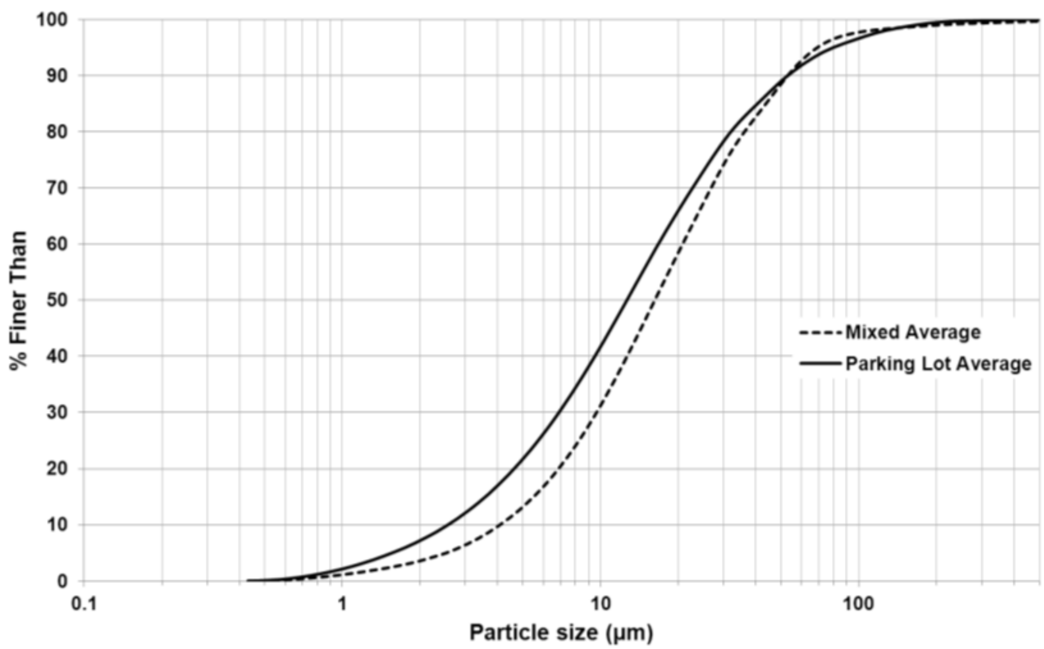

Figure B3: Average PSD for mixed use and parking lot sites in the GTA