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# Street Sweeping as a Method of Source Control for Urban Stormwater Pollution

Quintin Rochfort,[1]* Kirsten Exall,[1] Jonathan P'ng,[2] Vicky Shi,[2] Vesna Stevanovic-Briatico,[3] Sandra Kok,[1] and Jiri Marsalek[1]

[1]*Environment Canada, 867 Lakeshore Road, Burlington, Ontario, Canada L7R 4A6*
[2]*Toronto Water, City of Toronto, 55 John St., Toronto, Ontario, Canada M5V 3C6*
[3]*Transportation Services Division, City of Toronto, 55 John St., Toronto, Ontario, Canada M5V 3C6*

**The effectiveness of street sweeping as a source control measure for stormwater pollution was tested at a site in Toronto, using three types of sweepers employed by the City. A paired-plot experimental design was employed along an arterial road with a traffic volume of 26,000 vehicles/day. Typically, after several days of dry weather, one roadway plot was swept by the available sweeper (treated) and the following plot was left unswept (control). After sweeping, sediment on the roadway was sampled on both plots; wet samples were collected by washing off one half of each plot, and dry samples were collected by vacuum cleaning the remaining halves of both plots. Differences between swept and unswept plots were assessed by comparing: (a) conventional sediment quality parameters, total residue mass, and particle sizes for dry sediment samples, and (b) toxicity, conventional water quality parameters, and particle sizes in wet samples. Results were highly variable and contained large uncertainties. The greatest environmental benefits of sweeping were the reduction of the total mass of sediment on road surfaces and a reduction in some dissolved metals in the runoff (e.g., Cr and Zn).**

***Key words*: best management practices (BMPs), source control, street sweeping, urban runoff pollution**

## Introduction

Modern stormwater best management practices (BMPs) include various types of control measures applied at different spatial scales (MOE 2003). In recent years, much attention has focused on source controls, which represent "practices that prevent pollution by reducing potential pollutants at their source before they come into contact with stormwater…" (WEF and ASCE 1998). One such practice is street sweeping (also called street cleaning in the literature), which has been practiced in urban areas for centuries, but primarily as an aesthetic or housekeeping measure serving to improve street appearance. Only during the last 40 years has street sweeping been considered as a pollution control measure, serving to reduce the mass of pollutants on street surfaces potentially available for wash-off by street runoff (FWPCA 1969). After the FWPCA study, many others followed, but often with inconclusive or contradictory results. In the Nationwide Urban Runoff Program (NURP) (U.S. EPA 1983), no statistically significant reductions in pollution of stormwater from areas swept by conventional (brushing) equipment were found, and Sartor and Gaboury (1984) characterized such equipment as somewhat ineffective in removing the finest particles (<250 μm) carrying a large load of pollutants.

There have been considerable advancements in street sweeping technologies since the NURP studies, with newer street sweepers incorporating vacuum or regenerative air technologies. The vacuum assisted machines draw sediments, dislodged from the road surface by brushes, and deposit them in a hopper. The regenerative air sweepers use a blast of air to dislodge particles from the road surface, collect dislodged particles by vacuum action, and transport them into the separation chamber where filters clean the air prior to discharge or reuse. Advances in sweeping technology then generated the need to revisit the issue of stormwater pollution source control by sweeping.

The literature relevant to street sweeping studies can be divided into the following categories: (a) Accumulation of pollutants on street surface, (b) Efficiency of sweepers in collecting street deposits of solids, (c) Modelling improvements in stormwater quality by street sweeping [i.e., combining studies (a) and (b)], and finally (d) Changes in the quality of stormwater from swept streets or catchments. All of these studies are useful for developing an understanding of street sweeping benefits, or the lack thereof. Solids accumulation on street surfaces is a complex dynamic process, which is affected not only by land use activities, but also by processes reducing those accumulations by wind, traffic generated air currents, rainfall, street sweeping, and material decay (Shivalingaiah 1984). Chemical composition of solids accumulations shows a high pollution potential, with presence of heavy metals, polycyclic aromatic hydrocarbons, nutrients, and chloride (in cold climate areas) (Stone and Marsalek 1996; Deletic and Orr 2005). The efficiency of modern street sweeping equipment in collecting fine materials from the street surface has greatly improved, with the

* Corresponding author: Quintin.Rochfort@ec.gc.ca

most modern equipment (regenerative air) being capable of collecting "micron-sized" particles, and the overall collection efficiency in controlled (indoor) tests as high as 95% (ETV 2008), and only slightly lower (92%) in the case of freshly dispensed street sweepings in a 1-m swath on a street surface (Breault et al. 2005). Sweeping equipment may also produce some solids by surface attrition, as noted by German and Svensson (2002) in experiments with an industrial brush/vacuum sweeper, when applied on sites with low solids accumulations. At the same time, it is recognized that street sweeping does not remove oil and grease (WEF and ASCE 1998), and the presence of oily films or other processes may turn street solids into cohesive materials (aggregates), the presence of which greatly reduces the sweeping performance in actual conditions. The availability of solids accumulation and characteristics data, "potential" effectiveness of sweeping equipment, and local rainfall frequency data resulted in many modelling studies of street sweeping effectiveness. Using the aforementioned information, one can model the solids accumulation process, with removals caused by rainfall or sweeping, and the modelled pollutant buildup can be used to assess the resulting improvement in stormwater quality (e.g., Taylor and Wong 2002a, 2002b). In general, modelling results indicate potential improvements, which significantly exceed the actual performance observed in field studies.

Actual removals of pollutants from street surfaces very much differ from sweeper performance testing, and are affected by the aforementioned consideration of street sediments, sweeping frequency versus storm interevent times, the type and condition of the sweeping equipment, the operator's training and experience, and obstruction of sweeping operations by parked vehicles (WEF and ASCE 1998). For these reasons, the NURP (U.S. EPA 1983) report suggested that the only way of reliably assessing the environmental benefits of sweeping was by examining stormwater quality at the catchment outfall.

In stormwater quality change studies, only Sutherland and Jelen (1997), who investigated the runoff from loading docks (a different, more controlled situation than streets) concluded that modern sweepers, employing brushing/vacuuming biweekly, would be effective in reducing annual stormwater pollutant loads. Street sweeping appeared to have little effect on stormwater quality as reported in: (a) the NURP program (working with older mechanical sweepers, U.S. EPA 1983), (b) the study of Selbig and Bannerman (2007), even though they noted in their study with brush/vacuum sweepers a "reduced presence of road deposited sediments" after sweeping, and (c) a study of highway sweeping, in which brush/vacuum equipment malfunctions and poor pavement conditions led to high result variability (Waschbusch 2003).

Thus, the literature on the environmental effectiveness of street sweeping offers diverse results, with a general conclusion that aesthetic benefits and some improvements in stormwater quality can be achieved by using the most advanced well-maintained sweepers at optimized cleaning frequencies in areas with high accumulation of street debris (WEF and ASCE 1998). Furthermore, before adopting new, more intense street sweeping programs, one also needs to consider the associated costs and undertake a benefit/costs analysis.

