

Prepared in cooperation with the
Massachusetts Department of Environmental Protection, the
U.S. Environmental Protection Agency, and the City of Cambridge

Potential Reductions of Street Solids and Phosphorus in Urban Watersheds from Street Cleaning, Cambridge, Massachusetts, 2009–11



Scientific Investigations Report 2012–5292

Front cover. Photographs showing regenerative-air street cleaner and storm drain.

Back cover. Photograph of rotary gutter broom of a regenerative-air street cleaner in action.

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By Jason R. Sorenson

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**U.S. Department of the Interior
U.S. Geological Survey**

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Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi ²)	2.59	square kilometer (km ²)
acre	0.4047	hectare (ha)
acre	4046.94	square meter (m ²)
Volume		
gallon (gal)	3.79	liter (L)
gallon (gal)	0.003785	cubic meter (m ³)
cubic inch (in ³)	0.01639	liter (L)
cubic foot (ft ³)	0.02832	cubic meter (m ³)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound avoirdupois (lb)	0.4535	kilogram (kg)
pounds per curb-mile (lbs/curb-mi)	0.2819	grams per curb-meter (g/curb-m)
tons per day (ton/d)	0.9075	metric ton per day (mt/d)
Flow		
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
cubic feet per minute (ft ³ /min)	0.02831685	cubic meter per minute (m ³ /min)
Speed		
miles per hour (mph)	1.609	kilometer per hour (kmph)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Altitude, as used in this report, refers to distance above the vertical datum.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Concentrations of chemical constituents in solids are given either in milligrams per kilogram (mg/kg), or as a percent (%).

List of Abbreviations

COV	coefficient of variation
CTC	curb-to-curb
EIA	effective impervious area
HE	high efficiency
NIST	National Institute of Science and Technology
NOAA	National Oceanic and Atmospheric Administration
NRCS	National Resource Conservation Service
NURP	National Urban Runoff Program
PES	performance evaluation sample
RA	regenerative air
RPD	relative percent differences
SCM	stormwater control measures
SLAMM	Source Loading and Management Model
SS	single sided
SSC	suspended solids concentration
TMDL	total maximum daily load
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

Potential Reductions of Street Solids and Phosphorus in Urban Watersheds from Street Cleaning, Cambridge, Massachusetts, 2009–11

By Jason R. Sorenson

Abstract

Material accumulating and washing off urban street surfaces and ultimately into stormwater drainage systems represents a substantial nonpoint source of solids, phosphorus, and other constituent loading to waterways in urban areas. Cost and lack of usable space limit the type and number of structural stormwater source controls available to municipalities and other public managers. Non-structural source controls such as street cleaning are commonly used by cities and towns for construction, maintenance and aesthetics, and may reduce contaminant loading to waterways. Effectiveness of street cleaning is highly variable and potential improvements to water quality are not fully understood. In 2009, the U.S. Geological Survey, in cooperation with the Massachusetts Department of Environmental Protection, the U.S. Environmental Protection Agency, and the city of Cambridge, Massachusetts, and initiated a study to better understand the physical and chemical nature of the organic and inorganic solid material on street surfaces, evaluate the performance of a street cleaner at removing street solids, and make use of the Source Loading and Management Model (SLAMM) to estimate potential reductions in solid and phosphorus loading to the lower Charles River from various street-cleaning technologies and frequencies.

Average yield of material on streets collected between May and December 2010, was determined to be about 740 pounds per curb-mile on streets in multifamily land use and about 522 pounds per curb-mile on commercial land-use streets. At the end-of-winter in March 2011, about 2,609 and 4,788 pounds per curb-mile on average were collected from streets in multifamily and commercial land-use types, respectively. About 86 percent of the total street-solid yield from multifamily and commercial land-use streets was greater than or equal to 0.125 millimeters in diameter (or very fine sand). Observations of street-solid distribution across the entire street width indicated that as much as 96 percent of total solids resided within 9 feet of the curb. Median accumulation rates of street solids and median washoff of street solids after rainstorms on multifamily and commercial land-use streets were also similar at about 33 and 22 pounds per curb-mile per

day, and 35 and 40 percent, respectively. Results indicate that solids on the streets tested in Cambridge, Mass., can recover to pre-rainstorm yields within 1 to 3 days after washoff. The finer grain-size fractions tended to be more readily washed from the roadway surfaces during rainstorms. Street solids in the coarsest grain-size fraction on multifamily streets indicated an average net increase following rainstorms and are likely attributed to debris run-on from trees, lawns, and other plantings commonly found in residential areas.

In seven experiments between May and December 2010, the median removal efficiency of solids from street surfaces following a single pass by a regenerative-air street cleaner was about 82 percent on study sites in the multifamily land-use streets and about 78 percent on the commercial land-use streets. Median street-solid removal efficiency increased with increasing grain size. This type of regenerative-air street cleaner left a median residual street-solid load on the street surface of about 100 pounds per curb-mile.

Median concentrations of organic carbon and total phosphorus (P) on multifamily streets were about 35 and 29 percent greater, respectively, than those found on commercial streets. The median total mass of organic carbon and total P in street solids on multifamily streets was 68 and 75 percent greater, respectively, than those found on commercial streets. More than 87 percent of the mass of total P was determined to be in solids greater than or equal to 0.125 millimeters in diameter for both land-use types. The median total accumulation rate for total P on multifamily streets was about 5 times greater than on commercial streets. Total P accumulation in the medium grain-size fraction was nearly the same for streets within both land-use types at 0.004 pounds per curb-mile per day. Accumulation rates within the coarsest and finest grain-size fractions on multifamily streets were about 11 and 82 times greater than those on the commercial streets. Median washoff of total P was 58 and 48 percent from streets in multifamily and commercial land-use types, respectively, and generally increased with decreasing grain size. Total P median reductions resulting from a single pass of a regenerative-air street cleaner on streets in multifamily and commercial land-use types were about 82 and 62 percent, respectively, and were similar in terms of grain size between both land-use types.

A Source Loading and Management Model for Microsoft Windows (WinSLAMM) was applied to a 21.8 acre subcatchment in Cambridge, Mass. The subcatchment area consists of mostly commercial and multifamily land-use types to evaluate the potential reductions of total and particulate solids, and P attributed to street cleaning. Rainwater runoff from rooftops represented between 20 and 50 percent of the total basin runoff. Street surfaces only accounted for about 20 percent of the total basin runoff.

Monthly applications of mechanical-brush and vacuum-assisted street cleaners within the subcatchment as defined by SLAMM for areas with long-term (24-hour) on-street parking and monthly parking controls using five average climatic years resulted in total solid reductions of about 3 and 5 percent, respectively. Simulating the regenerative-air street cleaner tested as part of this study resulted in total solid reductions of about 16 percent. Increasing street cleaning frequency to three times weekly increased total solids removal for mechanical-brush, vacuum-assisted, and regenerative-air street cleaners to about 6, 14, and 19 percent, respectively. Monthly applications of mechanical-brush, vacuum-assisted, and regenerative-air street cleaners within the subcatchment resulted in total P reductions of about 1, 3, and 8 percent, respectively. A street cleaning frequency of three times each week for each of the three street-cleaner types increased total P removal to about 3, 7, and 9 percent, respectively.

Introduction

A TMDL (Total Maximum Daily Load) for total phosphorus (P) has been established for the lower Charles River basin (Massachusetts Department of Environmental Protection and others, 2007). To meet the total P criteria in this TMDL, the city of Cambridge, Massachusetts, is expected to achieve more than a 65-percent reduction in total P loading contributed to the Charles River from all city sources. Part of this reduction is expected from the management of stormwater runoff. Structural stormwater control measures (SCMs) are one type of nonpoint source runoff management, but urban areas are limited by the lack of usable space and high installation costs, thus making nonstructural SCMs, such as street cleaning (or street sweeping) a more practical alternative. Street cleaning may provide some load reduction, but monitoring these reductions in urban runoff as a result of a street cleaning program is difficult. Moreover, in Cambridge, Mass., which receives rain about every 3.5 days (National Oceanic and Atmospheric Administration, 2011), the effectiveness of street cleaning to reduce phosphorus loads to the lower Charles River is further minimized. To better quantify the potential benefits and limitations of street cleaning programs in urban areas at reducing total solids and P loads, a study was initiated in 2009 with the U.S. Geological Survey (USGS), in cooperation with the Massachusetts Department of Environmental Protection (MassDEP), the U.S. Environmental Protection Agency (USEPA), and the city of Cambridge, Mass.

Purpose and Scope

This report describes the physical characteristics of the solids found on street surfaces in predominantly high-density/multifamily residential and commercial land-use areas within Cambridge, Mass., during 10 months of sampling between August 2009 and March 2011. Analytical results of organic carbon and 32 elements including total P for selected samples also are presented. The report contains discussions of the physiochemical characteristics of street-solid samples before and after rain storms and during periods of dry weather to estimate street-solid accumulation and washoff because of precipitation. The development of removal efficiency coefficients based on street solids collected before and after a single pass of a regenerative-air street cleaner as part of a monthly street-cleaning program is presented. The report also documents the construction and evaluation of the model WinSLAMM version 9.4.0 (Pitt and Voorhees, 2002) to provide total and particulate solids and total and particulate P load reduction estimates resulting from three street-cleaning technologies operated at various frequencies within a predominantly commercial land-use subcatchment.

Description of the Study Area

The city of Cambridge is a 7.1 square mile (mi²) urban municipality located in eastern Massachusetts along the northern bank of the Charles River (fig. 1A). The city of Boston borders Cambridge to the south and east. The cities of Watertown, Belmont, Arlington, and Somerville also border Cambridge. Watertown lies to its southwest, Belmont and Arlington border the west, and Somerville borders Cambridge to the north. Topographically, the city generally slopes upward toward the west. Elevation to the northwest at Porter Square and to the southwest at Fresh Pond are about 47 to 40 feet (ft) above sea level, respectively, (Porter Square observation point, Weather Underground, 2011), and USGS Fresh Pond gage (USGS ID: 422302071083801). Fresh Pond, located in southwest Cambridge (fig. 1B) is a kettle pond with a 2,000 to 3,000 foot-wide moraine to its south that trends northwest. The surficial geology of the remainder of the city is characterized as outwash sands and gravels overlying tills associated with drumlins (Skeehan, 2001). Based on Boston climatic data between 1872 and 2002, the average annual temperature range for the area is about -6.1 to 27.2 degrees Celsius (°C) (21 to 81 degrees Fahrenheit). Total annual precipitation is about 42 inches (in.), which is evenly distributed throughout the year as rainfall and snow (National Oceanic and Atmospheric Administration, 2011).

