Storm-Water Management Using Street Sweeping

Joo-Hyon Kang[1]; Stephanie R. Debats[2]; and Michael K. Stenstrom, F.ASCE[3]

Abstract: Although street sweeping is commonly regarded as a cost-effective storm-water best management practice, there is little quantitative evidence that street sweeping directly improves runoff water quality. In this paper, several previous street sweeping studies were reevaluated using statistical power analysis. Two-group, independent-sample one-sided *t*-test power analyses were performed using log-transformed event mean concentrations (EMCs) of total suspended solids, suspended sediment concentration or chemical oxygen demand. The effect size between the two groups was estimated using the sweepers' pickup efficiency, which showed that the failure to detect the difference between mean EMCs of the two sample groups (i.e., unswept and swept groups) is likely due to limited sample numbers. Too few samples, which also resulted in a high coefficient of variation, were analyzed to detect the likely difference between swept and unswept observations. In addition, the temporal gap between street sweeping and subsequent storm events was not controlled to improve statistical power.

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Introduction

Transportation land uses such as residential and commercial streets, local roads and highways are storm-water pollutant sources in urban areas (Pitt 1985; Bannerman et al. 1993; Roger et al. 1998; Lau and Stenstrom 2005). Road deposited materials include anthropogenic material or litter, biogenic material such as fallen leaves, and sediments with different sizes and chemical compositions. Pollutants found in road deposited sediments include nutrients, oil and grease, heavy metals, polyaromatic hydrocarbons (PAHs), and other toxic compounds, resulting from dry and wet deposition, vehicular activities, and other anthropogenic sources (Sartor and Boyd 1972; Latimer et al. 1990; Herricks 1995; Ngabe et al. 2000). In particular, smaller particles have greater pollutant fractions and higher mobility during runoff, and therefore have higher potential to contaminate receiving water bodies (Roger et al. 1998; Vaze and Chiew 2002; Borst and Selvakumar 2003; Morquecho and Pitt 2003; Lau and Stenstrom 2005). In dry periods, fine particles on the road are dispersed into air due to wind or vehicle traffic turbulence to increase airborne particles (e.g., $PM_{2.5}$, PM_{10}), which can cause violation of the National Ambient Air Quality Standards (Cowherd and Englehart 1984; Chow et al. 1990).

The *Clean Water Act* (CWA) was amended in 1987 to establish the National Pollutant Discharge Elimination System (NPDES) for storm-water discharge, to address permit applications, regulatory guidance, and management and treatment requirements. For reducing storm water pollution, numerous types of best management practices (BMPs) have been suggested including structural treatment devices (i.e., swirl separators installed in storm drains, slow sand filters, etc.) as well as nonstructural source control strategies (i.e., education to prevent littering or illegal discharges, etc.). Street sweeping is considered a cost-effective source control method in urban areas.

Street sweeping is typically practiced to pick up large materials such as litter (defined as anthropogenic materials such as plastic bags and cigarette butts, etc.) and natural origin debris (gravel and vegetation) to improve aesthetics. Currently, street sweeping is being considered as an important BMP for storm-water management; however, early studies (Sartor and Boyd 1972; USEPA 1983; Sartor and Gaboury 1984; Smith 2002) claimed that street sweeping was ineffective at reducing pollutant concentrations in storm-water runoff due to low efficiency of fine particle removal. These early reports are fueling a debate over the value of street sweeping or the need for additional end-of-pipe treatment devices (Walker and Wong 1999; Schilling 2005).

Sweeping efficiency varies depending on sweeping frequency, sweeper operating speed, sweeping technologies, operator care, and initially deposited sediment load (Sutherland and Jelen 1997; USEPA 1999; Curtis 2002). The ability of sweepers to pick up fine particles is the most important factor to prevent pollutant discharge in subsequent storm events. The early studies suggested that street sweeping pickup efficiency for particles below 100 μm was less than 20% (USEPA 1983), where many if not most of the pollutants such as heavy metals are found. However, street sweeping is still considered effective by others (Sutherland and Jelen 1997; MWH Americas 2002; Brzozwski 2004; Selbig and Bannerman 2007) to improve storm-water quality when the right sweeper technologies and operation methods are used. Although there have been numerous studies to evaluate sweeping efficiencies, little evidence has been documented that street sweeping directly improves storm-water quality, despite the intuitive belief

[1]Researcher Professor, Dept. of Environmental Science and Engineering, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Korea (corresponding author). E-mail: joohyon@engineering.ucla.edu

[2]Graduate Research Assistant, Dept. of Civil and Environmental Engineering, Univ. of California at Los Angeles, Los Angeles, CA 90095-1593.

[3]Professor, Dept. of Civil and Environmental Engineering, Univ. of California at Los Angeles, Los Angeles, CA 90095-1593.

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that the large mass of swept material would have become water pollution.

In this paper, previous street sweeping studies were reviewed and critically assessed. Postulating that street sweeping causes reduction in pollutant event mean concentrations (EMCs) of end-of-pipe runoff, statistical power analysis was conducted using 15 datasets for total suspended solids (TSS), suspended sediment concentration (SSC), or chemical oxygen demand (COD) in 13 different locations from four previous street sweeping studies. Two-group, independent-sample, one-sided *t*-tests were used for the power analysis. The sample groups of EMCs under unswept and swept conditions were considered the control group and experimental group, respectively. The statistical power values of individual sites were calculated to assess the probability of rejecting the hypothesis that street sweeping does not cause reduction in EMCs. The goal of this study was to assess the statistical confidence of the previous street sweeping studies and to discuss important considerations in evaluating the effectiveness of street sweeping as a storm-water BMP.

Background

Types of Street Sweepers

Currently available street sweepers are categorized into three different types depending on the sweepers' technology: mechanical broom sweepers, regenerative air sweepers, and vacuum assisted sweepers.

Mechanical broom sweepers have the longest history among three different types of sweepers and are currently the most widely used in the United States, due to lower capital and operational costs (Keating 2002). A mechanical broom sweeper has a rotating gutter broom that carries material to a conveyor belt, which transports the collected materials into a hopper. A water spray is often used to reduce airborne particles. This type of sweeper can be operated at relatively higher speed with low noise, providing more flexibility in sweeping schedules. However, they are less efficient in removing fine particles, which are mostly likely to be transported in storm-water runoff and is their major drawback (Sartor and Boyd 1972; US EPA 1983; Curtis 2002). Some mechanical type sweepers recently developed are PM_{10} certified (Keating 2002), although little supporting evidence has been provided.