Recognizing this often conflicting information on street sweeping benefits in the literature, and the proposed use of street sweeping as a stormwater pollution source control measure in the Toronto Wet Weather Flow Management Master Plan (City of Toronto 2003), the City of Toronto partnered with the National Water Research Institute to study environmental benefits of street sweeping with respect to: (a) reductions in sediment deposits on street surfaces due to sweeping with various types of sweepers but without comparisons of performance of individual sweepers, and (b) reductions in constituent concentrations (and toxicity) of street wash off.

## Study Area

For the purposes of this study, an experimental area, defined as a section of roadway without interfering driveways and intersections, was selected on Markham Road just north of McNicoll Avenue, in Toronto, Ontario, Canada (Fig. 1). This road is located in a commercial / industrial area and comprises three traffic lanes in each direction, with a total traffic volume of 26,000 vehicles/day. Subsections of the curb lanes on both sides of the road, delineated by a single catchbasin drainage area (approximately 50 m in length), were marked out for "test" (swept) and "reference" (unswept) experimental plots. Swept areas were immediately followed by unswept areas (in the direction of travel), on both the northbound and southbound lanes. Two pairs of plots (four plots) were investigated each time: northbound swept (NBSW), northbound unswept (NBUS), southbound swept (SBSW) and southbound unswept (SBUS). The paired reference site was used for comparisons against the swept (treated) sites to gauge the effectiveness of the sweeping process, since the road dust in the unswept areas could be different on each side of the road, depending on the traffic flow and local air transport. Within each of these four sites, the pavement area was subdivided into "wet" and "dry" sampling sections; wet sampling occurred over the area immediately up-slope from the catchbasin and dry sampling occurred further away (see Fig. 1).

## Methods

### Street Sweeping

Three types of street sweepers were available during various phases of the study. During the 2004 field season, sweeping was done with an old-technology regenerative air (ORA) sweeper and a conventional mechanical sweeper (CM). The ORA sweeper employs a turbine fan

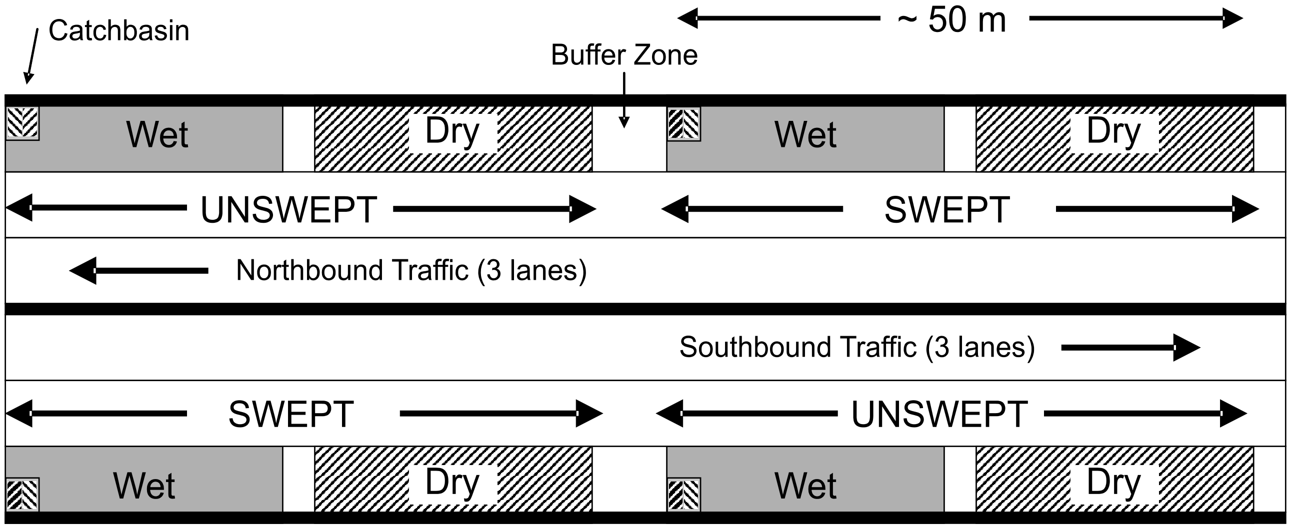


**Fig. 1.** Diagram of field site sampling locations.

and pickup head to apply a vacuum suction to the road surface and lift the sweepings into the hopper by this vacuum action. Gutter brooms with steel tines remove compacted debris from the curbs into the pickup head path. The CM sweeper uses a large counter-rotating main broom and gutter brooms to sweep road debris into a conveyer system which transports debris into the hopper.

In the 2005 and 2006 field seasons, two models of the new-technology regenerative air (NRA) sweepers were used. Both employ a technology which reuses air in a closed loop system that blasts air under pressure to dislodge sweepings from the street surface across the pickup head path and transfers them pneumatically into a collection hopper. Air containing the fine road dust (particulate matter) is cleaned by filtration, which prevents the fine road dust from being released into the ambient air environment. Gutter brooms move compacted debris from the curbs to the pickup head path. In 2005, an older model (not maintained by the City) was used, but in 2006 a new City-customized model was made available for this study.

All of the tested sweepers were equipped with dust control sprays, but these were not used during these tests in order to maintain dry surfaces for sampling. The operational speed of the sweepers was between 5 and 15 km/h, depending upon the model. Street sweepers were applied only to the "swept" experimental plots; the reference plots remained unswept. Sampling occurred between June and November each year. Following sweeping operation, dry and wet sampling was performed at each test plot. No routine sweeping took place at this site during test periods so that the solids could build up on the road surface during periods of dry weather. Ideally, sampling would take place after seven days or more of dry weather, but this was not always possible. The antecedent dry period (defined as the number of consecutive days before sampling with <7 mm of rainfall) ranged between 1 and 20 days, with an average of 7 days.

### Dry Sampling

Only the curb lanes were sampled at these sites, since previous studies have shown that almost all road-deposited sediment and litter accumulate within 1 m of the curb (Sartor and Boyd 1972; Novotny 2003). An area of asphalt pavement and concrete curb, 20 m in length by 4 m in width (the width of the curb lane), which was furthest away from the test catchbasin, was brushed and vacuumed with a powerful industrial vacuum (Nilfisk-Advance 2050, constructed of stainless steel), to collect a sample of the road-deposited sediment. The broom was moved back and forth gently in front of the vacuum head to loosen any attached fine particles. The vacuum head was moved from the curb to the road crown in overlapping strokes; each pass was overlapped by one-half the width of the vacuum head each time. The vacuum head was also run along the concrete curb edge to collect material retained in the corners. Total sampling time was 20 minutes, allowing the operator to pace the collection of the sample and maintain the same technique in each case.