The 2000 census determined there were about 15,936 persons per square mile in Cambridge, making it the fifth most densely populated city in the United States at that time (U.S. Census Bureau, 2010, table C-1), and the fifth most populated city in the State. High-density/multifamily residential and commercial land-use areas make up more than

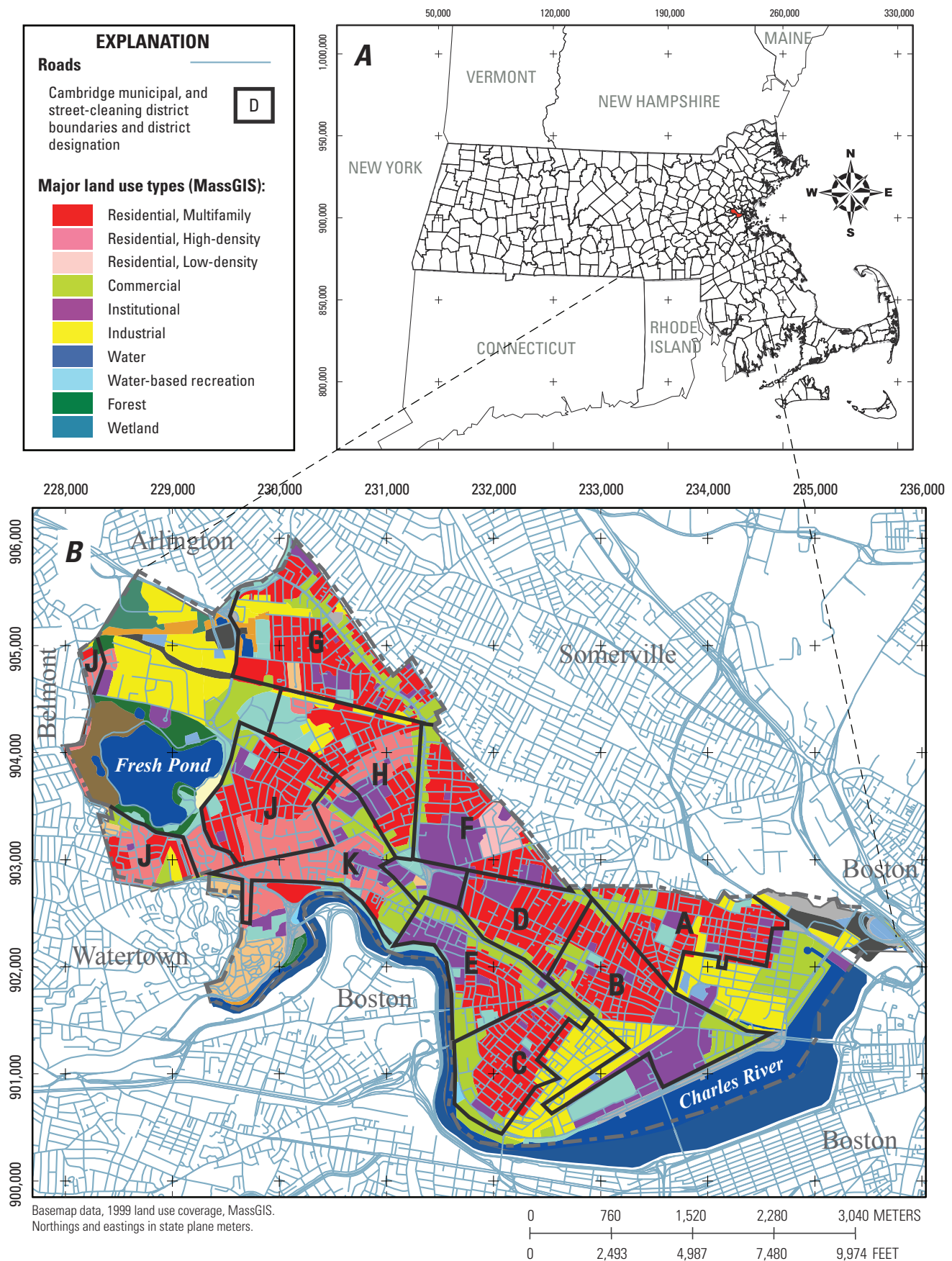


Figure 1. Location map of A, the City of Cambridge, Massachusetts, and B, land-use distribution, and municipal street-cleaning districts.

40 percent of the total area of the city of Cambridge (table 1, fig. 1B). Three streets representing predominantly high-density/multifamily residential (referred to as multifamily) and three streets representing predominantly commercial land-use types were selected within municipal street-cleaning districts D and E based on cleaning frequency, geographic orientation, traffic volume, street-surface condition, proximity to locations with existing stormwater loading data, and overall safety (table 2, fig. 2). Institutional and industrial, and residential and institutional land-use types also were present in the multifamily and commercial study street sections, respectively. Basic characteristics of the three multifamily and three commercial land-use street sections, including pavement condition index and 24-hour daily traffic count data where available (written commun., city of Cambridge), are listed in table 2. The lengths of the street sections ranged from 750 to 1,304 ft. The average street width was between 25 and 43 ft. In addition, observations of pavement texture and condition, and measurements of percent canopy closure were made at each of the six asphalt streets.

Table 1. Land-use types and percent of total area for Cambridge, Massachusetts (Based on 1999 land-use coverage).

[<, less than]

Land-use type	Area (acres)	Percent of total area
Cropland	1.0	0.0
Forest	71.7	1.6
Wetland	42.5	0.9
Open land	33.3	0.7
Participation recreation	245.3	5.4
Water-based recreation	5.9	0.1
Residential, multifamily	1,304.6	28.5
Residential, high density (lots <0.25 acre)	360.2	7.9
Residential, median density (lots 0.25–0.5 acre)	34.2	0.7
Commercial	590.9	12.9
Industrial	551.5	12.0
Urban open	31.0	0.7
Transportation	105.0	2.3
Waste disposal	10.4	0.2
Water	460.9	10.1
Golf	67.1	1.5
Urban public (schools, churches, govt offices)	505.4	11.0
Transportation facilities	68.3	1.5
Cemeteries	95.0	2.1
Total	4,584.2	100

The city uses a monthly street-cleaning program between April and December making use of primarily mechanical-brush sweepers, but during April and November, a tandem approach using a mechanical-brush followed by a regenerative-air street cleaner as a means to pick up extra street load associated with end-of-winter (EOW) and leaf-fall seasons. Monthly cleaning is scheduled such that even- and odd-numbered sides of the streets in a district are usually cleaned throughout the course of two days. Street cleaning activities are carried out by contractors and the public works department. Although certain squares, commercial streets, and surrounding areas with limited or no on-street parking are swept weekly or more, most city streets are grouped into well-defined monthly street-cleaning districts (fig. 1). In calendar years 2009 and 2010, about 1,605 and 1,042 tons of material were removed from Cambridge streets, respectively (written commun., Cambridge Department of Public Works, 2011).

Previous Studies

The National Urban Runoff Program (NURP) conducted from the late 1970s and through the early 1980s provided the basis for understanding of street cleaning effects on urban stormwater runoff. Sartor and Boyd (1972) performed the earliest direct experiments to determine street-solid accumulation and washoff. Pitt (1979) developed sampling techniques to better understand the nature of street-surface solids that are essentially still used. As part of the NURP projects, the U.S. Environmental Protection Agency (USEPA; 1983) determined that urban stormwater runoff contains high concentrations of P that contribute to eutrophication. The USEPA (1983) and Pitt (1987) reported that mechanical-brush sweepers were determined to be only 10 to 30 percent effective at removal of street solids. Since the NURP era, an increasing number of studies have examined the physical and chemical nature of urban runoff and the potential environmental benefits of street cleaning. Pitt and others (2004) provide tables of selected studies and their respective results in terms of material accumulation and washoff from street surfaces. Discussion of several selected studies investigating P in runoff and water-quality benefits of street cleaning follows below.

Steuer and others (1997) determined that Marquette, Michigan lawns were the dominant source (26 percent) of total P loading in the basin, yet only represented 6 percent of the total runoff. Waschbusch and others (1999) determined lawns and streets in Madison, Wisconsin, were the largest sources of total and dissolved P and total P loads from these source areas and were proportional to the percentage of runoff at one site (37 percent) and about one-half the percentage of runoff at the second site (14 percent). They also observed that 75 percent of the street-dirt mass was greater than 250 micrometers (μm) in diameter, and less than 5 percent was less than 63 μm in diameter.

Table 2. Characteristics of study-street sections, Cambridge, Massachusetts. Daily traffic count data and pavement-condition index data courtesy of the Cambridge Department of Public Works.

[ft, feet; --, no data]

Street name	Study section length (ft)	Average width (ft)	Predominant land-use type	24-hour average daily traffic counts	Traffic type, direction	24-hour on-street parking	Pavement condition index-entire street (percent)	Observed pavement texture* within the study street section only	Observed pavement composition/condition [†] within the study street section only	Canopy closure (percent)
Broadway	1,210	40	Multifamily	² 20,500	2-way, east/west	Both sides	67–80	Smooth	Asphalt/good	15
Highland Avenue	1,072	25	Multifamily	--	One way, south	Both sides	81–92	Intermediate	Asphalt/fair	55
Fayette Street	1,287	25	Multifamily	--	One way, north	Both sides	81–92	Rough	Asphalt/poor	54
Cambridge Street	1,304	43	Commercial	¹ 14,500	2-way, east/west	Both sides	81–92	Smooth	Asphalt/good	24
Mount Auburn Street	1,278	30	Commercial	² 9,860	One way, east, 2 lanes	One side	81–92	Intermediate	Asphalt/fair	17
Green Street	750	25	Commercial	--	One way, west	Both sides	93–100	Rough	Asphalt/poor	23

¹Cambridge, DPW traffic-count data, 2000.

²Cambridge, DPW traffic-count data, 2002.

[†]Observations of the smoothness or roughness of the street surface.

*Street-construction type/observations of breaks and open features in the street surface.

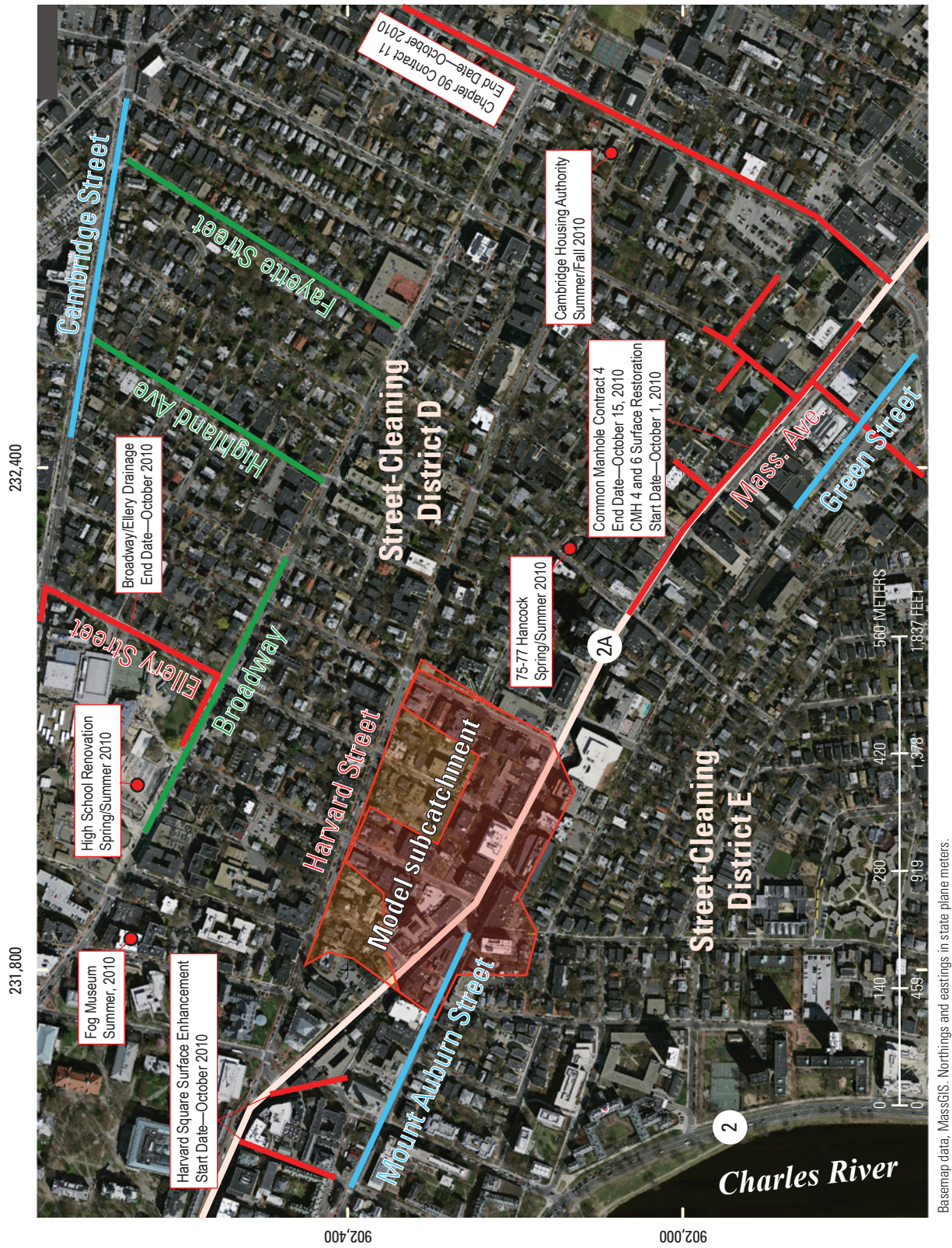


Figure 2. Aerial photograph showing the boundary between municipal street-cleaning districts D and E, approximate location of multifamily (green) and commercial (blue) study street sections, locations of city construction (red lines) and private development (red circles), and location of the predominantly commercial land-use subcatchment used in the Source Loading and Management Model, Cambridge, Massachusetts.