Regenerative air sweepers were developed more than two decades ago. A regenerative air sweeper uses an air jet to raise particles on the street surface, which are then vacuumed up into a hopper. The advantage of regenerative air sweepers is the ability to pick up most gross pollutants as well as fine particles with higher efficiency compared to mechanical broom sweepers (Sutherland and Jelen 1997). PM_{10} certified regenerative air sweepers are also available (Keating 2002).

Vacuum assisted sweepers have been available for over 10 years. A vacuum assisted sweeper uses a mechanical broom to place materials in the path of a vacuum intake that transports captured materials into a hopper. They are sometimes called small-micron-particulate sweepers, and they are the most effective among the three types for removing fine particles. A water spray is often used to suppress dust generation during operation. A vacuum assisted sweeper is usually PM_{10} certified (Keating 2002). Disadvantages of a vacuum assisted sweeper are reduced efficiency in removing large materials and wet vegetation (Schilling 2005), and low operating speed (Curtis 2002).

Tandem operation of two sweepers uses two different types of sweepers in sequence: a mechanical broom sweeper makes the first pass and a regenerative or vacuum assisted sweeper makes the second pass. Tandem operation is more labor and equipment intensive, but increases sweeping efficiency. Tandem operation is suitable for the residential areas where sweeping is less frequent and when targeting "hot spots" (Schilling 2005).

Previous Studies on Street Sweeping

Sweeping frequency in the United States varies from weekly (e.g., Milwaukee) to yearly (e.g., San Antonio) according to different locations and land uses. More frequent sweeping generally provides higher sweeping efficiency but results in higher costs. Through a simulation study, Sutherland and Jelen (1997) showed that sediment load reduction rate could increase from 50 to 88% by increasing sweeping frequency from monthly to weekly in residential streets using a high efficiency vacuum assisted sweeper. Not only the sweeping mechanism, but also other factors such as access to the source area, land-use activities, operation skill, sweeping time, and antecedent dry period can be significant factors that determine the effectiveness of street sweeping (Walker and Wong 1999). For this reason, an appropriate, site-specific sweeping strategy needs to be established to optimize sweeping efficiency.

There have been numerous studies to evaluate sweeping performance in different areas with different sweeping technologies and test protocols, and Table 1 summarized selected, previous street sweeping studies. Sartor and Boyd (1972) performed extensive work to characterize road deposited sediments and evaluate sweeping performances in ten cities across the United States. From field measurement using mechanical broom sweepers, they concluded that up to 50% of road sediment removal could be achieved but only 15–20% removal of particles less than 104 μm in diameter occurred, which implies little reduction in micropollutant in storm-water runoff. Unfortunately, their study did not focus on measured water quality improvements, and too few results exist to perform a power analysis. As a part of the Nationwide Urban Runoff Program (NURP), street sweeping efficiency was investigated by comparing end-of-pipe EMCs in runoff from swept and unswept conditions. They concluded that sweeping did not dramatically reduce runoff concentrations (US EPA 1983). These two studies are most often cited to show that street sweeping is not an effective BMP to improve storm-water quality, which is counterintuitive to the observation of large swept masses of litter, debris, and sediment. As a result, the effectiveness of street sweeping is still debated.

As sweeping technologies have improved to enhance the removal of fine particles, the effectiveness of street sweeping as a BMP needs to be reevaluated (Sutherland 2006). Curtis (2002) reported that road deposited pollutant mass could be reduced up to 78% for TSS and 62% for total nitrogen (TN) by vacuum assisted sweepers, whereas only 22 and 18% reduction, for TSS and TN, respectively, were obtained by regenerative air sweepers. Southerland and Jelen (1997) using modeling claimed that the majority of the street surface particles less than 125 μm can be removed by a regenerative air or a vacuum assisted sweeper. Martinelli et al. (2002) performed weekly sweeping with a vacuum assisted sweeper for a section of interstate highway in Wisconsin and concluded, using a regression analysis, that street sweeping was beneficial to runoff quality improvement. Vacuum assisted sweepers are expected to provide over 90% of total sediment pickup efficiency (NVPDC and ESI 1992).

Table 1. Summary of Previous Selected Street Sweeping Studies

References	Sweeper tested	Summary
Sartor and Boyd (1972)	M	To increase overall dust & dirt removal efficiency up to 70%, two cleaning cycle with slower speed operation was needed.
USEPA (1983)	M	According to the ten United States cities' street sweeping studies, there were no dramatic pollutant reduction by street sweeping.
Bender and Terstriep (1984)	M	By comparing median event mean concentrations (EMCs), sweeping was not effective to remove pollutant except total suspended solids (TSS) in storm-water runoff.
Sartor and Gaboury (1984)	M	Sweeper pickup efficiencies were 30–40% for solids, up to 80% for lead. However, sweeping efficiency must be measured in terms of runoff concentration reduction. Typical performance of sweeper is 10–30% reduction of runoff concentration.
Irish et al. (1995)	M	Biweekly sweeping provided measurable TSS reduction in runoff. However, little reduction occurred in other constituents including COD, nitrate and heavy metals.
Sutherland and Jelen (1997)	Modeled for M, R, and V	Modern sweeper technologies including regenerative and vacuum sweeper provide high efficiency at removing fine particles, and therefore, street sweeping can be an effective BMP to improve storm-water quality. Modeling results showed that annual TSS load and associated pollutants can be reduced by 80% using bimonthly to weekly sweeping.
Fitz (1998)	R	Street sweeping was not effective in reducing PM_{10} emission from major roadways, except after first time sweeping in routinely non-swept area.
Walker and Wong (1999)	R	Particles less then 300 μm in diameter were less affected by street sweeping. New small-micron surface cleaning technology is required to obtain larger than 50% removal of particle less than 125 μm.
Fitz and Bumiller (2000)	M, V	Vacuum type sweeper was good to remove blows and, resulting in PM_{10} reduction in sand blow area.
MWH Americas (2002)	Modeled for tandem operation (M+V)	Sweeping is cost-effective tool for storm-water management. Mechanical and vacuum should be operated in tandem.
Smith (2002)	M	No observable effect of sweeping on subsequent sediment loading in the runoff because the sweeper did not remove fine particles less than 0.062 mm. The mechanical sweeper was effective at removing particles greater than 8 mm.
Martinelli et al. (2002)	V	Weekly sweeping using a vacuum assisted sweeper was beneficial to reduce suspended sediment concentration in highway runoff.
Kuhns et al. (2003)	M, V	Sweeping offered no reduction in PM_{10}. PM_{10} emission potential instantly increased after vacuum sweeping. Long term effect should be examined.
Pacific Water Resource (2004)	M, V	Modeling results showed 90% of runoff will meet drinking water standards when using vacuum sweeper three times per year during wet season.
Chang et al. (2005)	R+washing	Reductions in silt (<75 μm) and dust (<297 μm) were 10–98%, and 52–100% respectively. For total suspended particles (TSP), 0–35% reduction was achieved but short lived (3–4 h).
Breault et al. (2005)	M, V	Sediment removal efficiencies were 20–31% for mechanical broom sweeper and 60–92% for vacuum sweeper. A vacuum sweeper showed 1.5–5 times greater removal compared to a mechanical broom sweeper for smaller particles (2–250 μm).