Samples were removed from the vacuum using stainless steel trowels and disposable brushes, and were stored in amber glass jars. Total mass of the sample was determined for each site prior to sample splitting. Samples were split using the coning and quartering method, and a whole subsample was prepared for particle size analysis. The rest of the sample was sieved using two mesh sizes to create three fractions: <64 µm, 64 µm to 2,000 µm, and >2,000 µm. Sample fractions >2,000 µm were weighed and discarded. The remaining two fractions were submitted to a Canadian Association for Environmental Analytical Laboratories (CAEAL, now CALA) accredited laboratory for chemical analyses using in-house analytical methods based either on the U.S. Environmental Protection Agency methods (U.S. EPA 2008) or *Standard Methods* (APHA et al. 2005). Polycyclic aromatic hydrocarbons (PAHs) were Soxhlet extracted using a hexane / acetone mixture, and the samples were run in hexane on a gas chromatograph equipped with a mass-selective detector (GC-MSD) operating in selective ion mode (SIM) (based on U.S. EPA 2008). All of the remaining solids-based analytical methods were based on *Standard Methods* (APHA et al. 2005). Acid extractable metals were determined using a microwave-assisted, concentrated nitric acid extraction of the sediments, followed by inductively coupled plasma-mass spectrometry (ICP-MS) analysis. Total Kjeldahl nitrogen (TKN) and total phosphorus (TP) were digested using sulfuric acid (with potassium sulfate and mercuric oxide catalysts) at 380°C, and analyzed using an automated spectrophotometer. Total organic carbon (TOC) was analyzed by high temperature combustion with nondispersive infrared (NDIR) detection.

### Wet Sampling

The wet sampling was performed on an area equal (in length) to that used for the dry sampling (20 m by 4 m), but located immediately upstream of, and directly draining into, the catchbasin. The round catchbasin grate ($D$ = 0.61 m) was removed and replaced with a catchbasin insert that collected all of the runoff from the site. The insert was sealed to the catchbasin with a flexible temporary caulking and a small recirculating pump was lowered to the bottom to provide mixing and facilitate sample removal from the insert. In addition, berms were placed downstream of the catchbasin to ensure that all of the runoff was retained within the test area. Wash water was municipal tap water which had been dechlorinated by bubbling air through it and by further aging the water overnight. A stainless-steel pump and reservoir fed either a gentle rain-like spray head (used during the first year) or a water broom (more focused water jets) which was used to generate runoff. The surface was washed from the crown of the road towards the curb and then down along the curb. For most tests, 110 L of tap water was applied within the 16 minutes and generated roughly 70 L of runoff. This simulated a rainfall event with an intensity of 5.16 mm/h, and a runoff coefficient of 0.64, indicating the initial hydrological abstraction (surface wetting and depression storage) of 0.5 mm.

Three 20-L pails of wash-off water were collected for toxicity testing. Laboratories at the Ontario Ministry of Environment performed both rainbow trout (*Oncorhynchus mykiss*) LC50 96-hour static nonrenewal tests (EPS 1/RM/13, Environment Canada 2000a) and *Daphnia magna* LC50 96-hour static nonrenewal tests (EPS 1/RM/11, Environment Canada 2000b). Microtox tests were performed at Environment Canada. The acute Microtox EC50 15-minute test was performed on the samples following the standard protocol (AZUR Environmental 1998).

Water samples collected at the sites were analyzed for total suspended solids (TSS) according to *Standard Methods* (APHA et al. 2005). Particle size analysis was performed using a Malvern laser particle size analyzer. All other sample analyses were performed by a CAEAL-accredited laboratory. PAHs were liquid/liquid extracted using dichloromethane and analyzed by gas chromatography-mass spectrometry in selective ion mode (SIM) (U.S. EPA 2008). All remaining analyses were performed using methods based on *Standard Methods* (APHA et al. 2005). Total and dissolved (0.45-μm-filtered) metals were analyzed by ICP-MS. TKN and TP were digested using sulfuric acid at 380°C and analyzed using an automated spectrophotometer. TOC was analyzed by high temperature combustion with nondispersive infrared detection.

All data collected from both wet and dry sampling were analyzed using a statistical software package (Graphpad / Prism V. 4.03). Box and whisker plots were used in preference to parametric statistical tests based on a normal distribution of data and requiring a higher number of replicates. Log-transformed data sets were analyzed using the Wilcoxon Matched-Pairs Signed-Rank test with $\alpha = 0.05$, in order to determine the significance of differences between median values before and after sweeping.

## Results and Discussion

### Road Deposited Sediment

Road deposited sediments (RDS) were defined as those substances originating from the erosion of surrounding soils, dry and wet atmospheric deposition, biological inputs from leaf material, road surface wear, road marking degradation, vehicle wear (tires, brakes, body, etc.), vehicle fluids, and particulate emissions (Pitt and Clark 2003). In spite of the relative wealth of literature on street sweeping (reviewed, e.g., in Pitt et al. 2004), the knowledge of street sediment processes and of their variability, including sediment removal by washing/sweeping and rainfall/runoff, appears to be incomplete. Sediment accumulation rates greatly varied at the plots studied, ranging from 18 to 405 kg/curb km in individual runs, for comparable dry weather periods of accumulation, but from different sides of the road. In these accumulations, the finest fraction (silt and clay) represents a minor component, typically less than 6% of the total accumulation; the rest is gravel and sand. Recognizing that all types of sweepers should easily remove coarse particles, field comparisons of sweepers suffer from low sensitivity of such tests; differences in removing the finest fraction may be masked (overshadowed) by experimental errors and low numbers of field tests (given by frequent rainfalls). For this reason, no comparisons of the four different sweepers employed at various times in this study have been attempted. In fact, for low accumulations (about 30 to 50 kg/curb km), it was impossible to discern between RDS accumulations in unswept and swept plots.

Figure 2A shows the results of sediment loading analysis before and after sweeping for all runs combined

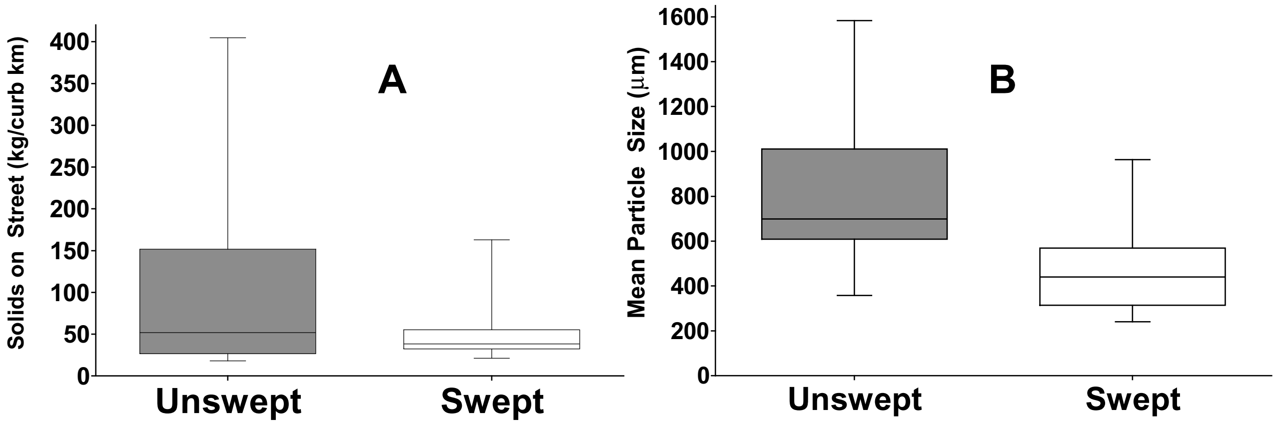


**Fig. 2. A.** Total mass of solids (RDS) collected at swept and unswept sites ($n$ = 25 data pairs); **B.** Particle size of RDS at swept and unswept sites ($n$ = 25 data pairs).