Breault and others (2005) conducted a study examining the organic and inorganic chemistry and accumulation rates of street dirt in residential areas, and evaluated the relative performance of a mechanical-brush and vacuum street cleaners as part of a pilot study in New Bedford, Mass. (not shown). An accumulation rate of about 50 pounds per curb-mile per day (lbs/curb-mi/day) was reported, and coarser size fractions between 2.0 and 0.250 millimeter (mm) appeared to accumulate most rapidly. About 93 percent of the material was determined to be greater than very fine sand (greater than 0.125 mm). Organic and inorganic constituent concentrations of street solids were similar to those reported in other studies, and total P was about 3.60 milligrams per kilogram (mg/kg) with the highest concentrations attributed to size fractions less than 0.125 mm in diameter. The vacuum street cleaner removal efficiencies were between 62 and 92 percent compared to removal efficiencies between 20 and 31 percent observed for the mechanical-brush street cleaner.

Selbig and Bannerman (2007) used a paired-basin approach (Clausen and Spooner, 1993) in Madison, Wis., to evaluate street-dirt particulate and stormwater loading under control conditions without street cleaning and under street-cleaning conditions using multiple frequencies and three different street-cleaning technologies. Average and median residential street-dirt yields were reported to be about 614 and 569 lbs/curb-mi, respectively, or about 1.6 times the national average reported by Sartor and Boyd (1972). Comparison of paired-basin results indicated that potential load reductions from street cleaning are likely limited by the extreme variability in stormwater runoff loads. The removal efficiency of street cleaners was determined to increase with increasing street-dirt yield. Average street-dirt removal efficiencies of regenerative-air and vacuum-assist cleaners were 25 and 30 percent, respectively. Weekly operation of mechanical-brush sweepers reduced average street-dirt loads by 5 percent. An increase in street-dirt particles less than 0.250 mm in diameter was reported after street cleaning. The largest and most evenly distributed yield of street dirt was measured during the spring.

Law and others (2008) conducted sampling and chemical analysis of street solids from streets in a control and treatment subcatchment in Baltimore, Md. A conceptual model of pollutant removal rates for weekly and monthly frequencies of mechanical and regenerative/vacuum-assist treatments was developed. A street cleaner removal efficiency of 14 percent was reported, and the lower value was attributed to frequent and intense storms and the twice weekly cleaning frequency during their experimental period. An average street-solid load of 645 lbs/curb-mi for their treatment area and an average street-solid load of 1,100 lbs/curb-mi was estimated from the control area, which was not swept. Law and others (2008) determined that particle-size distribution was similar for before- and after-cleaning street-solid load samples. They reported about 40 percent of sampled street-solid load particles were between 0.250 to 1.0 mm in diameter, and 70 percent of the total street-solid load consisted of particles larger than 0.250 mm in diameter. Lead (Pb) and total P concentrations

were determined to be significantly higher in their unswept control basin. The concentration of total P and total Kjeldahl nitrogen (TKN) was greater for solids larger than 0.250 mm in diameter. This tendency was attributed to organic matter, such as leaf litter that often contains substantial amounts of these constituents, in their samples. The resulting estimated range of reductions for total solids, total nitrogen, and total P as a result of street cleaning were 9 to 31, 3 to 8, and 3 to 7 percent, respectively.

Seattle Public Utilities and Department of Transportation (2009) sponsored a 1-year paired-basin study in 2006 to determine the effectiveness of street cleaning to reduce the mass of organic and inorganic constituents to urban waterways and the effectiveness of reducing the frequency of catch-basin cleaning. Median yields of street solids that included organic matter ranged from 69 to 2,200 lbs/curb-mi on streets that were swept twice per month. Analysis of grain-size fractions of street solids showed between 43 and 95 percent of the total mass was greater than 0.250 mm in diameter. Monthly samples of solids from streets in residential land-use areas had organic carbon concentrations between 6 and 38 percent. TKN and total P dry-weight concentrations in street-solid samples ranged from 49 to 36,600, and 191 to 1,610 mg/kg, respectively. Although reductions in street-solid yields resulting from bi-monthly street cleaning ranged from 48 to 90 percent in Seattle, no significant reductions in constituent concentrations or reductions in catch-basin cleaning were reported.

Street-Solid Collection, Processing, and Chemical Analysis

Street-solid samples were collected from the surfaces of six street sections (table 2 and fig. 2). Three streets were selected in predominantly high-density/multifamily residential land-use areas (referred to as multifamily) and three streets were selected in predominantly commercial land-use areas. Study street sections were selected based on land-use designation, safety considerations, and street-cleaning frequency. Samples were collected to characterize the accumulation of street solids, the washoff of street solids because of rainfall runoff, the removal efficiency of street solids by a regenerative-air street cleaner, and the concentrations of organic carbon and 32 elements including P in street solids.

Street-Solid Sample Collection

Samples were collected to represent average street-solid characteristics found in the two land-use types. Sampling methods were the similar to those used by Pitt (1979) and Burton and Pitt, (2002), and the same equipment used in this study was used by Selbig and others (2007). Four 9-gallon, stainless steel wet/dry vacuums with a maximum air flow of 92 cubic feet per minute were used to collect the samples.

Each street had a dedicated intake-hose setup that included a 6-inch wide aluminum intake nozzle attached to a 6-foot long stainless steel wand connected to the vacuum by a 2-in. diameter reinforced black neoprene hose between 15 and 35 ft long (fig. 3). All equipment was kept in the bed of a pickup truck and covered with a hard cap. Aluminum nozzles wore down and their intake width narrowed with use over the rough street surfaces. Nozzle widths were measured before each sampling event and recorded on field sheets. When nozzle widths were less than 5 inches, they were replaced.

Ten subsamples also were collected from each street and weighed individually to determine the variability in street-solid yields (Selbig and others, 2007), and were used to calculate the number of subsamples needed in a composite sample to accurately represent street-solid yields as described by Hansen and others (1984). Using an allowable error of 0.50 (or plus or minus (\pm) 50 percent), the calculated number of samples needed was less than 7; however, if the allowable error was reduced to 0.25, the number of subsamples increased to 49. For this study 10 subsamples were collected for all composites on all streets. Unusual loading conditions such as piles of debris, potholes or areas near construction track out were avoided during sampling to maintain the representativeness of the composite sample. Although 10 markers were painted on the vertical side of the curb on each street section, the sampling locations varied for each sampling event because of the heavy on-street parking, which often limited where sampling crews could collect subsamples. The reproducibility of the street-solid sample collection procedures was evaluated using a Mann-Whitney/rank-sum test. Twelve street-solid composite sample pairs were used and results indicated no significant difference between the pairs of samples ($p = 0.68$). The good precision between sample pairs indicates that sources of variability in street-solid yields were not introduced by sample-collection techniques.

A single subsample involved vacuuming from curb to curb across the street moving at about 1 foot per second or less with increasing street surface roughness. It was common to see a cleaned path where material was removed following a vacuumed pass (fig. 4A). Autumn brought a large amount of leaf material to street surfaces that would often clog the intake nozzle. Under these conditions, leaves along the sample path were manually sampled and placed into pre-weighed and labeled plastic bags. Eleven composite samples were collected during the summer of 2009, and were collected in a manner similar to the procedure described by Selbig and others (2007) where street-dirt material was collected directly into the vacuum stainless steel canisters, its cloth filter was brushed off, shaken into the canister, then all material was brushed out into pre-weighed clear plastic bags. Sample collection was modified for all 2010–2011 vacuumed composite samples, which were collected in pre-weighed 0.1 μ m paper filter bags. Paper filter bags were chosen to limit field crew exposure to particulate matter, minimize loss of finer fraction to the air, and reduce overall time spent in the field. Composite samples contained in the 0.1 μ m paper filter bags were removed from the vacuum

canisters, the intake port closed, and material within the bag was allowed to settle to the bottom before it was folded and sealed inside a labeled clear plastic ziplock bag (fig. 5A).

Street-Solid Sample Processing and Chemical Analysis

Street-solid samples were processed and prepared for shipment to SGS Environmental Services Laboratory in Ontario, Canada for analysis of 32 elements and organic carbon. Performance evaluation samples (PESs), equipment blank samples, and replicate samples also were prepared and submitted for analysis. Street solids in this study are defined as all material collected on street surfaces including all gravel and asphalt and all organic material to as much as about 50 mm in diameter. All visible anthropogenic material such as plastic, metal, and cigarette butts was not included.

Street-Solid Sample Processing

Samples were taken to the USGS Northborough, Massachusetts laboratory, where they were weighed and dried within the paper filter bags for 14 hours at 105 °C. Dried samples were weighed again and separated into three grain-size fractions herein designated as: “coarse,” or material greater than or equal to 2 mm, “medium,” or material less than 2 mm to greater than or equal to 0.125 mm, and “fine,” or material less than 0.125 mm in diameter using stainless steel sieves. A 4-mm stainless-steel sieve was used to screen out larger material before sieving; when the sample material was too great for a single set of sieves, multiple sets were used. Sieves were washed using phosphate-free detergent and rinsed with tap water, followed by three rinses with deionized water, then dried before each use. Emptied paper filter bags were weighed again and the difference between its tare weight and the weight of the emptied bag was added to the less than 0.125-mm size fraction (defined as very fine sand). The sample mass results for each street are listed in appendix tables 1–15 and 1–16 (on CD-ROM at back of report). Data were omitted if the relative percent difference between the sum of the three grain-size fraction masses and the initial total dry mass was more than 15 percent.

About 10 to 20 grams (g) of representative street-solids material was subsampled from each of the three separated grain-size fractions, placed into labeled Whirl-pak bags and shipped to SGS laboratories for analysis of organic carbon, total P, and 31 other elements (table 3). In cases where there were large amounts of material or the material was too heterogeneous to be subsampled representatively, a riffle splitter (fig. 5B) was used to yield representative subsamples for analysis. Although leaves and organic debris were not removed from street-solid subsamples, all visible anthropogenic debris and litter was removed before submission for chemical analysis. Resulting total-recoverable concentrations of all curb-to-curb (CTC; composite samples collected by vacuuming



Figure 3. Photograph of curb-to-curb street-solid composite sampling equipment and municipal police detail to ensure traffic safety, Cambridge, Massachusetts.



Figure 4. Photograph of A, two cleaned vacuumed paths typical of street-solid composite sampling, and examples of a rough street-surface and a poor street-surface condition (photo courtesy of Tom Maguire, MassDEP), and B, a smooth street surface with good street-surface condition, curb-and-gutter drainage system, and an example of unusual loading avoided during sampling, Cambridge, Massachusetts.



Figure 5. Photograph of A, a street-solid composite sample contained within a 0.1 micrometer paper filter bag being extracted from the vacuum, folded, and placed into a labeled clear plastic ziplock bag, Cambridge, Massachusetts (photo courtesy of Tom Maguire, MassDEP), and B, stainless steel riffle splitter and receiving pans used for large volumes or heterogeneous street-solid sample.

Table 3. Target analytes and analytical techniques for samples submitted to SGS Laboratories, Toronto, Ontario, Canada.