Note: M=mechanical broom sweeper; R=regenerative air sweeper; and V=vacuum assisted sweeper.

Methodology

In order to evaluate the performance of street sweeping as a storm-water BMP, datasets of end-of-pipe EMCs under swept and unswept conditions (unswept and swept sample groups) can be compared. The paired basin approach (unswept and swept basins located near each other are simultaneously observed in a test period) or serial basin approach (unswept and swept modes in a test basin are sequentially observed) can be used for the comparison study (i.e., two-group research) (US EPA 1983). The difference between the two sample groups might be difficult to detect due to the low removal rate of water quality pollutants, or the limited number of observations may obscure statistical conclusions because the variation within each group is relatively high when compared to the difference between sample groups. The high variability occurs because of regional and seasonal differences, random nature of meteorological conditions (i.e., rainfall intensity, rainfall duration, and dry period between storms), and measurement errors. For example, the US EPA (1983) and Bender and Terstriep (1984) did not observe statistically significant differences between the two sample groups. They used 15–60 samples (typically 30 samples) per group, which may be insufficient to detect a statistically significant difference. A larger number of samples per group provides a higher probability (i.e., statistical

Table 2. Pickup Efficiency of Mechanical Broom Sweepers

Size range of particles (μm)	Fraction (%)	Pollutant fraction (mg/kg TS)			Pickup efficiency for particles (%)	
		COD	Cu	Zn	Mechanical broom sweeper	Vacuum assisted sweeper[a]
0–43	5.9	261,077	201	791	15	81
43–104	9.7	314,801			20	60–78
104–246	27.8	30,267	98	444	48	57–78
246–840	24.6	35,859	95	302	60	78
840–2,000	7.6	40,178	376	1,582	66	78
>2,000	24.4	6,674	131	93	79	90
Weighted average (<2,000 μm)	—	—	—	—	47	74

Note: Adapted from Sartor and Boyd (1972) except vacuum sweeper efficiency. Mean values of residential, commercial, and industrial streets.
[a]By Breault et al. (2005), mean of two experiments

power) of detecting the difference that actually exists between two underlying populations (Cohen 1977). The high variability of storm water samples which impacts monitoring programs (Lee and Stenstrom 2005; Lee et al. 2007) contributes to the difficulty in detecting differences.

Probability Distribution of EMCs for Power Analysis

Statistical power analysis was performed using two-group, independent-sample one-sided *t*-tests. The goal was to evaluate statistical reliability of the earlier street sweeping studies including the NURP study, which is a canonical reference for criticizing the effectiveness of street sweeping. Control and experimental groups were the EMCs observed under unswept and swept conditions (unswept and swept sample groups). Because EMCs within a specific location typically follow lognormal distribution (USEPA 1983; FHwA 1990), log-transformed EMCs (ln[EMC]s) were used as the variable in the power analysis to meet the requirement of the population's normality for the *t*-test. The probability distribution of a control group can be characterized by mean ($\mu_{\ln[X]}$) and standard deviation ($\sigma_{\ln[X]}$) on the basis of ln[EMC], which were calculated by substituting the values of median (Md) and coefficient of variation (COV) of EMCs into the relationships of lognormal distribution as follows (Aitchison and Brown 1957):

$$\mu_{\ln[X]} = \ln[\mathrm{Md}] \tag{1}$$

$$\sigma_{\ln[X]} = \sqrt{\ln[1+\mathrm{COV}^2]} \tag{2}$$

where $\mu_{\ln[x]}$=mean of log-transformed data; n=number of data; Md=median of data; $\sigma_{\ln[x]}$=standard deviation of log-transformed data; and COV=coefficient of variation of data. It was also assumed that the log-transformed EMCs for swept conditions (experimental group) had smaller $\mu_{\ln[X]}$ but the same $\sigma_{\ln[X]}$, as opposed to a control (unswept) group.

Effect Size Estimation

The effect size (ES) between two groups is defined as the difference between means of two groups divided by pooled standard deviation. The ES reflects the strength of experimental effects in practice. In this study, the difference between means of a control (unswept) and experimental (swept) group was approximated using the sweeper's pickup efficiency. That is, assuming that street sweeping is always performed right before a storm and ignoring wet deposition (i.e., no buildup occurs after street sweeping until the end of a subsequent storm), the EMC can be proportionally related to the initial pollutant mass available on the road surface. The pooled standard deviation was approximated by $\sigma_{\ln[x]}$, assuming the control and experimental group have the same standard deviation. Because a sweeper directly reduces the pollutant mass available on the road surface, the ES can be formulated as follows:

$$\begin{aligned}\mathrm{ES} &= \frac{\mu_{\mathrm{unswept}} - \mu_{\mathrm{swept}}}{\sigma_{\ln[x]}} \\ &= \frac{\ln[\mathrm{Md}_{\mathrm{unswept}}] - \ln[\mathrm{Md}_{\mathrm{swept}}]}{\sigma_{\ln[x]}} \\ &= \ln(\mathrm{Md}_{\mathrm{unswept}}/\mathrm{Md}_{\mathrm{swept}})^{1/\sigma_{\ln[X]}} \\ &= \ln[\mathrm{Md}_{\mathrm{unswept}}/(1-R_s)\mathrm{Md}_{\mathrm{unswept}}]^{1/\sigma_{\ln[X]}} \\ &= \ln[1-R_s]^{-1/\sigma_{\ln[X]}} = \ln[1-R_s]^{-1/\sqrt{\ln[1+\mathrm{COV}^2]}}\end{aligned} \tag{3}$$

where μ_{unswept} and μ_{swept}=means of ln[EMC]s under unswept and swept conditions, respectively; $\mathrm{Md}_{\mathrm{unswept}}$ and $\mathrm{Md}_{\mathrm{swept}}$=medians of EMCs under unswept and swept conditions, respectively; and R_s=reduction rate of road deposited pollutant by street sweeping. The value of R_s can be estimated using sweeper's pickup efficiency and the percentage of pollutants deposited on the sweeper's path (typically on the curb area) as opposed to total catchment area as follows:

$$R_s = f_{\mathrm{curb}} \cdot E_p \tag{4}$$

where f_{curb}=mass fraction of sediments deposited in curb areas; and E_p=sweeper's pickup efficiency. Table 2 shows the pickup efficiencies of mechanical broom sweepers and vacuum assisted sweepers for different particle size ranges (Sartor and Boyd 1972; Breault et al. 2005). Because the runoff particles are typically smaller than 500 μm and rarely larger than 2,000 μm (Walker and Wong 1999; Li et al. 2006), the value of E_p can be calculated using the weight-averaged pickup efficiency of five different particle size ranges less than 2,000 μm (i.e., <43, 43–104, 104–246, 246–840, and 840–2,000 μm) as follows:

$$R_s = f_{\mathrm{curb}} \cdot \frac{\sum_{i=1}^{m} w_i e_i}{\sum_{i=1}^{m} w_i} \tag{5}$$

where m=number of particle size ranges less than 2,000 μm; w_i=weight fraction of particles in ith size range; and e_i=sweeper's pickup efficiency for particles in ith size range. Applying 0.8 of

f_{curb} (Sartor and Boyd 1972), R_s for solids (TSS or SSC) for mechanical broom sweepers, and vacuum assisted sweepers were calculated as 38 and 59%, respectively. Similarly, E_p for COD can be estimated using the fraction of COD in different particle size ranges (Table 2) and calculated as 24 and 59% for mechanical broom sweepers and vacuum assisted sweepers, respectively. Mean, median, and standard deviation of EMCs reported in each study were used to calculate the ES (column 11 of Table 3).

Calculations of Statistical Power and Sample Size for Previous Studies

Our power analyses included 15 studies (i.e., 15 EMC datasets) from 13 different locations: ten datasets for TSS from different NURP sites (US EPA 1983), datasets for COD and TSS in a single site from Irish et al. (1995), one SSC dataset from Smith (2002), and datasets for TSS and SSC in a single site from Martinelli et al. (2002). The statistical description and calculated parameters for the 15 studies are shown in Table 3. Using 0.05 of significance level (α) and statistical parameters given in columns 5–11 of Table 3, values of statistical power (β), and required sample number at $\beta=0.8$ were calculated for each site, and are shown in columns 12 and 13 of Table 3.

Values of β for seven NURP studies were from 0.42 to 0.69, lacking statistical power to detect the effects of street sweeping on EMCs. Therefore, it was highly probable that Type II errors (i.e., probability to accept null hypothesis that is actually false) were made, given the values of ES and sample numbers. The required sample numbers per group at $\beta=0.8$ for these studies are from 37 to 87, which are two to three times larger than the actual number of observations. Conversely, a relatively large number of samples and small values of COV existed in the data for the other three NURP studies (i.e., Lake Hills, Wash., Surrey Downs, Wash., and Rustler, Wis.) and provided larger β values (0.8–0.99).

Irish et al. (1995) measured EMCs from highway runoff using the serial basin approach in Austin, Tex. with biweekly street sweeping. They performed a two-group *t*-test, which showed a significant reduction in EMCs after sweeping for TSS; COD, metals, and nutrients did not show a significant reduction. The reduction in TSS concentration was highly significant (confidence level $>99\%$). The calculated values of β for TSS and COD were 0.77 and 0.34, respectively, which reflects strong statistical power to detect the difference between the two sample groups for TSS and weak statistical power for COD. The smaller ES for COD occurs because a greater portion of the COD is typically associated with smaller particles, which results in smaller ES when a sweeper is less efficient at removing smaller particles. A practical way of describing this situation is to say that if the removal efficiency is lower, but the variability in the data is similar, there is less chance of detecting the smaller difference.

Smith (2002) evaluated sweeping efficiency by observing SSCs before and after three sweeping events for a single site, as follows: SSC was measured during a storm event, the site was swept, and the SSC was measured during the next storm event. The process was repeated three times and a series of grab samples were collected. EMCs were estimated by averaging grab sample concentrations, weighted by the instantaneous flow rate at the time of sample collection. There were 47 storm events during the entire period of the test (1999–2000). The data showed no improvement in runoff quality in the rainfall event immediately after street sweeping. The power analysis suggests that no significant difference could be detected, and that 37 or more paired observations (only three were observed in the study) would have been needed to detect the removals expected from sweeper pickup efficiency. Additionally the serial approach for observing efficiency cannot account for the differences in individual storms, which had different rainfall and flow conditions, and likely contributed to the high variability in EMCs.

Martinelli et al. (2002) conducted both paired and serial basin approaches using a vacuum assisted sweeper with weekly sweepings. Using regressions between EMCs under swept and unswept conditions for control and test basins, respectively, they concluded that street sweeping improved water quality. However, they observed no direct reduction in EMCs of most pollutants including TSS and SSC. They indicated data reproducibility, limited data numbers, and operational problems as possible reasons for the lack of direct improvement. According to the power analysis, the number of observations was too small to detect the relatively small ES in this case. In spite of using a vacuum assisted sweeper that can efficiently remove fine particles, the ES is relatively small (0.51 and 0.40 for TSS and SSC, respectively) because the highway center was not swept and therefore f_{curb} was estimated as $0.8/2=0.4$. The power analysis showed that over 49 TSS samples per group are required to acquire 0.8 of β.