($n$ = 25). It was noted that there were large differences in RDS mass between the southbound and northbound lanes, which contributed to the large difference in upper and lower limits in the figure. The difference in the median values of RDS mass before and after sweeping was found to be statistically significant ($p$ = 0.0236) according to the Wilcoxon Signed-Rank test. Additionally, sweeping reduced variability in the mass of solids on the road under various conditions, as indicated by the reduction in span between upper and lower limits after sweeping (i.e., the whiskers), as well as the smaller interquartile range (i.e., the box).

The difference between the southbound and northbound lanes was further analyzed by plotting the total RDS mass versus the number of dry days (Rochfort et al. 2007). While the northbound data showed a typical trend—slowly increasing rates during the first 1-3 days, followed by more or less constant accumulation values (30-50 kg/curb km) for longer dry weather periods—the southbound data showed a number of high rates (160-360 kg/curb km) greatly exceeding the normal rates, which were reported in the literature to range from 50 to 115 kg/curb km (Pitt et al. 2004). Accumulations of RDS observed at the study site greatly varied, both temporally and spatially, and no clear correlation with the antecedent dry period could be detected.

The very high rates indicate the presence of another mechanism contributing to RDS build up, which could be construction traffic through the site, with loaded trucks travelling southbound and empty northbound. Particle size analysis showed that the composition of RDS samples was highly variable, with gravel content ranging from 4 to 42% by weight; sand from 54 to 91%; and silt and clay from 2 to 6%. Mean particle size of the sediment samples from unswept sites was 544 μm northbound and 761 μm southbound; both sizes correspond to a coarse sand classification.

With respect to sweeping data, there appeared to be a lower RDS loading limit of about 30 kg/curb km, below which sweeping was ineffective (compared to the 'no sweeping' alternative). Within the realm of experimental uncertainties, for high RDS loadings, sweeper effectiveness was largely due to better removal of gravel (up to 88%) and sand (up to 62%).

These findings are confirmed by other studies. In six trials performed by Waschbusch (2003) with the Enviro Whirl street sweeper (which employs brushing and vacuum action), the sweeper was capable of removing 50% of the RDS at a loading of 140 kg/curb km (the upper limit for their tests); for comparison, the NRA sweeper employed in our study removed 65% at the same loading rate (which was mid-range for our tests). Waschbusch (2003) experienced the same lower limit of RDS of 28 kg/curb km (100 lb/curb mile), below which sweeping becomes ineffective in RDS removal. Recognizing the cost of sweeping, it appears that sweeping operations are not beneficial in areas with low RDS mass, or when such accumulations were reduced by an antecedent rain storm.

Following particle deposition on street surfaces, other processes take place: particle aggregation, consolidation, coating by oil, decay (Shivalingaiah 1984), mechanical processing by sweeping equipment (brushing, wetting, vacuuming), and removal by rainfall and runoff. These processes are poorly understood and this contributes to large uncertainties when assessing the effectiveness of street sweeping in pollution control. Notwithstanding this caveat, the data collected by dry sampling of experimental plots in our study indicate that the sweepers produced significant reductions ($p < 0.05$) in the case of relatively large solids accumulations. It can be speculated that these sweepers would provide some measure of stormwater pollution source control if applied, according to the recommendations of WEF and ASCE (1998) in urban areas where high solid deposits exist (e.g., major traffic corridors), at a relatively high sweeping frequency (related to the local rainfall inter-event time), with well-trained staff using well-maintained sweeping equipment (which should be kept in peak operating condition to maximize the efficiency of sweeping).

**TABLE 1.** Qualitative reductions of solids and chemical loads (mass/curb km) from roads by sweeping[a,b]

| | *Solids* | *TOC* | *TKN* | *TP* | *Cu* | *Cr* | *Pb* | *Zn* | *Phe* | *Fl* | *Py* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Dry RDS | – – | δ– | δ+ | – – | δ– | δ– | δ– | δ– | δ+ | δ+ | δ+ |
| Road wash-off | δ– | δ+ | δ– | δ+ | δ– | – – | ++ | – – | δ+ | δ+ | δ+ |

[a] Significance of differences evaluated by Wilcoxon signed-rank test with α = 0.05: δ– statistically insignificant reduction; – – statistically significant reduction; δ+ statistically insignificant increase; + + statistically significant increase.
[b] Phe = phenanthrene; Fl = fluoranthene; Py = pyrene.

The mean particle sizes on individual swept and unswept plots were calculated by the method of moments, which produces a weighted average based on the entire particle size distribution (Folk 1965). Sweeping significantly ($p < 0.0001$) reduced the median value of the above mean particle sizes in RDS on swept plots by 37%, indicating a preferential removal of coarser particles (Fig. 2B). It is important to note that even for the best performing sweeper, there were solids left on the road surface after sweeping that had a mean particle size of over 400 µm, and the mass of fine particles (<64 µm) left on the surface was over 2 kg/curb km.

Removal of RDS from street surfaces is beneficial for such reasons as reducing the entry of sediment into runoff and sewers, and reducing export of sediments from the catchment and their deposition in downstream BMP structures, with concomitant adverse impacts of such deposits on BMP structure performance (e.g., reductions in the dynamic storage of stormwater management ponds). Concerning stormwater quality, the main interest is in removing chemical constituents from the street surface, which after rainfall may contribute to either suspended or dissolved loads of pollutants in stormwater. Qualitative removals of eleven constituents (solids, TOC, TP, TKN, Cu, Cr, Pb, Zn, and the PAHs phenanthrene [Phe], fluoranthene [Fl], and pyrene [Py]) by sweeping street solids are summarized in Table 1. The data in the table indicate that there were only 2 statistically significant removals (solids with $p = 0.023$ and TP with $p = 0.006$), and the remaining parameters displayed no statistically significant change.

Two examples of constituent removals are shown in Figs. 3A and 3B for TP and Zn, respectively. The TP data closely mimic the solids removal chart (Fig. 2A), similarly showing a significant ($p = 0.027$) reduction after sweeping, and indicating that TP is mostly bound to solids. Zinc was removed in experiments with high solids loadings (>50 kg/curb km), which was also true for all the other trace metals and PAHs studied. In general, however, sweeping did not significantly reduce the mass of Zn in RDS ($p = 0.214$).