[MDL, method detection limit; USEPA, U.S. Environmental Protection Agency; ICP-MS, Inductively Coupled Plasma-Mass Spectrometry; ppm, parts per million]

Analyte	Units	Analytical techniques	MDL	USEPA method
Aluminum, recoverable	ppm	ICP-MS	100	EPA IC3050B/ICP40
Antimony, recoverable	percent	ICP-MS	5	EPA IC3050B/ICP40
Arsenic, recoverable	ppm	ICP-MS	3	EPA IC3050B/ICP40
Barium, recoverable	ppm	ICP-MS	1	EPA IC3050B/ICP40
Beryllium, recoverable	ppm	ICP-MS	0.5	EPA IC3050B/ICP40
Bismuth, recoverable	ppm	ICP-MS	5	EPA IC3050B/ICP40
Cadmium, recoverable	percent	ICP-MS	1	EPA IC3050B/ICP40
Calcium, recoverable	ppm	ICP-MS	100	EPA IC3050B/ICP40
Chromium, recoverable	ppm	ICP-MS	1	EPA IC3050B/ICP40
Cobalt, recoverable	ppm	ICP-MS	1	EPA IC3050B/ICP40
Copper, recoverable	ppm	ICP-MS	0.5	EPA IC3050B/ICP40
Iron, recoverable	percent	ICP-MS	100	EPA IC3050B/ICP40
Lanthanum, recoverable	percent	ICP-MS	0.5	EPA IC3050B/ICP40
Lead, recoverable	ppm	ICP-MS	2	EPA IC3050B/ICP40
Lithium, recoverable	ppm	ICP-MS	1	EPA IC3050B/ICP40
Magnesium, recoverable	percent	ICP-MS	0.01	EPA IC3050B/ICP40
Manganese, recoverable	ppm	ICP-MS	2	EPA IC3050B/ICP40
Molybdenum, recoverable	ppm	ICP-MS	1	EPA IC3050B/ICP40
Nickel, recoverable	percent	ICP-MS	1	EPA IC3050B/ICP40
Phosphorus, recoverable	ppm	ICP-MS	100	EPA IC3050B/ICP40
Potassium, recoverable	percent	ICP-MS	100	EPA IC3050B/ICP40
Scandium, recoverable	ppm	ICP-MS	0.5	EPA IC3050B/ICP40
Silver, recoverable	ppm	ICP-MS	0.2	EPA IC3050B/ICP40
Sodium, recoverable	ppm	ICP-MS	100	EPA IC3050B/ICP40
Strontium, recoverable	ppm	ICP-MS	0.5	EPA IC3050B/ICP40
Tin, recoverable	ppm	ICP-MS	10	EPA IC3050B/ICP40
Titanium, recoverable	percent	ICP-MS	100	EPA IC3050B/ICP40
Tungsten, recoverable	ppm	ICP-MS	10	EPA IC3050B/ICP40
Vanadium, recoverable	ppm	ICP-MS	2	EPA IC3050B/ICP40
Yttrium, recoverable	ppm	ICP-MS	0.5	EPA IC3050B/ICP40
Zinc, recoverable	ppm	ICP-MS	0.5	EPA IC3050B/ICP40
Zirconium, recoverable	ppm	ICP-MS	0.5	EPA IC3050B/ICP40
Total organic carbon	percent	Coulometric titration	0.01	EPA 9060

across the street from one curb to the opposite curb) and single sided (SS; composite samples collected by vacuuming 9 ft out from the curb) street-solid composite samples can be seen in appendix tables 1–17, 1–18, 1–19, and 1–20 (on CD-ROM at back of report).

Performance Evaluation Sample Analysis

Six National Institute of Standards and Technology (NIST) standard reference soil 2710 samples and five NIST standard reference soil 2781 samples served as PESs, and were submitted to SGS laboratories with street-solid samples to determine potential contamination bias and overall method performance. The median analytical results and relative standard deviations shown in table 4 are of selected constituents for two types of analyses performed on standard reference soil samples consist of the following: total concentrations, measured in samples fully digested by hydrofluoric acid, and total-recoverable concentrations, measured in samples digested by less aggressive acid mixtures. The USEPA has determined that the total-recoverable concentration represents the bioavailability of elements in the environment (U.S. Environmental Protection Agency, 1986). Most analytical results included in this report were obtained using the total-recoverable digestion.

Concentrations certified by the NIST are based on several measurements using two or more techniques from multiple laboratories using hydrofluoric acid to achieve a complete digestion. About 26 percent of the median total concentrations of elements associated with the NIST reference soil 2710 certified values, and about 12 percent of the median total concentrations of elements associated with NIST reference soil 2781 certified values that were measured were within their respective certified concentration ranges (table 4). The elements with median concentrations outside the certified concentration ranges were within 16 percent or less of the lower range of certified values of NIST reference soil 2710, and within 15 percent or less of the lower range of certified values of NIST reference soil 2781 (table 4). The relative standard deviations for blind sample concentrations of total P and six other elements of concern (shaded values seen in table 4) were between 4 and 16 percent for the NIST 2710 results and between 2 and 20 percent for the NIST 2781 results.

Total-recoverable element concentrations obtained using the milder digestion described above resulted in concentrations that were generally lower than the total-recoverable concentrations for both NIST standard soils 2710 and 2781 (table 4). However, median total-recoverable concentrations of all constituents in NIST standard 2710 were within about 30 percent or less of the lower range of certified values except for aluminum (Al), barium (Ba), calcium (Ca), potassium (K), sodium (Na), antimony (Sb) and titanium (Ti), which were between 45 and 94 percent less than the lower range of certified values. All median total-recoverable concentrations of constituents in NIST standard 2710 were within the recovery range except for K, P, Ti, and vanadium (V). Concentrations of Ti, K, and V were 18, 14, and 4 percent

greater than the upper limit of the recovery range, respectively. The median concentration of P was about 18 percent less than the lower limit of the recovery range for analyses of NIST standard 2710, indicating a potential negative bias in the total-recoverable concentrations for P. Median total-recoverable concentrations of all constituents in NIST standard 2781 were within about 9 percent or less than the upper limit of the recovery range except for Al, cadmium (Cd), chromium (Cr), iron (Fe), magnesium (Mg), and manganese (Mn), which were 1 to 28 percent greater than the upper limit of the recovery range. Total P was about 7 percent less than the noncertified value of NIST standard 2781, supporting the potential negative bias in the total-recoverable concentrations for total P indicated by the results for NIST standard 2710.

Blank Sample Analysis

Analyses of organic carbon, total P, and 31 other elements also were done on samples of graded unground silica sand. Median results of selected elements were at or below the method detection limit, indicating the silica sand was an appropriate blank material (table 5). The silica sand was then exposed to a precleaned aluminum intake nozzle, neoprene hose, and a preweighed 0.1- μ m paper filter bag weighed and dried and then stored for more than 48 hours in a similar manner as street-solid samples collected in the field. The samples were then emptied into stainless steel sieves and shaken for 30 minutes. Analytical results of total P and other selected elements in the equipment blank silica sand were also at or below the method detection limit and demonstrate the sampling equipment, filter bags, and processing equipment were not a source of sample contamination.

Replicate Sample Analysis

Mean and median RPDs between the sum of the sieved fractions and the total dried mass were 5.6 and 0.87 percent, and ranged between 0.02 and 70 percent. However, there were only five instances where the RPD was greater than 25 percent.

Replicate samples of the PESs (NIST 2710 and 2781 described above) were analyzed using the total and total-recoverable digestions. Median relative percent differences (RPDs) between certified values and resulting total concentrations were about 8 percent using NIST standard reference soil 2710 and about 15 percent using NIST standard reference soils 2781. Total P median concentration RPDs using NIST 2710 and 2781 were about 6 and 3.4 percent, respectively. These results are within the 25-percent limit established by the quality assurance project plan (Sorenson, Quality Assurance Project Plan, written commun., accepted May 2010)

Thirty replicate splits of street-solid samples were submitted for analysis and the median RPD of resulting total concentrations for all elements was about 2 percent and about 10 percent for total-recoverable concentrations of all

Table 4. Median values and relative standard deviations (RSD) for selected concentrations of total and total-recoverable trace elements in quality-control samples.

[Shaded rows represent major elements of concern; NIST, National Institute of Standards and Technology; ppm, parts per million; RSD, relative standard deviation; ±, plus or minus; --, no data; >, greater than]

Analyte	NIST standard reference soil 2710 reported concentrations				NIST standard reference soil 2710 blind sample analytical results				NIST standard reference soil 2781 reported concentrations				NIST standard reference soil 2781 blind sample analytical results			
	Certified total value (ppm)	Leach range concentrations (ppm)	Total concentration		Total-recoverable concentration	Certified total value (ppm)	Leach range concentrations (ppm)	Total concentration	Median con- centration (ppm)	RSD	Total concentration	Median con- centration (ppm)	RSD	Total-recoverable concentration	Median con- centration (ppm)	RSD
			Median con- centration (ppm)	RSD												
Aluminum	64,400 ± 800	12,000–26,000	61,200	4	23,250	66	980–8,040	14,700	115	10,300	31					
Arsenic	626 ± 38	490–600	625	2	554	9	--	11	--	12	--					
Barium	707 ± 51	300–400	693	1	347	48	65–570	579	--	517	--					
Calcium	12,500 ± 300	3,800–4,800	12,100	2	4,150	71	1,830–36,440	12,100	3	36,100	5					
Cadmium	21.8 ± 0.2	13–26	24	7	24.5	8	1–2	11	11	12	4					
Cobalt	10 ¹	6.3–12	8	16	7	25	--	5	--	5	--					
Chromium	38 ¹	15–23	31	16	22	39	15–23	152	20	142	25					
Copper	2,950 ± 130	2,400–3,400	2,600	9	2,730	5	16–601	550	9	585	5					
Iron	33,800 ± 1,000	22,000–32,000	31,300	5	27,750	14	2,100–24,300	24,200	10	24,600	9					
Lanthanum	34 ¹	--	26.5	18	22.4	29	--	17.6	--	17.4	--					
Potassium	21,100 ± 1,100	3,700–5,000	19,700	5	5,700	81	--	4,100	13	2,500	46					
Magnesium	8,530 ± 420	4,300–6,000	7,600	8	5,950	25	4,850–290	5,200	9	5,000	12					
Manganese	10,100 ± 400	6,200–9,000	9,460	5	7,960	17	33–745	733	--	765	--					
Molybdenum	19 ¹	13–27	17	8	15.5	14	--	37	16	38	15					
Sodium	11,400 ± 600	490–620	10,600	5	600	127	--	1,900	6	900	57					
Nickel	14.3 ± 1.0	8.8–15	12	12	11.5	15	6.3–72.3	67	13	69	11					
Phosphorus	1,060 ± 150	1,060–1,100	1,000	4	900	12	--	23,400	2	22,600	5					
Lead	5,532 ± 80	4,300–7,000	4,910	8	5,085	6	15–183	173	11	179	9					
Antimony	38.4 ± 3	--	35	7	6	103	--	10	--	5	--					
Scandium	8.7 ¹	--	8.6	1	4.8	42	--	64	--	8.7	--					
Silver	35.3 ± 1.5	24–30	>10	--	>10	--	1.7–86.3	>10	--	>10	115					
Strontium	330 ¹	94–110	317	3	105	73	--	215	--	206	--					
Titanium	2,830 ± 100	920–1,100	2,300	15	1,300	52	--	2,400	20	300	117					
Tungsten	93 ¹	--	110	12	35	64	--	10	--	10	--					
Vanadium	76.6 ± 2.3	37–50	64	13	52	28	3.8–81.9	77	--	80	--					
Yttrium	23 ¹	--	17.4	20	14.5	32	--	20.4	--	17	--					
Zinc	6,952 ± 91	5,200–6,900	6,340	7	6,010	10	34–1,120	1,090	11	1,090	11					

¹Noncertified value.

Table 5. Selected analytical results of graded unground silica sand used as blank material (determined using one-half the detection limit for “less than” values) sourced from Ottawa, Illinois (U.S. Silica Company).