Results and Discussion

Evaluation of Previous Studies

Fig. 1 shows the functional relationships between β and sample number per group for different values of ES at $\alpha=0.05$, which was created using two-group independent-sample one-sided *t*-tests. Data points corresponding to the 15 studies (15 EMC data sets in Table 3) were also superposed on the graphs. For the NURP studies, in general 70 samples per group are required for 0.8 or larger β. Using the same statistical procedures, the functional relationship between the number of samples per group and the ES can be obtained for $\beta=0.8$ and $\alpha=0.05$, and is shown in Fig. 2. The positions on the graph corresponding to the 15 studies are also designated in the figure.

Fig. 1 shows that only four of the 15 previous studies had the statistical power large enough to detect a difference in water quality from street sweeping. The four studies [Austin, Tex. (TSS) ($\beta=0.77$); Rustler, Wis. (TSS) ($\beta=0.80$); Surrey Down, Wash. (TSS) ($\beta=0.98$); Lake Hills, Wash. (TSS) ($\beta>0.99$)] were likely to find a statistically significant difference, if one existed. Of the four studies with sufficient statistical power, however, only one study [Austin, Tex. (TSS), Irish et al. 1995] found a difference in water quality, and they reported a reduction in TSS with a high confidence level using *t*-statistics ($|t|=3.53>t_{0.01,\infty}=2.33$). They did not find a difference in other water quality parameters (i.e., COD, metals, nutrients), but this is not surprising because the statistical power for these other water quality parameters is lower (e.g., $\beta=0.34$ for COD), reducing the probability of detecting the difference, even if it has existed. Despite high statistical power, the other three studies (all from NURP studies) observed no statistical differences between EMCs under unswept and swept conditions. Several researchers noted that the frequency of sweeping affects the street sweeping efficiency (Sutherland and Jelen 1997; US EPA 1999; Curtis 2002) and this might be the cause of the negative findings. Note that the values of ES calculated in Table 3 are the maximum values possible assuming no pollutant buildup between sweeping and the following storm event. This assumption assures that the maximum value of ES is assumed, but the ES could be much smaller if there is a large temporal gap between

Table 3. Statistical Summary of Pollutant EMC from Previous Street Sweeping Study Sites

				Values available in Literatures				Calculated values in this study				
				Statistics under unswept condition						Parameters for power analysis ($\alpha=0.05$)		
Reference	Location	Land use	Measured parameter/ sweeper type	Mean (mg/L)	Median (mg/L)	COV (−)	Number of observation[a] [swept+unswept]	$\mu_{\ln[x]}$[b]	$\sigma_{\ln[x]}$[c]	ES[d]	Statistical power, β	Sample number per group at $\beta=0.8$
USEPA (NURP) (1983)	John Street N, Ill.	Residential	TSS/M	205	122	1.36	51(25)	4.8	1.02	0.47	0.50	57
	John Street S, Ill.	Residential	TSS/M	248	138	1.5	49(25)	4.9	1.09	0.44	0.46	65
	Mattis N, Ill.	Mixed	TSS/M	282	199	1.01	58(29)	5.3	0.84	0.57	0.69	39
	Mattis S, Ill.	Residential	TSS/M	311	211	1.08	59(30)	5.4	0.88	0.54	0.66	44
	CBD, N.C.	Commercial	TSS/M	163	107	1.15	66(33)	4.7	0.92	0.52	0.67	47
	Residential, N.C.	Residential	TSS/M	291	135	1.92	60(30)	4.9	1.24	0.38	0.42	87
	Lake Hills, Wash.	Residential	TSS/M	127	100	0.8	125(63)	4.6	0.70	0.68	0.98	28
	Surrey Downs, Wash.	Residential	TSS/M	113	101	0.51	119(60)	4.6	0.48	0.99	>0.99	14
	Rustler, Wis.	Commercial	TSS/M	202	167	0.68	42(21)	5.1	0.62	0.78	0.80	22
	State Fair, Wis.	Commercial	TSS/M	412	296	0.97	29(15)	5.7	0.81	0.59	0.47	37
Irish et al. (1995)	Austin, Tex.	Highway	TSS/M	280	263	0.63	35(17)	5.6	0.58	0.83	0.77	19
			COD/M	115	86	0.70	35(17)	4.5	0.63	0.43	0.34	68
Smith (2002)[e]	Boston	Highway	SSC/M	499	359	0.97	49(−)[f]	5.9	0.81	0.59	—	37
Martinelli et al. (2002)[g]	Milwaukee	Highway	TSS/V	193	135	0.76	44(22)	4.9	0.68	0.51	0.50	49
			SSC/V	363	249	1.04	44(22)	5.5	0.86	0.40	0.37	78

Note: TSS=total suspended solids; SSC=suspended sediment concentration; COD=chemical oxygen demand, M=mechanical broom sweeper; V=vacuum assisted sweeper, COV=coefficient of variation; $\mu_{\ln[x]}$=mean of log-transformed EMCs; $\sigma_{\ln[x]}$=standard deviation of log-transformed EMCs; and ES=effect size.

[a]Number in parenthesis is estimated sample size per group.

[b]Mean of log-transformed EMCs for unswept condition.

[c]Standard deviation of log-transformed EMCs for unswept condition.

[d]Calculated using weight averaged sweeper's pickup efficiency in Eq. (3).

[e]EMCs of SSC were calculated by instant flow-weighted averages.

[f]No comparable two data groups exist.

[g]0.4 of f_{curb} was applied because the highway center was not properly swept.