Concentrations of chemicals in RDS are also of interest, partly because of concerns about disposal / reuse of street sweepings, and partly because such information contributes to the wealth of data on pollutant accumulations on streets. Detailed listings of such concentrations can be found in Rochfort et al. (2007); median concentrations (in mg/kg) of the metals Cr, Cu, Pb, and Zn, and the PAHs Phe, Fl, and Py in whole RDS samples (i.e., <2,000 µm) are presented in Table 2. The concentrations of metals in RDS actually increased slightly with sweeping, as would be expected when larger solids (i.e., those with lower relative surface area and lower metal concentrations) are preferentially removed.

Similar findings were reported by Deletic and Orr (2005), and Robertson and Taylor (2007) who monitored three urban sites in Manchester, U.K. Lead and Zn displayed local variability in time, whereas Fe and Mn showed temporal variability, which was consistent across sites. As expected, the silt and clay fraction (<63 µm) contained the highest Pb, Cu, and Zn concentrations,

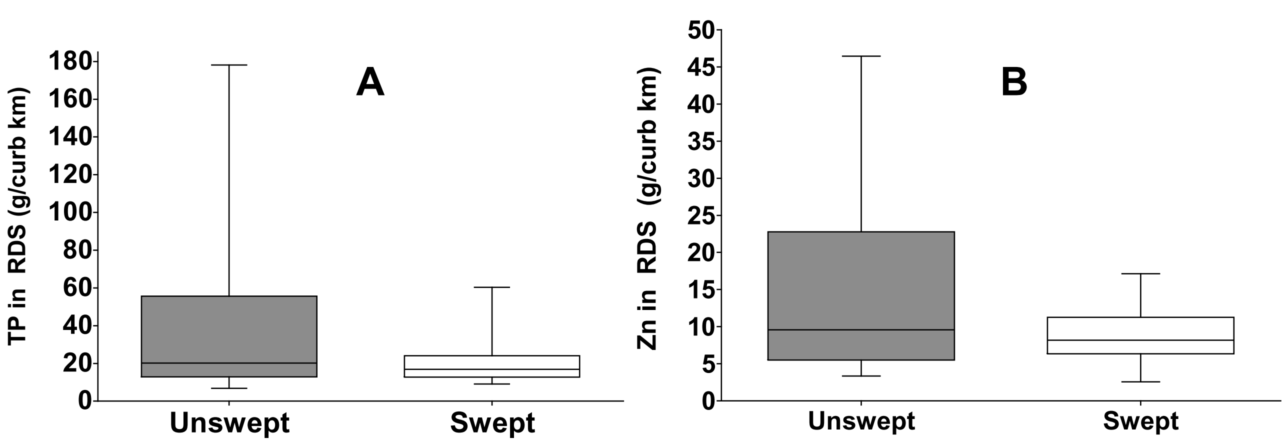


**Fig. 3. A.** Mass of TP in RDS ($n = 25$); **B.** Mass of Zn in RDS ($n = 25$).

**TABLE 2.** Selected median trace metal and PAH concentrations in street sediment (<2,000 µm) from swept and unswept test sites compared with sediment quality guidelines

| | Sample size "*n*" | | Median metal concentration in RDS (mg/kg) | | | | Median PAH [a] concentration in RDS (µg/kg) | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | *Cr* | *Cu* | *Pb* | *Zn* | *Phe* | *Fl* | *Py* |
| Sediment quality guideline | | ISQG [b] | 37.3 | 35.7 | 35 | 123 | 41.9 | 111 | 53 |
| | | PEL [b] | 90 | 197 | 91 | 271 | 515 | 2,355 | 875 |
| Unswept | 25 | | 50.5 | 76.9 | 27.0 | 170 | 258 | 452 | 347 |
| Swept | 25 | | 70.3 | 81.2 | 37.7 | 196 | 398 | 666 | 561 |

[a] Phe = phenanthrene; Fl = fluoranthene; Py = pyrene.

[b] ISQG = interim sediment quality guideline; PEL = Probable Effect Level. Source: Canadian sediment quality guidelines (CCME 2002)

which would cause the greatest environmental concerns due to risk of resuspension and inhalation, and transfer to receiving waters during rain events. Furthermore, these fine particulates may not be easily controlled by street sweeping.

The median concentrations of all of the selected metals and PAHs exceeded the interim sediment quality guideline (ISQG; CCME 2002), but not the probable effect level (PEL), values in almost all cases. The only exception was that of Pb in the unswept samples, which was slightly below the ISQG value. In 50% of all RDS samples from unswept sites, one or more PEL guideline limits for the selected metals or PAHs were exceeded, and such materials would represent a pollution risk if transported to the receiving waters. A comparison of the PAH concentrations of RDS samples from this study with PAH concentrations from a multilane divided highway (Marsalek et al. 1997), found that those in the current study were 10 times lower. As sweeping primarily removes coarser particles with lower concentrations of trace metals and PAHs, the concentrations of trace metals and PAHs in RDS samples from swept sites showed increasing trends, but few of these comparisons were statistically significant.

Furthermore, concentrations of Cr, Pb, and Zn compared well with those reported by Stone and Marsalek (1996) for an industrial city, but concentrations of Cu, Pb, and Zn represented only 20 to 50% of those in sediment from the aforementioned highway, with a 3.6-times higher volume of traffic (Marsalek et al. 1997). Note also that metal concentrations in northbound lane RDS were consistently greater than those in the southbound lane RDS, supporting the notion of southbound RDS dilution by construction truck traffic.

## Road Wash-Off

Comparisons of dry and wet sampling of experimental plots in this study revealed differences in sizes of the particles collected by these two methods. Catchment wash-off in wet sampling removed practically only clay and silt from the street surface (more than 90% of the total mass was in particles <50 µm), with a median particle size of approximately 10 µm. The total mass removed by this process greatly exceeded the mass of silt and clay removed by dry sampling with gentle brushing and vacuuming with an industrial vacuum cleaner. This suggests that washing may be a more effective process for detaching the finest particles from the street surface or breaking up fine particle aggregates than brushing/vacuuming, as also observed by Deletic and Orr (2005). In a few cases, increased solids wash-off was noted after sweeping. This was also reported in earlier studies by other researchers who surmised that those solids left behind after sweeping became detached from the surface and were fine enough that they could then be more easily washed off (Sartor and Gaboury 1984), or that the solids removed provided a protective covering for the fine material, which was then exposed and thus more easily washed off the surface. It was also noted by German and Svensson (2002) that sweeping "produced" some solids by attrition of road surfaces.

Median particle size in street wash-off collected in the catchbasin was 10.1 µm for the unswept areas, and 9.59 µm for the swept areas, indicating that there was little to no effect of sweeping on the size of particles transported by "gentle" washing from the street surface to the sewer inlet. Overall, the median for the total solids mass washed off from unswept sites was 9.8 kg/curb km; or just 19% of the total RDS mass collected by vacuuming. Assuming the same loading of both (wet and dry) plots, this showed that only a small portion of the material that the sweepers left on the street was actually transported by wash-off during a simulated rainfall event; the actual amount washed off during rainfall would vary depending upon the intensity and duration of the rainfall. In the wash-off experiments, the equivalent rainfall intensity was low and duration short. Furthermore, the kinetic energy of rain drops landing on the street surface may be important for dislodging particles from the surface, and this process was not simulated in wet sample collection.