[ppm, parts per million; n, number of samples; E, estimated]

Constituent in ppm n =15	Organic carbon	Cadmium	Chromium	Copper	Nickel	Phosphorus	Lead	Zinc
Detection level	500	1.00	1.00	0.50	1.00	100	2.00	1.00
Maximum	E250	E0.05	3.00	0.90	1.00	E50	2.00	4.70
Median	E250	E0.05	4.00	0.25	1.00	E50	1.00	1.80
Average	E250	E0.05	2.78	0.40	0.94	E50	1.22	1.94
Minimum	E250	E0.05	1.00	E0.25	E0.50	E50	1.00	E0.25

32 elements. The median RPD for organic carbon analyses was about 8 percent. Evaluation of replicate sample RPDs by grain-size fraction indicate median RPDs of the greater than or equal to 2 mm (coarse), less than 2 mm to greater than or equal to 0.125 mm (medium), and less than 0.125 mm (fine) size fractions of about 23, 15, and 5 percent, respectively. Smaller RPDs are likely due to the more homogeneous material of the smaller grain-size fractions. Gravel and organic debris such as leaves or sticks were common in the larger grain-size fraction material. Median RPDs of total P for all samples were near zero, but ranged from zero to about 111 percent. The larger RPD was associated with the coarse size fraction. The median RPDs for total P by grain size from coarse to fine were about 26, 11, and 7 percent, respectively.

Street-Cleaner Efficiency Sample Collection and Processing

Both sides of Mount Auburn Street (fig. 2) were swept in a single day each month after the city adjusted the cleaning schedule of the southern side of the street from weekly to monthly cleaning for consistency. However, street sweepers were seen operating on Mount Auburn Street by field crews at a frequency greater than the established monthly schedule on two occasions, which may have affected street-solid accumulation observations. Washoff sampling was done within 24 hours or less and removal-efficiency sampling was typically done within 4 hours or less, minimizing the effect of unscheduled street cleaning operations.

On days scheduled for cleaning, the sampling crew would collect single-sided subsamples from 10 locations along each street before the street cleaner made a single pass. Each vacuumed strip was 108 in (9 ft) from the curb, which represents the width of the street affected by the street cleaner in a single

pass. Following the collection of the “pre-treatment” samples, a regenerative-air street cleaner was operated over the street at 5 miles per hour (mph) or less using a single gutter broom (fig. 6). Although waterless operation would have provided the most effective removal of all particles, water was applied to the gutter broom, not to the street surface, to minimize pedestrian dust exposure. Immediately following the single street cleaner pass (within about 30 minutes), a second composite sample was collected and labeled as a “post-treatment” sample. The difference between the pre- and post-sample masses allowed the determination of the street cleaner removal efficiency. All samples were collected after the street cleaner made a single pass except for samples collected on November 9 and 12, 2010, when the leaf load on the streets required two passes by the regenerative-air street cleaner. On the same dates on non-study streets, mechanical-brush sweepers made two to four passes before a smaller vacuum-assist machine, operating in tandem with the brush sweeper, made its single pass. No samples were collected on November 10, 2010, because of rain.

Post-treatment samples contained about 48 g of material and when separated into three grain-size fractions, did not yield sufficient material to subsample for submission to the laboratory for analysis. Seasonal composite samples were created to provide sufficient material by combining and thoroughly mixing pre- and post-treatment street-cleaner efficiency samples within the following spring, summer and fall periods: May to June, July to September, and October to December. Samples were combined into large labeled clear plastic ziplock bags and sealed. The seasonal composite sample was then shaken and rotated until a homogeneous color and texture was achieved. Representative subsamples of these seasonal composites were obtained using the riffle splitter (fig. 5B) and were submitted for chemical analysis as described above.



Figure 6. Photograph of a TYMCO Dustless Sweeping Technology-6 (DST-6) regenerative-air street cleaner in Cambridge, Massachusetts (photo courtesy of Tom Maguire, MassDEP).

Characterization of Street Solids

Street-solid loadings are the result of deposition and removal rates plus “permanent storage” and seasonal components such as leaf-fall and accumulation of material including winter deicing and maintenance materials (Pitt and others, 2004). Thirty-five CTC street-solid sampling events yielded 195 total mass composite samples collected in July and August 2009, between May and December 2010, and March 2011. Another 98 single sided (SS) street-solid sampling events yielded 194 total mass composite samples collected between May and December 2010. Estimates of accumulation and washoff of street solids were determined using the CTC street-solid sample composites, and removal efficiency estimates were calculated using street-solid sample composites collected from one side of the street (SS) before and after a single pass of a regenerative-air street cleaner.

Although some samples were collected from late July to early September 2009, most samples were collected between May and December 2010. The two additional sampling events in early March 2011 represent an end-of-winter (EOW) load. SS street-solid composite samples representing pre- and post-street cleaning street-solid yields were used to develop a productivity function, or removal efficiency equation for the regenerative-air street cleaner.

Street-Solid Mass

The average mass of CTC street-solids composite samples for 132 selected composite samples from multifamily and commercial streets between May and December 2010 was 612 ± 8 and 427 ± 3 g, respectively. With the inclusion of the large amounts of street solids collected in March 2011, the average mass of street solids for the two land-use

types increased to 742 ± 10 and 720 ± 13 g, respectively. Comparison of initial sample mass and the mass following 14 hours at 105°C in samples from multifamily and commercial streets indicate the street solids had an average moisture content of about 21 and 14 percent, respectively. Although sampling protocols required street surfaces to be dry for the collection of composite samples, and areas where water ponded were avoided, substantial water content was observed within organic debris along curb areas and during several cold-weather sampling events, water was frozen to the street-solid material itself.

Pitt (1979) reported that street-dirt yield was a better unit of measure for street cleaner performance as it represents the actual mass removed from the street surface. In keeping with this convention, all collected street-solid mass composites were converted to a composite street-solid yield lbs/curb-mi using the following expression:

$$P = \frac{\sum_{i=1}^n \left[\left(\frac{M \times 0.0022}{WN} \right) L_{fi} \right]}{\sum_{i=1}^n L_{mi}} \quad (1)$$

where

- P is the mass of the dirt on a street, in pounds per curb-mile;
- n is the total number of streets in each basin;
- i is an index to each street sampled in the study area;
- M is the total mass of sampled street-dirt, in grams;
- W is the width of the vacuum nozzle, in feet;
- N is the number of individual strips vacuumed per street;
- L_{fi} is the length of each street, in feet; and
- L_{mi} is the length of each street, in miles.

0.0022 is the unit conversion factor between grams and pounds, and dividing by 2 accounts for two curblanes. This expression also was used to determine yields from single-sided street-solid composite masses but the numerator was not divided by two.

Sample composite yields and rain events that occurred from May 2010 to March 2011 are shown in figure 7. Street solids sampled in Cambridge, Mass., by land-use type and grain-size fraction are summarized in table 6. Street-solid yields for multifamily and commercial streets in Cambridge, Mass., are compared to other studies in the United States in table 7. Average multifamily street-solid yield was about 740 lbs/curb-mi. Median multifamily street-solid yield was about 602 lbs/curb-mi. Commercial land-use average and median street-solid yields were about 522 and 467 lbs/curb-mi, respectively. Average multifamily and commercial yields are about 1.9 and 1.7 times the national average (Sartor and

Boyd, 1972), respectively (table 7). Average and median multifamily and commercial street-solid yields increased to about 898 and 615, and 887 and 498 lbs/curb-mi, respectively when including the large amounts of EOW material collected in March 2011. Including the EOW samples increased average multifamily and commercial yields to about 2 to 3 times the reported national average, respectively. Evaluation of average street-solid yields on a seasonal basis required combining results between May and June, July to September, October to December 2010, and March 2011, street solid yields from each land-use type to represent spring, summer, fall, and EOW periods, respectively. The distribution of these seasonal sample groups are seen as boxplots in figure 8. Although there are only two sampling events on each street in March to represent the EOW, an annual street-solid yield cycle is seen in both land-use types that is lowest in the spring following spring washoff and EOW cleanup, then yields increase through the summer and into autumn before the end of the street-cleaning season in December, which allows yields to reach their peak levels at the EOW. Median street-solid yields from commercial streets were about 16 and 22 percent greater than those from multifamily streets for spring and EOW periods, respectively. Summer yields from both land-use types were within 2 percent of each other. However, multifamily median street-solid yields were about 42 percent greater than those in commercial streets in the fall. Individual CTC sample dates and resulting masses and yields for streets in both multifamily and commercial land-use types are seen in appendix table 1–15 (on CD-ROM at back of report).

Particle-Size Distribution

Samples were split into three grain-size fractions: coarse, medium, and fine, using stainless-steel sieves and sieve shaker. The median percent distribution of material in the three grain-size fractions found on the multifamily and commercial streets from coarse to fine was about 30, 61, and 9 percent and about 15, 71, and 14 percent, respectively. It is likely the greater proportion of coarse street solids in multifamily street samples is due to the tree density and other plantings on those streets compared to commercial streets (table 1). In addition, median organic carbon yields on multifamily streets were about 2.5 times greater than those from commercial streets. About 87 percent of the composite samples from both land-use types consisted of material coarser than very fine sand (or greater than 0.125 mm). These results are similar to those determined in other studies. Waschbusch and others (1999) reported about 75 percent of sampled street-solid mass in Madison, Wis., was greater than 0.250 mm and less than 5 percent was less than 0.063 mm in diameter; Breault and others (2005) reported more than 93 percent of the street solids was greater than 0.125 mm in diameter in New Bedford, Mass.; and Law and others (2008) reported about 70 percent of the street solids was greater than 0.250 mm in diameter in Baltimore, Md.

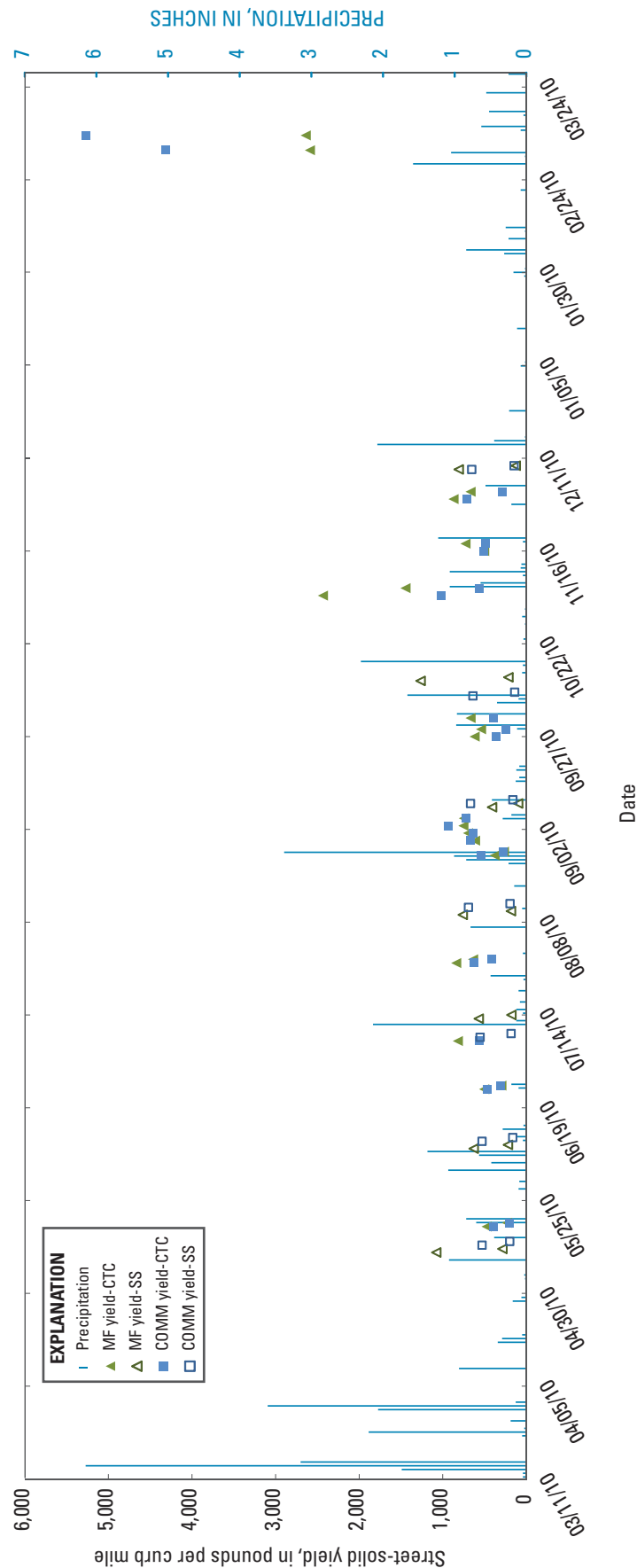


Figure 7. Daily precipitation and average street-solid yields between March 2010 and 2011 measured within multifamily (MF) and commercial (COMM) land-use types during periods of dry weather and bracketed rainstorms from curb-to-curb (CTC) composite samples, and estimated yields during removal-efficiency experiments from single side (SS) composite samples. Precipitation data courtesy of the Cambridge Department of Public Works.