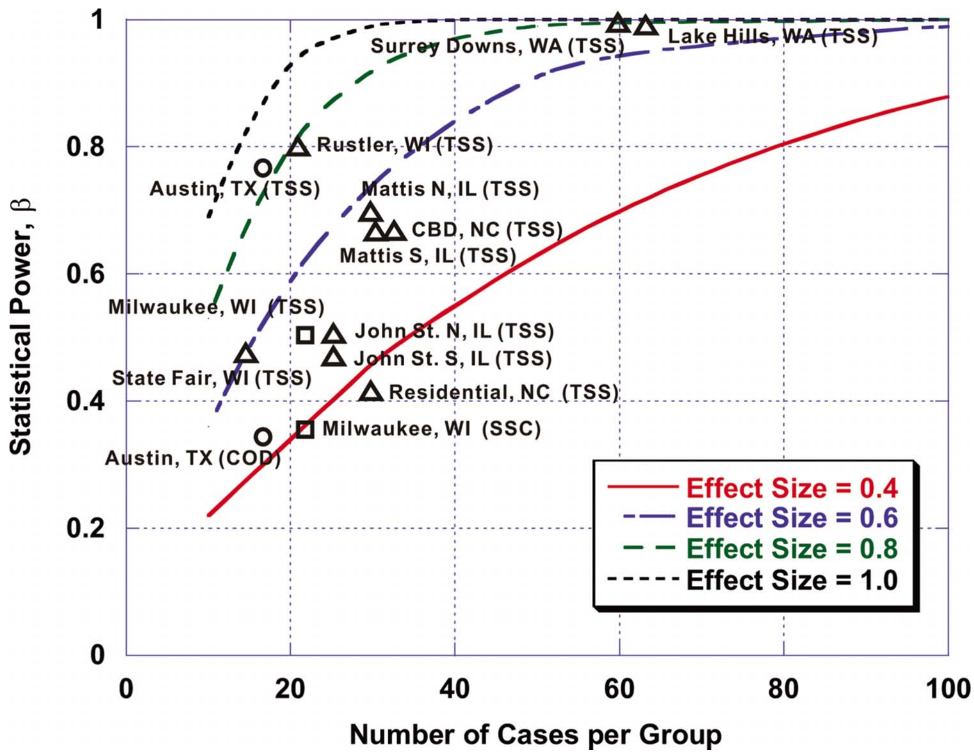

Fig. 1. Functional relationships between β and sample number per group for different values of ES at $\alpha = 0.05$ (one-sided *t*-test)

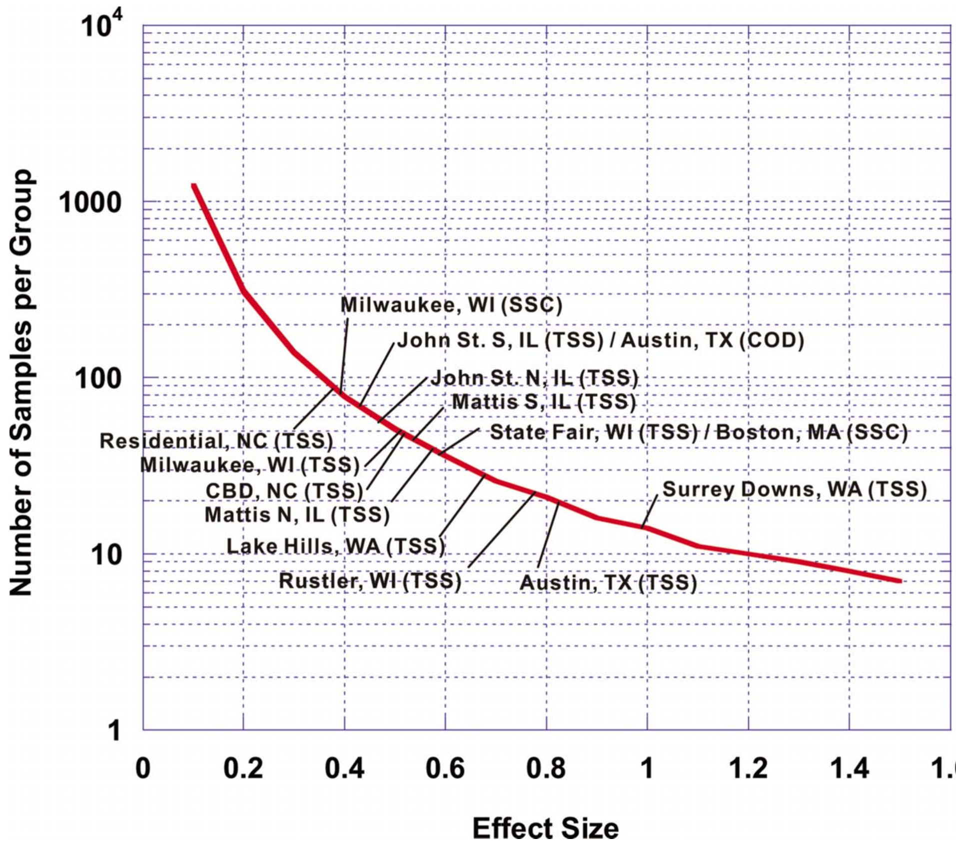

Fig. 2. Functional relationship between number of samples per group and ES (one-sided *t*-test with $\alpha = 0.05$ and $\beta = 0.8$)

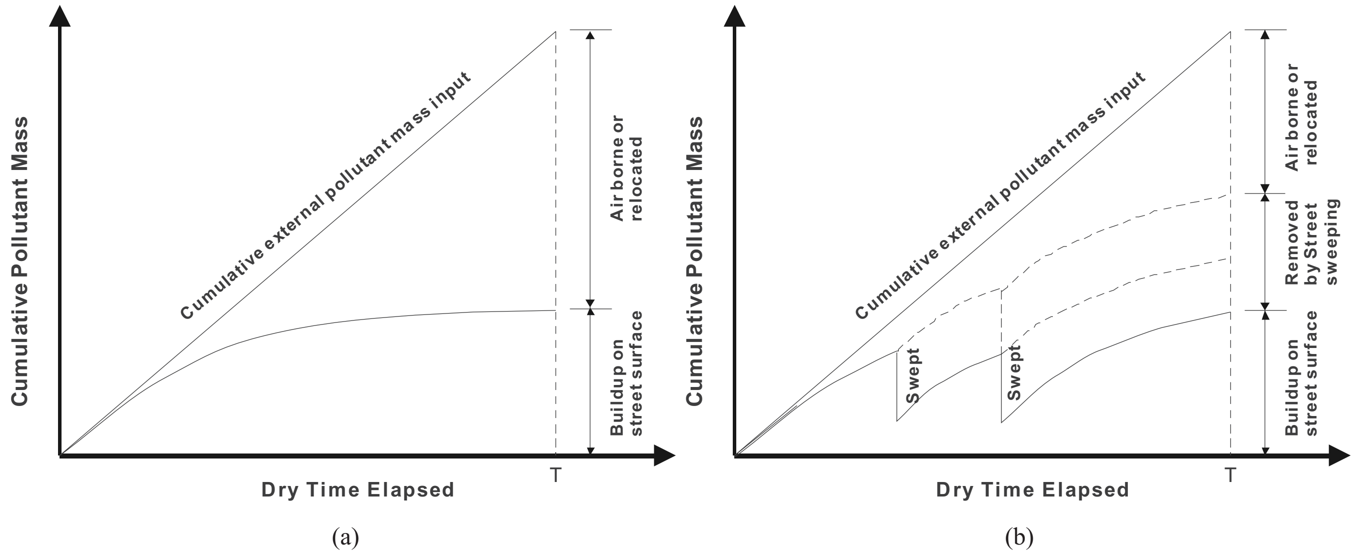

Fig. 3. Destination of external pollutant sources in street surface system: (a) under unswept condition; (b) under swept condition