It has been suggested that the RDS possesses high contents of organic materials, and the surface of coarser sediment particles is coated with various chemicals, oil, or fine particles (Brinkmann et al. 1999). As the sediment ages on the road surface, it may become cohesive (or

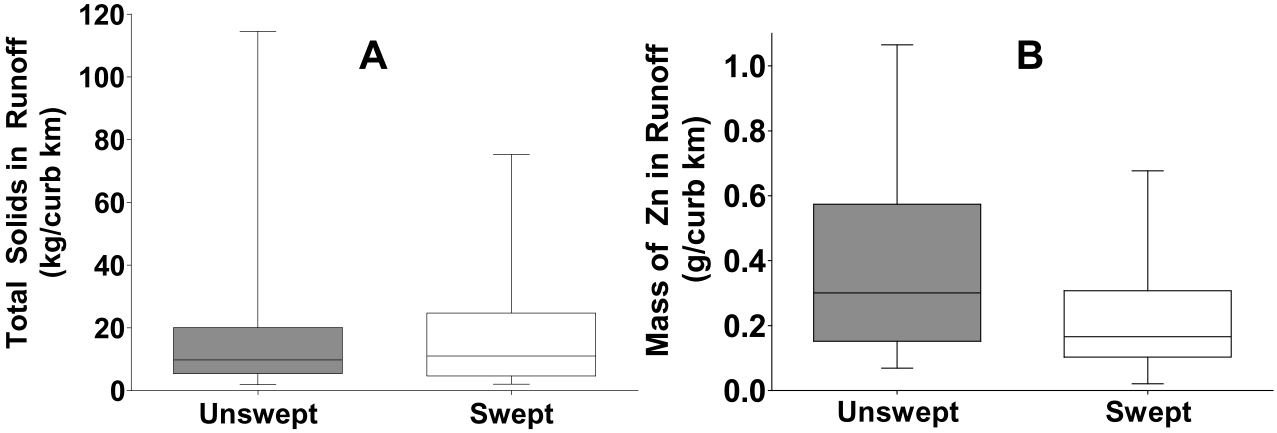


**Fig. 4. A.** Changes in total solids washed off ($n$ = 25); **B.** Changes in dissolved Zn washed off ($n$ = 25).

aggregated) and more resistant to wash off. Street sweeping may remove this coating and make the fine particles susceptible to wash off. This theory was not supported by observations in the current study. Figure 4A shows that with minor exceptions (i.e., when there were very high masses of solids on unswept sites), the mass of solids washed off during wet sampling was relatively unaffected by sweeping. The Wilcoxon Signed-Rank test confirmed that differences in the masses of solids washed off of swept and unswept areas were statistically insignificant ($p$ = 0.224). High (dry) RDS loads in 2006 contributed to the highest observed values of solids washed off; solids levels were lower in 2004 and 2005. The change in 2006 may have been the result of alterations to the type of sediments being imported into the area. On average, washing removed only 19% of the RDS on unswept plots, and 29% on swept plots. Further attention has turned to dissolved constituents, summarized in Table 1, to determine whether dissolution could be a more effective transport mechanism than sediment transport.

Statistically significant reductions in constituent transport were only observed for dissolved Zn ($p$ = 0.0001) and Cr ($p$ = 0.0005), indicating reduced runoff of these constituents from swept plots (e.g., Zn shown in Fig. 4B). Surprisingly, dissolved Pb in runoff was significantly ($p$ = 0.002) increased after sweeping, indicating increased susceptibility to wash-off after sweeping or some contribution of Pb by the sweepers themselves. Dissolved Cu, TOC, TKN, TP, and the PAHs Phe, Fl, and Py in wash water were not significantly affected by sweeping at the $\alpha$ = 0.05 level, although on at least one occasion, the old regenerative air sweeper did appear to release some PAHs during sweeping (this may have been due to transport of PAH contaminated dirt from outside sources into the test area). Transfer of solids from other locations was found to be a potential problem in the operation of sweepers, as also encountered by other researchers (e.g., Waschbusch 2003). It was likely that the November 10, 2004 sweeping operation had a much higher level of contamination than on other test dates since the same street sweeper was also being used in nearby residential areas to clear up leaf debris at that time. This additional material was likely the source of solids contamination for the runoff TSS and street dry sampling. The recommendation for future testing was to pre-clean the sweeper and then provide a "clean" area to run the sweeper as a warm-up loop, to ensure that contamination would be minimized. Sampling in 2005 and 2006 suggested that the transfer of solids from outside sources was no longer a problem during the tests.

Irish et al. (1998) found that TSS in stormwater runoff could be impacted by street sweeping and the antecedent dry period. The intensity of the previous storm event was also a factor in predicting TSS in runoff. Street sweeping would therefore be an important means of controlling TSS in runoff. Constituents such as oil and grease, chemical oxygen demand, and biochemical oxygen demand were more likely to be predicted by traffic intensity during a storm event. Nutrients such as TP and TKN were best predicted based on traffic counts during the antecedent dry period and the total duration of the dry period. Metals such as Cu and Pb were predicted by traffic volume during a storm event, and street sweeping was unlikely to reduce these concentrations. Iron was better predicted by dry weather period, but street sweeping did not appear to influence the concentrations in runoff. Zinc in runoff could be mostly determined from traffic volume during the antecedent dry period and the intensity of the previous storm, and they concluded that other stormwater management BMPs might be better than street sweeping to control this metal. In this study, however, Zn was found to be removed from runoff when using the regenerative air sweepers.

When assessing the sweeping efficiency from runoff data, the high variability of runoff and sediment quality data is a major concern in these types of studies. Kang and Stenstrom (2008) reanalyzed a number of previous studies to determine if enough samples had been collected to provide the statistical power required to detect

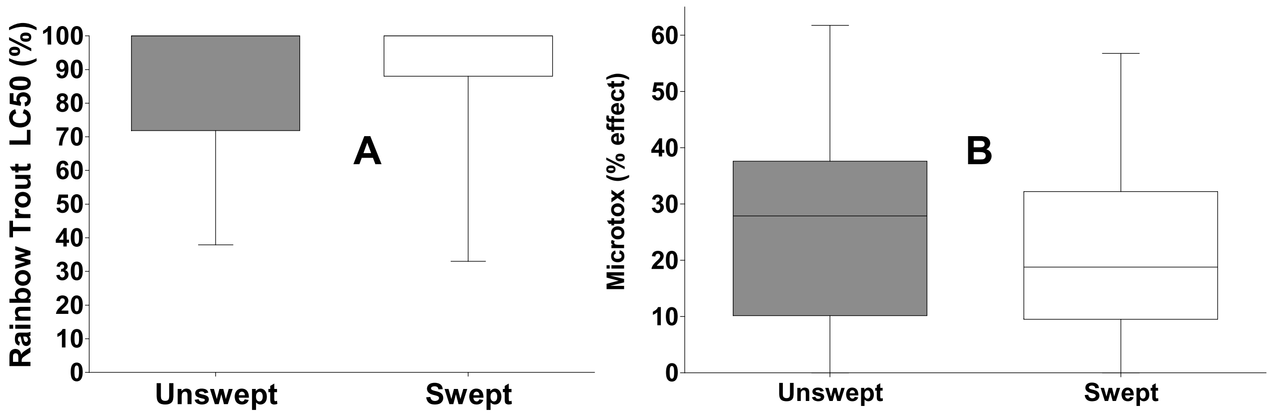


**Fig. 5. A.** Changes in toxicity to rainbow trout (note: 100% is nontoxic) ($n$ = 25) **B.** Changes in Microtox 15-minute % effect (note: % effect is the reduction in light output and therefore a greater % effect is more toxic) ($n$ = 25).