Table 6. Summary of Cambridge, Massachusetts, street-solid yields by land-use type and grain-size fraction.

[n, number of samples; mm, millimeters; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

Street-solid yield, in pounds per curb-mile				
Statistic	Total	Coarse	Medium	Fine
Multifamily n = 65				
Mean	740.1	301.0	346.9	63.6
Median	601.5	129.2	277.4	37.9
Minimum	168.8	11.7	95.1	6.1
Maximum	3,847.5	2,935.1	974.6	280.9
Commercial n = 64				
Mean	521.5	111.6	331.2	64.5
Median	466.7	65.1	305.0	60.7
Minimum	179.7	21.0	126.6	4.2
Maximum	1,471.0	707.3	918.7	307.2

Spatial Distribution of Street Solids

Distribution of material on street surfaces is highly variable and controlled by many factors including presence of berms or curbing, condition of street-surface texture, prevailing winds, traffic density, on-street parking, and parking controls. Sartor and Boyd (1972) and Pitt (1979) observed that on smooth streets with moderate to heavy traffic without on-street parking, about 90 percent of the material was located within 1 foot of the curb. Pitt (1979) also reported street dirt on rough-textured streets typically is distributed more evenly as more material is retained within cracks and pits on the surface. In addition, they reported on-street parking can act to buffer traffic action and prevailing winds to further limit consolidation of street solids near the curb. Seasonal effects also determine street solids distribution. This is demonstrated in areas with relatively cold winters requiring street maintenance during snow events in the form of deicers or sand. Although the Cambridge Department of Public Works (DPW) does not apply maintenance sand to their streets during snowstorms, maintenance sand tracked into the city from daily traffic and use of sand to improve traction on sidewalks and other pedestrian areas may be available to “wash on” to street surfaces.

Selbig and Bannerman (2007) collected curb samples from 3 ft out from the curb in addition to the crown (or center lane). Their streets had minimal on-street parking, and they reported an even distribution of street material at the EOW such that the crown contained a greater proportion of material than the curb lanes; however, by early summer 75 percent of the street dirt was confined to within 3 ft of the curb.

Table 7. Comparison of Cambridge, Massachusetts, street-solid yields by land-use type to those in other areas of the United States (Modified from Selbig and Bannerman, 2007).

[--, no data; all values in pounds per curb-mile]

Statistic	Cambridge, Massachusetts	Madison, Wisconsin ¹	Champaign, Illinois ²	Bellevue, Washington ³	Seattle, Washington ⁴	San Jose, California ⁵	Baltimore, Maryland ⁶	U.S. Nationwide ⁷
Multifamily								
Mean	740	614	408	815	970	310	645	391
Median	602	569	--	705	1,060	--	--	--
Commercial								
Mean	522	--	--	--	--	509	--	302
Median	467	--	--	--	--	--	--	--

¹Selbig and Bannerman, 2007.

²Bender and Terstriep, 1984.

³Pitt, 1985.

⁴Seattle Public Utilities and Herrera Environmental, 2009.

⁵Pitt, 1979.

⁶Law and others, 2008.

⁷Sartor and Boyd, 1972.

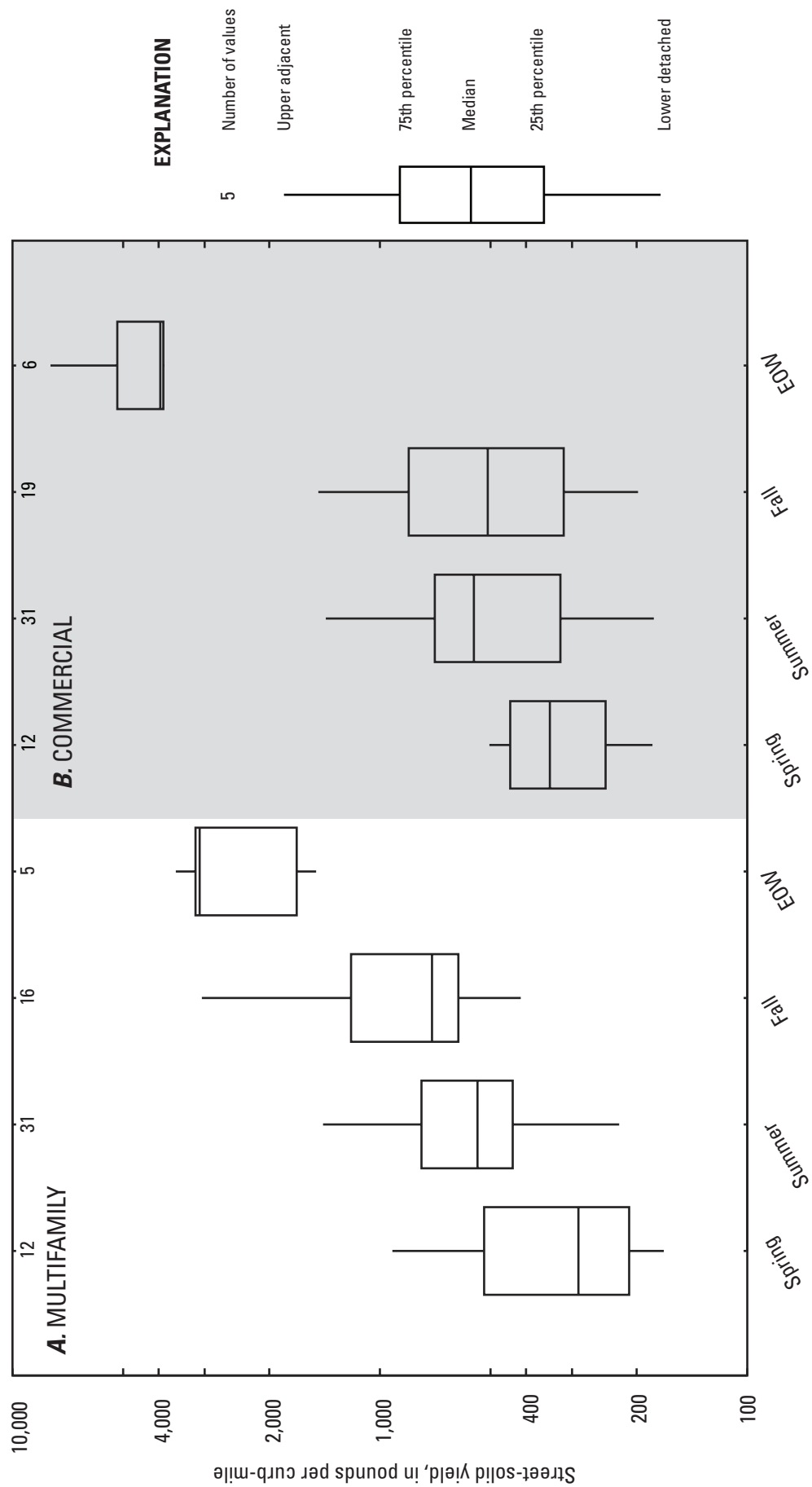


Figure 8. Seasonal and end-of-winter (EOW) street-solid yields, in pounds per curb-mile from streets in *A*, multifamily, and *B*, commercial land-use types, Cambridge, Massachusetts. Time periods represent samples collected during SPRING, May to June 2010; SUMMER, July to September 2010; FALL, October to December 2010; and EOW, March 2011.

Three sets of street-solid distribution samples were collected on each street in Cambridge in July and October 2010, and in March 2011, such that one portion of the composite represented a curb lane and a second composite represented the remaining center lane or crown of the street. July composite samples represented street-solids within 3 ft of the curb and the remaining street crown. About 57 percent of the total street-solids was found within 3 ft of the curb and about 43 percent of the total street-solids was found in the street crown. About 67, 55, and 63 percent of street solids from the coarse, medium, and fine grain-size fractions were within 3 ft of the curb, respectively. Within the crown, the distribution of street solids from coarse to fine grains were about 33, 45, and 37 percent, respectively. Samples were collected from the curb extending 9 ft towards the crown in October 2010. About 95 percent of total street solids were observed within 9 ft of the curb, and the remaining 5 percent resided within the crown. Distribution of street solids by grain size indicated 97, 91, and 94 percent of material in the coarse, medium, and fine grain-size fractions were within 9 ft of the curb, respectively. The remaining 3, 9, and 6 percent of the coarse to fine grain-size fractions were within the crown, respectively. EOW samples were collected 6 ft from the curb in March 2011, and about 74 percent of the total material was within this area. From coarse to fine grain-size fractions, 81, 72, and 75 percent of street solids was within 6 ft of the curb, respectively. These samples suggest a fairly even distribution of street solids throughout the year in Cambridge on the smooth to rough-textured streets with heavy on-street parking. The most even distribution was observed within the two grain-size fractions greater than or equal to 0.125 mm, which represents more than 86 percent of the total mass of street solids on both multifamily and commercial streets.

Street-Solid Accumulation

Street-solid composite samples from each street were used to estimate the accumulation rate (build-up rate or deposition loading) of street solids on street surfaces by dividing the difference in total yields between successive samples before and after a rainstorm by the number of days between sampling events. Accumulation results for Mount Auburn Street were negative, indicating a loss of material with time rather than a buildup, although results from the five other streets were positive. Considering the additional street cleaning by mechanical-brush street cleaners observed outside the monthly schedule on this street, commercial accumulation-rate estimates exclude data from Mount Auburn Street, which may exhibit a negative bias resulting from additional street cleaning activity.

Accumulation rates from streets in each land-use type are shown in figure 9. Overall accumulation patterns were similar between land-use types by grain-size fraction and total yield. Median total accumulation rates were 33 and 22 lbs/curb-mi/day, and ranged between -43 to 84 and -23 to

308 lbs/curb-mi/day for multifamily and commercial land-use streets, respectively (extreme values truncated in figure 9). Median multifamily accumulation rates were largest within the medium grain-size fraction at about 19 lbs/curb-mi/day, though the coarse and fine grain-size fractions accumulate similarly at about 7 lbs/curb-mi/day. Median commercial accumulation rates for the medium grain-size fraction were about 15 lbs/curb-mi/day, the fine grain-size fraction was about 6 lbs/curb-mi/day and the coarse grain-size fraction was the smallest at about 2 lbs/curb-mi/day.

The average accumulation of street solids on the study streets increased quickly within a few days of a street cleaning or rainstorm in both multifamily and commercial land-use types (fig. 10). The drop in yields after nearly two days on streets in both plots is attributed to sample loss during processing that resulted in an average accumulation value based on only one street for multifamily and commercial streets. These results indicate that the street solids on multifamily and commercial streets in Cambridge can accumulate to near median yields within 1 to 3 days after the streets are cleaned or following a rainstorm (fig. 10). After this steep increase, the estimated street-solid yield in each land-use type remained somewhat consistent. The overall accumulation pattern of these data is similar to the early research of Sartor and Boyd (1972) for both land-use types with a steep increase within the first few days of a washoff or street-cleaning event, then increasing more slowly and reaching maximum yields in about 5 days. Yields also became constant after about 7 days in Bellevue, Washington, an area where rainfall occurs about every 3 days (Pitt, 1985). Burton and Pitt (2002) suggest that yields of street solids on roadways in areas such as Bellevue, Wash., remain close to the initial yields and do not increase with time.