sweeping performance and the subsequent storm event (the time between sweeping and the following storm event is not reported in the NURP documents). This possibility must be considered when evaluating the reasons for no improvement in water quality for the three examples with high ES. The effect of frequency on sweeping efficiency is discussed more in the next section.

Fig. 2, or similar figures generated in the same way but with different values of α and β, can be used to determine the number of samples required to detect a significant difference. Power analysis for other pollutants such as COD or heavy metals associated with the particulates can be performed in a similar way using the information of pollutant fractions shown in Table 2. Because of the lower removal rates of smaller particles by the sweepers, the values of ES for COD or other pollutants are usually smaller than the values of ES for TSS or SSC, and will require a larger number of observations to detect the difference between the EMCs under swept and unswept conditions. Ideally, an exercise to determine the required number of samples should be performed before undertaking an experimental program. This can be easily done if the variability of the measurements (i.e., for this case, the COV of the pollutant EMCs in the runoff) is known.

Among the 15 previous study results contained in Fig. 2, the four studies with sufficient statistical power discussed earlier, correspond to the largest four ES values and the smallest four required sample numbers (<30). As stated earlier, one of the four studies [Austin, Tex. (TSS)] matched our power analysis well but the other three studies [Rustler, Wis. (TSS), Surrey Down, Wash. (TSS), Lake Hills, Wash. (TSS)] reported negative results. This can be explained by overestimated ES used in the power analysis. Fig. 2 implies the significant impact of the overestimated ES on the statistical power; that is, a linear decrease in ES results in an exponential increase in the required number of samples per group to keep the same level of statistical power.

Our observation of the previous studies, with one exception (Irish et al. 1995) is that their statistical designs were not sufficiently robust to detect improvements in water quality due to sweeping. Therefore the previous references to the NURP studies on street sweeping ineffectiveness on water quality should be reevaluated. Future references should be made as "unable to detect differences due to statistical design or limited numbers of samples."

Effect of Street Sweeping

The inability of previous studies to detect differences in water quality from swept and unswept conditions is due in part to the limited number of observations, but also to other phenomena, such as sweeping frequency, buildup rate, and rainfall characteristics. This section discusses how these parameters affect the statistical power and how a study design can be improved.

The ES is strongly affected by the differences in the two means, and for street sweeping, this is determined by the sweeper efficiency as well as the sweeping schedule. More efficient sweepers should produce a greater difference in means which should be easier to detect. The sweeping schedule is also a critical factor that affects the ES. Pollutant mass on street surfaces builds up by different mechanisms, and little improvement in runoff water quality will be observed if buildup occurs between street sweeping and the sampled storm event. Therefore, the ES should be chosen as a function of the timing and frequency of street sweeping. More conservative ES (i.e., smaller ES) is required for infrequent sweeping or in high buildup areas.

Fig. 3 shows two conceptual examples of pollutant buildup on streets: one with and one without sweeping. The mass of pollutants eventually reaches a steady state and various models have been used to describe the buildup (Southerland and Jelen 1993; Charbeneau and Barrett 1998; Kim et al. 2006). As the pollutant mass on the street surface reaches steady state, the mass that would have accumulated is released to other environmental sinks, and can become an airborne pollutant, increasing ambient particle concentrations (e.g., PM_{10}, $PM_{2.5}$) or can be transported to adjacent or distant locations by advection and dispersion mechanisms. If rainfall occurs at time T, the swept condition [Fig. 3(b)] has the same amount of deposition as the unswept condition [Fig. 3(a)] which will result in the same runoff water quality (i.e., no observed improvement from sweeping), but pollutant mass released to other environmental sinks is reduced.

Street sweeping may provide benefits in addition to water quality improvements. This example shows that an evaluation of street sweeping benefits, solely on the basis of water quality and litter mass recovered, does not capture all the benefits. Long-term studies to evaluate the changes in PM_{10} and $PM_{2.5}$ for routinely

Table 4. Example Sampling Design of Street Sweeping Study

Study site (Charbeneau and Barrett 1998)	Pollutant to be examined	Sweeper type	Dry period[a] (day)	E_p	R_s	ES[b]	Sample number per group[c]
MoPac ($k=0.110$ day^{-1})	TSS	M	0	0.38	0.30	0.33	112
			7	0.38	0.14	0.14	632
			14	0.38	0.07	0.06	3,218
		V	0	0.59	0.47	0.59	37
			7	0.59	0.22	0.23	241
			14	0.59	0.10	0.10	1,289
	COD	M	0	0.24	0.19	0.30	136
			7	0.24	0.09	0.13	711
			14	0.24	0.04	0.06	3,436
		V	0	0.59	0.47	0.91	16
			7	0.59	0.22	0.35	102
			14	0.59	0.10	0.15	536
Jollyville ($k=0.054$ day^{-1})	TSS	M	0	0.38	0.30	0.33	112
			7	0.38	0.21	0.22	269
			14	0.38	0.14	0.14	614
		V	0	0.59	0.47	0.59	37
			7	0.59	0.32	0.36	97
			14	0.59	0.22	0.23	233
	COD	M	0	0.24	0.19	0.30	136
			7	0.24	0.13	0.20	307
			14	0.24	0.09	0.13	690
		V	0	0.59	0.47	0.91	16
			7	0.59	0.32	0.56	41
			14	0.59	0.22	0.36	99

Note: k=buildup coefficient; TSS=total suspended solids; COD=chemical oxygen demand; M=mechanical broom sweeper; V=vacuum assisted sweeper; E_p=pickup efficiency of a sweeper; R_s=reduction rate of road deposited pollutants by street sweeping considering pollutant buildup; and ES =effect size.