significant differences. They found that only four studies had enough replicate results to determine significant differences in runoff characteristics. Of those four studies, only one showed a significant result: a reduction in concentration of TSS in runoff after sweeping (Irish et al. 1998). Kang and Stenstrom (2008) also noted that street sweeping effects may be difficult to detect in runoff due to the variability of the antecedent dry period, rainfall intensities, and the transport of particulate material by wind and other processes. They suggested that street sweeping may reduce part of both the airborne and the wash-off components of the RDS. This makes it more difficult to attribute differences in runoff quality directly to street sweeping practices.

## Road Wash-Off Toxicity

Wash-off toxicity was evaluated by three acute toxicity tests which had been shown in past studies (Marsalek et al. 1999) to provide a wide range of ecotoxicological responses to urban pollution. Of the three applied tests, the 96-hour rainbow trout LC50 test was found to be the most sensitive at detecting acute impacts in this study; Microtox and *Daphina magna* tests did not show acute toxicity. Figure 5A shows the impact that street sweeping had on the toxicity of the wash-off. The toxicity was defined by the lethal concentration required to kill 50% of the population and was expressed as LC50. When the LC50 was 100% (or greater), it was an indication of no toxicity. As the LC50 value decreased, the severity of the toxicity increased. Rainbow trout toxicity results were highly variable for all sites. During the 2005 testing, very little toxicity was encountered (almost all sites were nontoxic), but in other years toxicity was minor. For comparison purposes, a "fail" in this test was considered to be LC50 <50%. None of the tests showed this acute level of toxicity. This may have been due to a combination of considerable rainfall (and therefore a lack of dry days over which to accumulate pollutants) during the test periods and a lack of heavy traffic. Although on occasion some paired tests showed a slight reduction of toxicity after sweeping, none of the tests demonstrated a clear tendency to reduce the toxicity of the wash-off. It should be further noted that as applied in this study, wash-off with a low volume of water represented the first flush, which is a phenomenon describing high concentrations of pollutants during the initial phase of runoff. Thus, samples that would be collected during later phases of runoff should be even less toxic than those presented here (Marsalek et al. 1999).

Microtox test results did not show any acute toxicity, since the sublethal percent effect result (which measures the reduction in light output by the test organisms) was used to gauge the differences between swept and unswept sites. On this scale, zero percent effect would indicate no impact (no reduction in light output relative to controls); as the percent effect climbs, so does the toxicity. Fig. 5B shows that the effect of street sweeping was to reduce the level of toxicity somewhat, but the median percent effects before and after sweeping were not significantly different ($p$ = 0.24). The most toxic samples were found in the southbound unswept runoff in 2006, but the corresponding swept site runoff showed a similar level of toxicity.

The toxicity of samples in this study were low, but given that the 26,000 vehicles per day traffic volume was below the 30,000 vehicles per day threshold proposed by Driscoll et al. (1990) for acute effects to appear, this result may not be unusual. It is also possible that inert sediment from construction areas was responsible for "diluting" toxic sediment generated from traffic. Higher than normal rainfall during the test period may also have resulted in the wash-off of some of the more toxic materials from the test areas prior to sampling. The complete absence of toxicity to *Daphnia magna* was unusual, since in previous studies, *Daphnia magna* reacted quite strongly to urban runoff pollution (Marsalek et al. 1999). The 96-hour rainbow trout LC50 and Microtox EC50 15-minute tests (using the sublethal "percent effect" rather than EC50 values), appeared to be the most sensitive tests to apply at this location in terms of identifying changes in the toxicity of runoff. Even so, only limited differences were discernable at best. Swept sites were generally less toxic than the unswept sites, although since the variation in the results was so great, none of the results were significant at the $\alpha = 0.05$ level. Tiefenthaler et al. (2001) were able to use sea urchin fertilization, mysid survival and growth, and Microtox in toxicity identification evaluations to demonstrate that Zn was a major factor in runoff toxicity for a commercial parking lot, but due to low toxicity at this Toronto site, such determinations were not possible.

## Conclusions

Conflicting literature data on street sweeping efficiency and continuing advances in sweeping technology provided the impetus for studying sweeping as a source control measure for pollution conveyed by urban stormwater. The study adopted a new approach to assessing the environmental benefits of sweeping; both toxicity and chemistry were used to evaluate the changes in runoff from swept (treated) and unswept (control) test areas. Within the limitations of this study and the realm of experimental uncertainties, the study results indicate that sweeping reduced significantly street sediment deposits on experimental plots with high sediment accumulations (well in excess of 50 kg/curb km). Such reductions were also reflected in reductions of chemical loads associated with such sediment, particularly with respect to TOC, TKN, TP, Pb, Zn, phenanthrene, fluoranthene, and pyrene. Wet sampling of swept and unswept plots by washing produced somewhat different results; washing produced much higher loads of silt and clay than dry vacuuming, and a significant reduction in washed-off load was only observed for dissolved Zn and Cr. Toxicity results for wash-off from swept and unswept plots were about the same, and indicated no toxicity for *Daphnia magna*, and only limited toxicity for rainbow trout and Microtox. In general, the swept sites were usually slightly less toxic than the unswept ones (not statistically significant).

The experience reported in the literature and gained in this study indicates that the most modern and efficient sweeping operations do provide environmental benefits when applied in areas with high solids deposits. Experimental field proofs of such benefits remain elusive because of extreme uncertainties in the assessment of improvements in stormwater quality due to street sweeping. Furthermore, pollution source control by sweeping should be subject to cost-benefit analysis and, with respect to the protection of receiving waters, compared with other BMPs providing comparable benefits.

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## References

**APHA, AWWA, WEF.** 2005. Standard methods for the examination of water and wastewater. 21st edition. Published jointly by the American Public Health Association, The American Water Works Association and the Water Environment Federation. New York.

**AZUR Environmental.** 1998. Microtox methods manual. AZUR Environmental, Newark, Delaware, USA.

**Breault RF, Smith KP, Sorenson JR.** 2005. Residential street-dirt accumulation rates and chemical composition, and removal efficiencies by mechanical- and vacuum-type sweepers, New Bedford, Massachusetts, 2003-04. U.S. Department of the Interior and U.S. Geological Survey – Scientific Investigations Report 2005-5184.