Street-Solid Washoff

The washoff of street solids from roadway surfaces and mobilization of local soils adjacent to streets are dependent on the initial load, and the rainfall intensity or volume of stormwater on the roadway to loosen dirt and other solids from the pavement and transport it off/from the street (Pitt and others, 2004). Pitt and others (2004) also suggest that urban stormwater runoff during small and less intense rainstorms represent most of the solid load resulting from wear of the road surface and the deposition of traffic-related materials. Furthermore, Pitt and others (2004) reported that washoff is affected by distribution of street solids on road surfaces and extent of armoring (or the sheltering of smaller particles by larger ones).

Street-solid composite samples were collected before and after rainstorms. The time between the end of a rainstorm and when samples were collected varied, and percent washoff from streets in the two land-use types was estimated based on samples collected between 3 and 23 hours of the end of six rainstorms. The narrow window between the collection

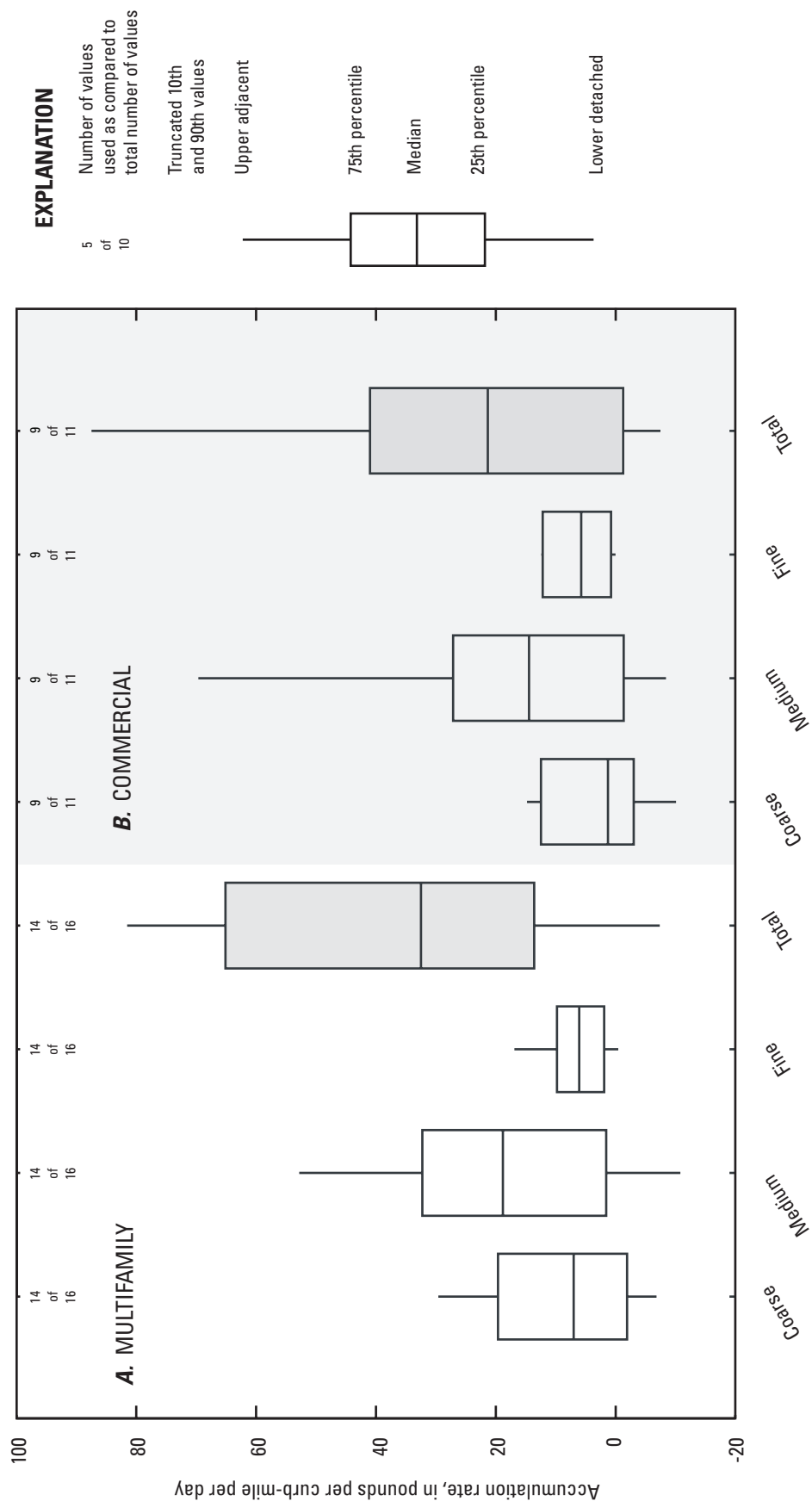


Figure 9. Accumulation rates by grain-size fraction and total solids, in pounds per curb-mile per day from streets in A, multifamily and B, commercial land-use types, Cambridge, Massachusetts. COARSE represents all solids greater than or equal to 2 mm; MEDIUM, less than 2 mm to greater than or equal to 0.125 mm; FINE, less than 0.125 mm in diameter. TOTAL represents sum of all grain-size fractions. COARSE solids include all organic material and gravel up to about 50 mm in diameter. Commercial plots do not include data from Mount Auburn Street.

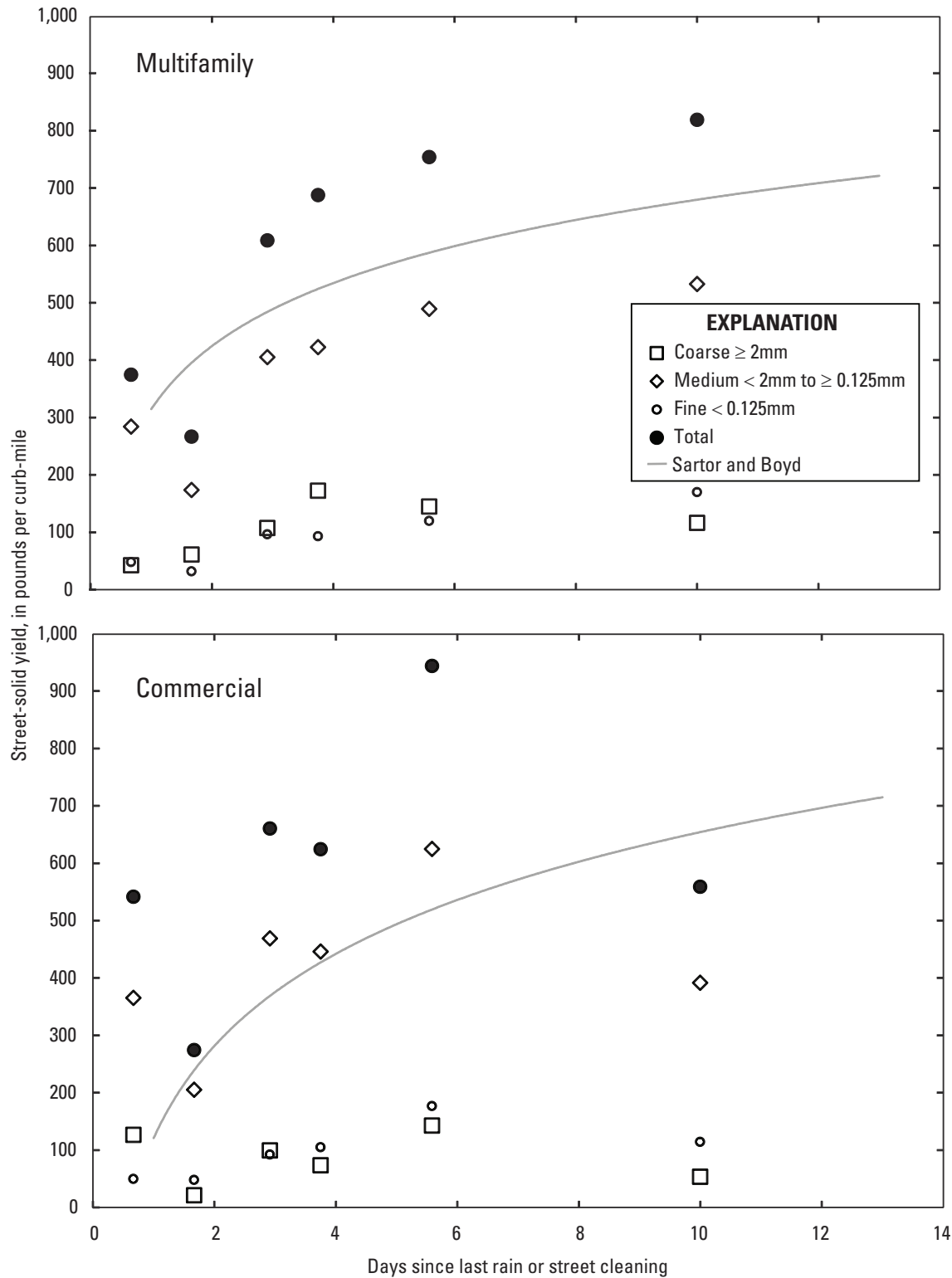


Figure 10. Street-solid yield by grain-size fraction and total yield, in pounds per curb-mile per day as a function of time in days since the last rain or street cleaning on streets in multifamily and commercial land-use types, Cambridge, Massachusetts. U.S. nationwide residential and commercial results from Sartor and Boyd (1972) also are shown. Commercial plots do not include data from Mount Auburn Street.

of prestorm and poststorm samples likely eliminated effects of unscheduled street cleaning on Mount Auburn Street. The average amount of street solids removed from the roadway by rainfall (washoff) was calculated by subtracting the difference of street-solid mass in total composite samples and by grain-size fraction before and after a rainstorm for six sample pairs. Total storm volumes and rainfall intensities based on the Cambridge DPW rain gage on Hampshire Street ranged between 0.32 to 1.71 inch and 0.027 to 0.185 inches per hour (in/hr), respectively. Net increases of street solids following rainstorms result in negative washoff values. One of the six composite sample pairs bounds a rainstorm during heavy leaf-fall season, which may explain the negative washoff values. Deposition of leaves/seeds/woody debris from trees, dirt, soils, and other debris transported from impervious surfaces or saturated pervious surfaces adjacent to the street surface, and dirt and soils tracked in from construction vehicles (track-out) are possible sources that may increase the amount of street solids after a rainstorm. Every effort was made to avoid areas with unusual loading or obvious additional street solids from active construction sites (fig. 2) during sampling.

The percent washoff of street solids from each street in terms of grain-size fraction, and an average percent washoff of all three grain-size fractions from each street as a result of the six rainstorms are presented as boxplots in figure 11. Percent washoff of solids from streets in multifamily and commercial areas increased similarly with decreasing grain-size. Median average street-solid washoff also was similar between land-use types at about 36 and 42 percent for multifamily and commercial streets, respectively.

An average percent washoff for each grain-size fraction and an average total washoff from both land-use types for each of the six storms were calculated and plotted as a function of rainfall volume and intensity (fig. 12). Plots in figure 12A show the percent washoff is generally highest in the fine grain-size fraction, and there were two instances with negative washoff of primarily coarse street solids on multifamily streets and one instance of negative washoff of fine size fraction street solids on commercial streets. Observed storm intensities in figure 12B were less than 0.20 in/hr, and the highest percent washoff values are seen in the fine fraction at intensities less than 0.10 in/hr. Negative washoff of primarily coarse street solids are observed only from streets in the multifamily land-use type and washoff occurs at lower intensities compared to negative washoff from streets in commercial land use.

Regenerative-Air Street Cleaner Removal Efficiency

The removal efficiency of a TYMCO Dustless Sweeping Technology-6 (DST-6) regenerative-air street cleaner, herein referred to as the “RA street cleaner,” was determined by comparing the difference between street-solid composite samples collected before and after the streets were cleaned by a single

pass of the machine in multifamily and commercial land-use areas.