[a]Dry period between sweeping and sampling.

[b]Values of COV for TSS and COD are assumed 1.5 and 0.8, respectively.

[c]Number of samples to be collected at $\alpha=0.05$ and $\beta=0.8$.

swept and unswept streets, to the best of our knowledge, have not been performed, but should be to fully assess the benefits of sweeping.

Design of Experimental Study

To design a monitoring program for sweeping efficiency, the number of samples to be collected should be determined using the previous knowledge of the EMCs of the pollutants to be monitored, such as mean and variance, as well as a specified statistical power and significant level. The number of samples to be collected should be determined as a function of the street sweeping technique, expected pollutant buildup, and street sweeping protocols such as frequency and coverage. More efficient sweeping technologies such as vacuum assisted sweepers have higher pickup efficiency, resulting in a larger effect size for power analysis and will require fewer samples.

The use of power analysis can be demonstrated using a hypothetical example as illustrated in Table 4. Two monitoring sites (MoPac, Jollyville) in Austin, Tex. from a previous buildup study (Charbeneau and Barrett 1998) were selected as example sites having different buildup rates. TSS and COD were selected as pollutants and COVs of 1.5 and 0.8 were assumed, respectively, and are typical of those observed in the NURP study.

Pollutant buildup on the watershed during the dry period between street sweeping practice and the subsequent storm event can be estimated using the two parameter buildup model (Charbeneau and Barrett 1998)

$$P_t = P_0 + (P_{ss} - P_0)(1 - e^{-kt}) \tag{6}$$

where P_t=pollutant mass on the watershed before the storm event after a dry period, t (kg); P_0=pollutant mass on the watershed at the end of the previous storm event or after the previous street sweeping (kg); P_{ss}=steady state pollutant mass on the watershed (kg); k=buildup coefficient (day^{-1}); and t=number of dry days (days) between sweeping and rainfall. Assuming pollutant mass before street sweeping is equal to P_{ss} and 80% of total pollutant mass is deposited on the curb area ($f_{curb}=0.8$), which is sweepers' path, P_0 can be expressed as

$$P_0 = 0.2P_{ss} + (1 - E_p)(0.8P_{ss}) \tag{7}$$

Using Eqs. (6) and (7), R_s can be calculated as

$$R_s = \frac{P_{ss} - P_t}{P_{ss}} = 0.8E_p e^{-kt} \tag{8}$$

ES can be calculated using Eqs. (4) and (8). Table 4 shows calculated ES and required number of samples per group at α

$=0.05$ and $\beta=0.8$ for the two example sites, different sweeper types, and pollutants to be examined. As can be seen, the number of samples to be collected exponentially increases as the dry period after street sweeping increases. Therefore, in a watershed with high buildup rate and low sweeping frequency, a street sweeping study using EMC data is not recommendable because too many samples need to be collected. This example reinforces our previous statements about why it should not be surprising that previous street sweeping studies with few samples did not find significant differences in water quality before and after sweeping.

When a street sweeping study is focused on air pollution issues such as abating ambient particle concentrations, long-term investigations are recommended because a single sweeping cannot provide dramatic reduction in airborne pollutant mass. For example, several previous studies showed that little instantaneous reduction or even a short-lived increase in ambient particle concentrations will be observed after street sweeping (Fitz 1998; Kuhns et al. 2003; Chang et al. 2005). This can be inferred from Fig. 3(b), where the distance between the dotted line and the 45° diagonal is the mass of airborne particles. The time required between sweeping and the time to achieve equilibrium of pollutant mass on the surface can be significant. A simple measurement of airborne particle mass, just before and just after sweeping does not measure a longer term reduction in particle mass that can occur after equilibrium is achieved.

Swept and Unswept Areas

It is important to recognize the area contribution of the swept area. Typically roads or transportation land use in less urban watersheds was approximately 1% (Fam et al. 1987; Park et al. 2007) and increased to 7% in a moderately urbanized watershed (Park and Stenstrom 2006). Transportation land uses of small or ultraurban watersheds can be much higher but these watersheds are typically smaller (Ha and Stenstrom 2008). Including unswept areas in experimental evaluations of sweeping effectiveness will reduce the ES since runoff from the unswept area receives no benefit (no pollutant removal) from sweeping. When evaluating the contribution of street sweeping to large watersheds, a simple model should be used to calculate the overall benefit based on swept and unswept areas to avoid over- or underestimating the benefits of sweeping (Park and Stenstrom 2006).

Conclusions

A statistical power analysis was performed to reevaluate the effectiveness of street sweeping using 15 EMC datasets from the four street sweeping studies previously performed by other researchers. End-of-pipe EMCs for TSS, SSC, or COD from 13 different locations were used in logarithmic form for two-group independent-sample one-sided *t*-test power analysis. The probable difference between EMCs under unswept and swept conditions (two sample groups) was estimated using the pickup efficiency of the street sweeper and its coverage area.

The results show that, in general, the NURP study and other previous street sweeping studies used too few samples, resulting in low statistical power and inability to detect the benefits of street sweeping to water quality. Only four of the 15 EMC datasets reevaluated had sufficient numbers of samples to produce high power values ($\beta > \sim 0.8$). Three of the four datasets with high statistical power failed to detect a water quality improvement after sweeping for TSS. This may have resulted from an inability to detect large particles in the runoff, which has been suggested by others (Gray et al. 2000), or the buildup mechanism, which reduces effect size. The other dataset with high statistical power (Irish et al. 1995) detected TSS reduction after street sweeping. Their results matched our power analysis well; that is, after street sweeping, measurable reduction was observed for TSS with high statistical power and no reduction was observed for COD with low statistical power.

The contribution of street sweeping to environmental quality in urban areas should not be underestimated because of previous studies, which had insufficient statistical power to detect water quality improvements, had they existed. New studies using modern sweeping technology and better statistical designs to detect probable differences should be performed. The statistical design can be optimized to create the smallest number of samples to detect the expected difference and avoiding high analytical costs.

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