**Brinkmann R, Emrich C, Billus M, Dwyer B, Ryan J.** 1999. Chemical and physical characteristics of street sweeping sediments in Tampa, Florida. Report #98-12, State University of Florida, Gainesville, FL.

**CCME (Canadian Council of Ministers of the Environment).** 2002. Canadian Sediment Quality Guidelines. Available on-line at: http://ceqg-rcqe.ccme.ca [Accessed: Sept. 2008].

**City of Toronto.** 2003. Wet-Weather Flow Master Plan. City of Toronto, July 2003.

**Deletic A, Orr DW.** 2005. Pollution buildup on road surfaces. J. Environ. Eng. **131(1)**:49–59.

**Driscoll ED, Shelley PE, Strecker EW.** 1990. Pollutant loadings and impacts from highway stormwater runoff. Vol. III: Analytical investigation and research report. Federal Highway Administration, Office of Research and Development, Report No. FHWA-RD-88-008.

**Environment Canada.** 2000a. Environment Canada biological test method EPS 1/RM/13: Reference method for determining acute lethality of effluents to rainbow trout. Second edition.

**Environment Canada.** 2000b. Environment Canada biological test method EPS 1/RM/11: Acute lethality test using *Daphnia spp*. Second edition.

**ETV (Environmental Technology Verification Canada).** 2008. Operational on-street protocol and $PM_{10}$ and $PM_{2.5}$ street sweeper efficiency test protocol. ETV Canada.

**Folk RL. 1965.** Petrology of sedimentary rocks. Hemphill publishing, Austin, Texas, U.S.A.

**FWPCA (Federal Water Pollution Control Administration).** 1969. Water pollution aspects of urban runoff. Water Pollution Control research Series WP-20-15, FWPCA, U.S. Department of Interior, Washington, D.C.

**German J, Svensson G.** 2002. Metal content and particle size distribution of street sediments and street sweeping waste. Water Sci. Technol. **46(6–7):**191–198.

**Irish LB Jr, Barrett ME, Malina JF Jr, Charbeneau RJ.** 1998. Use of regression models for analyzing highway storm-water loads. J. Environ. Eng. **124(10):**987–993.

**Kang J-H, Stenstrom MK.** 2008. Evaluation of street sweeping effectiveness as a stormwater management practice using statistical power analysis. Water Sci. Technol. **57(9):**1309–1315.

**Marsalek J, Brownlee B, Mayer T, Lawal S, Larkin GA.** 1997. Heavy metals and PAHs in stormwater runoff from the Skyway Bridge, Burlington, Ontario. Water Qual. Res. J. Can. **32(4):**815–827.

**Marsalek J, Rochfort Q, Mayer T, Servos M, Dutka B, Brownlee B.** 1999. Toxicity testing for controlling urban wet-weather pollution: Advantages and limitations. Urban Water **1:**91–103.

**MOE (Ontario Ministry of Environment).** 2003. Stormwater management planning and design manual. Ontario Ministry of Environment, Toronto, Ontario.

**Novotny V.** 2003. Water quality: Diffuse pollution and watershed management. J. Wiley & Sons, New York, NY.

**Pitt R, Clark S.** 2003. Emerging stormwater controls for critical resource areas. *In* Sullivan D and Field R (ed.), Management of wet-weather flow in the watershed. CRC Press, Boca Raton.

**Pitt R, Williamson D, Voorhees J, Clark S.** 2004. Review of historical street dust and dirt accumulation and washoff data. In James W, Irvine KW, McBean EA and Pitt RE (ed.), Effective modeling of urban water systems monograph 13. ISBN 0-9736716-0-2, CHI, Guelph, Ontario.

**Robertson DJ, Taylor KG.** 2007. Temporal variability of metal contamination in urban road-deposited sediment in Manchester, UK: Implications for urban pollution monitoring. Water Air Soil Pollut. **186:**209–220.

**Rochfort Q, Exall K, Marsalek J, P'ng J, Shi V, Stevanovic-Briatico V, Kok S.** 2007. Effectiveness of street sweeping in stormwater pollution source control – Final report. WSTD Technical Note: AEMR-TN07-006, Environment Canada.

**Sartor JD, Boyd G.** 1972. Water pollution aspects of street surface contaminants. EPA/R2/72/081, U.S. EPA, November 1972.

**Sartor JD, Gaboury DR.** 1984. Street sweeping as a pollution control measure – Lessons learned over the past ten years. Sci. Tot. Environ. **33:**171–183.

**Selbig WR, Bannerman RT.** 2007. Evaluation of street sweeping as a stormwater-quality-management tool in three residential basins in Madison, Wisconsin. Scientific Investigations Report 2007-5156, U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia.

**Shivalingaiah B.** 1984. Modelling Stormwater Pollutants in Hamilton, Canada. Ph.D. Thesis, McMaster University, December 1984.

**Stone M, Marsalek J.** 1996. Trace metal composition and speciation in street sediment: Sault Ste. Marie, Canada. Water Air Soil Pollut. **87:**149–167.

**Sutherland RC, Jelen SL.** 1997. Contrary to conventional wisdom, street sweeping can be an effective BMP, p. 179–190. *In* James W (ed.), Advances in modelling the management of stormwater impacts. Vol. 5, CHI, Guelph, Ontario.

**Taylor AC, Wong THF.** 2002a. Non-structural stormwater quality best management practices: an overview of their use, value, cost and evaluation. Cooperative Research Centre for Catchment Hydrology. Technical report: 02/11 December 2002.

**Taylor AC, Wong THF.** 2002b. Non-structural stormwater quality best management practices: a literature review of their value and life-cycle costs. Cooperative Research Centre for Catchment Hydrology. Technical report: 02/13 December 2002.

**Tiefenthaler LL, Schiff KC, Bay SM.** 2001. Characteristics of Parking Lot Runoff Produced by Simulated Rainfall. Appendix F, City of Long Beach Storm Water Monitoring Report 2000-2001. SCCWRP Technical Report No. 343. www.sccwrp.org, ftp://ftp.sccwrp.org/pub/download/DOCUMENTS/TechnicalReports/343_characteristics_of_parking lot_runoff.pdf [Accessed: Sept. 2008].

**U.S. EPA (U.S. Environmental Protection Agency).** 2008. PAH standard analytical methods for wastewater. Method 610 and 625, Appendix 1, Article 304h Part 136 of U.S. EPA code of Federal regulations. Established 1977, current as of November 14, 2008.

**U.S. EPA (U.S. Environmental Protection Agency).** 1983. Results of the Nationwide Urban Runoff Program (NURP), Vol. 1 – Final Report. U.S. EPA Report PB84-185552, Washington, D.C.

**Waschbusch RJ.** 2003. Data and methods of a 1999-2000 street sweeping study on an urban freeway in Milwaukee County, Wisconsin. Open File Report 03-93, Middleton, Wisconsin, U.S. Dept. of the Interior, U.S. Geological Survey.

**WEF and ASCE (Water Environment Federation and American Society of Civil Engineers).** 1998. Urban runoff quality management. WEF Manual of Practice No. 23, ASCE manual and report on engineering practice No. 87, WEF, Alexandria, VA.

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