The difference between pre- and post-median yields of total street solids from multifamily streets was 82 and 78 percent on commercial streets (table 8). Removal efficiency of the RA street cleaner decreased with smaller grain-size fractions, and was nearly the same for streets in both land-use types. The median percent removal efficiency for the machine on multifamily and commercial streets was 92, 83, and 53 percent, and 92, 79, and 51 percent for the coarse, medium, and fine grain-size fractions, respectively. Negative values, or net increases in material were occasionally observed within the fine grain-size fraction. However, this typically occurred on streets with rough surfaces, and is possibly a result of the action of the street cleaner’s gutter broom removing coarse dirt and other material from cracks and holes near the curb, exposing finer material in addition to fine-grained material left behind by the wet gutter broom. Median street-solid yields before a single RA street cleaner pass within 9 ft of the curb on multifamily and commercial streets were 735 and 521 lbs/curb-mi, respectively. Street-solid yields before street cleaning ranged from about 269 lbs/curb-mi in both land-use types to 1,685 to 1,377 lbs/curb-mi on multifamily and commercial streets, respectively (fig. 13). Median residual yields after the street was cleaned were nearly identical for streets in both land-use types at about 100 lbs/curb-mi, but ranged between 18 and 513 lbs/curb-mi, and 46 and 222 lbs/curb-mi on multifamily and commercial land-use streets, respectively. Individual removal efficiency (or single-sided) sample dates and resulting masses and yields for streets in both multifamily and commercial land-use types are seen in appendix table 1–16 (on CD-ROM at back of report).

A residual yield of street solids always remained on the street surface following a single street cleaner pass in the study sections as a function of the initial yield. Evaluation of the removal efficiency data based on season, individual streets, land-use type, street condition, and traffic volume did not present any clear patterns, and resulted in poor relations. Closer inspection of available removal efficiency data indicate a nonnormal, cloud-like pattern without a strong linear relation, whether or not the data was corrected for the whole street or not. The Kendall-Thiel robust line, described by Helsel and Hirsch (2002), is a nonparametric regression technique that is less affected by outliers and nonnormality of residuals that commonly characterize hydrologic datasets (Granato, 2006). The Kendall-Thiel Robust Line program (KTRLLine-version 1.0; Granato, 2006) was used to develop a regression of residual yield (post-street cleaning) and initial yield (pre-street cleaning) or productivity function data corrected for the whole street for the regenerative-air street cleaner. The slope is calculated as the median of all possible pairwise slopes and the intercept is calculated so that the line will run through the median of the input data (Granato, 2006). The slope of the regression between street-solid yield before and after street cleaning is low, and the data indicate that the efficiency of the street cleaner increased with increasing initial yields, but also

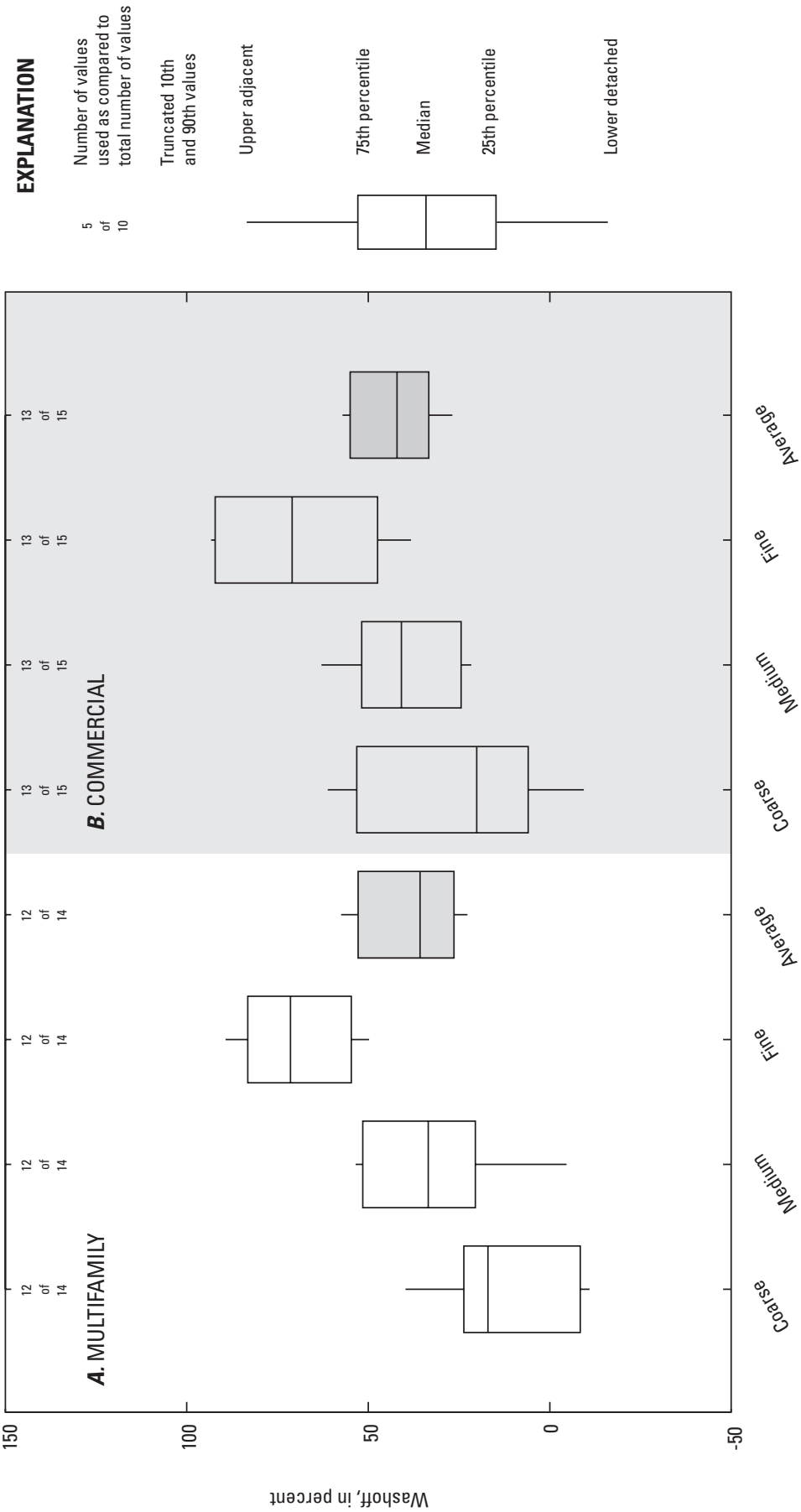


Figure 11. Percent washoff of street solids by grain-size fraction estimated for storms with a recorded rainfall volume range of 0.32 to 1.71 inches, from streets in A, multifamily and B, commercial land-use types, Cambridge, Massachusetts. COARSE, represents all solids greater than or equal to 2 mm; MEDIUM, less than 2 mm to greater than or equal to 0.125 mm; FINE, less than 0.125 mm in diameter. AVERAGE represents the range of average percent washoff for each street. COARSE solids include all organic material and gravel up to about 50 mm in diameter.

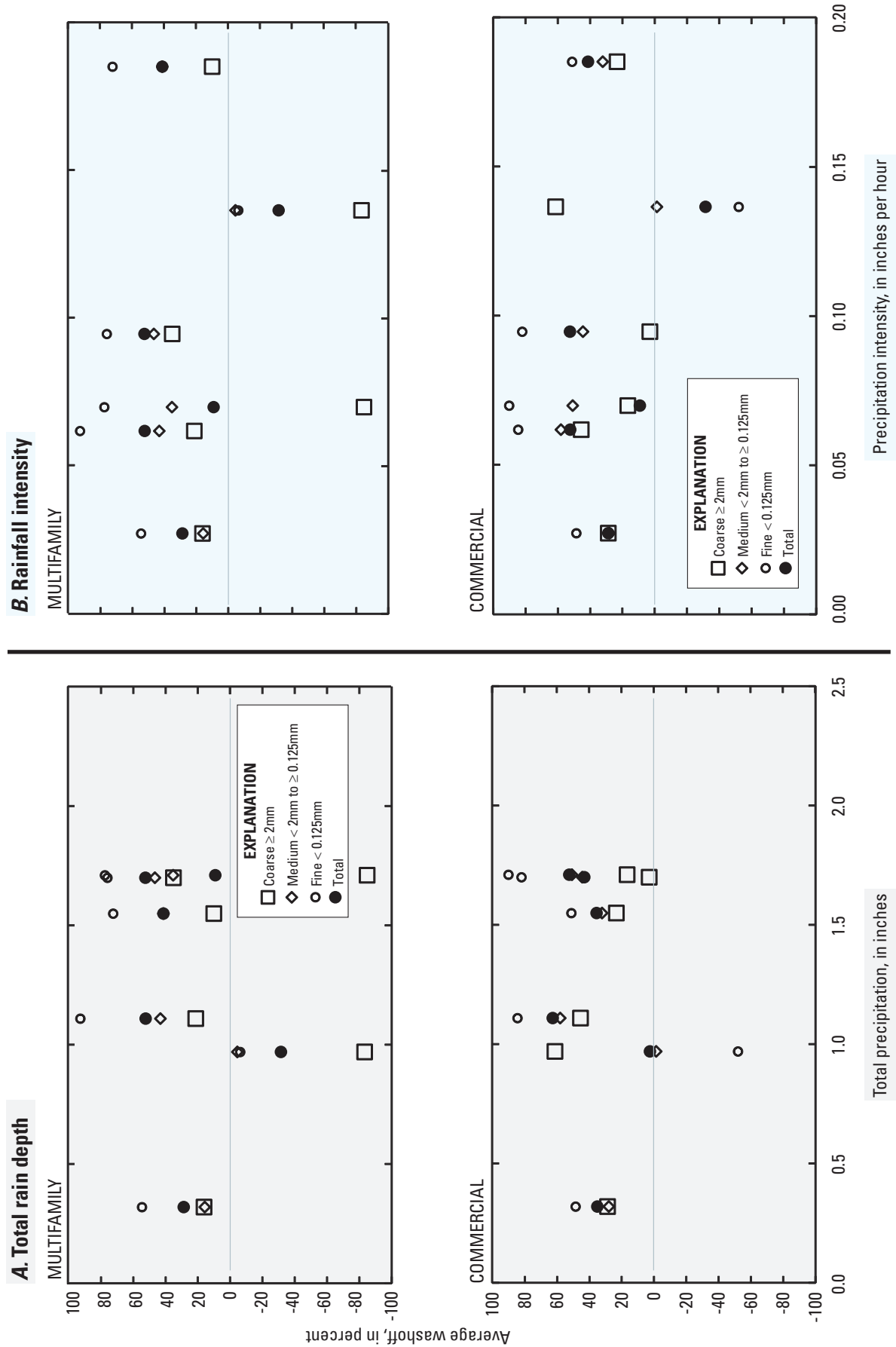


Figure 12. Average percent washoff for each grain-size fraction, and average total washoff for storms with a recorded rainfall volume range of 0.32 to 1.71 inches as a function of A, total rain depth, and B, rainfall intensity from streets in multifamily and commercial land-use types, Cambridge, Massachusetts.

Table 8. Average, median, maximum, and minimum removal efficiency, in percent, of a regenerative-air street cleaner on multifamily and commercial land-use streets in Cambridge, Massachusetts.

[Negative values indicate an increase in material following a single regenerative-air street-cleaner pass; n, number of samples; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

	Removal efficiency, in percent			
	Total	Coarse	Medium	Fine
Multifamily n = 33				
Average	83.3	89.5	82.6	49.8
Median	86.2	95.8	88.5	65.9
Maximum	98.3	99.8	96.9	94.9
Minimum	35.7	75.1	42.8	-87.1
Commercial n = 39				
Average	78.2	92.4	79.4	48.6
Median	79.7	94.1	80.1	63.6
Maximum	92.6	99.3	95.9	92.8
Minimum	43.8	63.9	45.3	-86.7

left a consistent residual yield regardless of the initial street-solid yield. The slope (0.066), and y-intercept (69.57) of the KTRLLine (fig. 14) represent the productivity function coefficients applied in the SLAMM model to simulate the performance of the regenerative-air street cleaner evaluated in 2010.

Street-Solid Chemistry

Constituents on street surfaces in urban areas may come from a variety of sources and may vary depending upon the age of the materials used for construction. For example, fiberglass and asphalt roof types are known to have better runoff quality than slate tile, rubber, or galvanized metal (Davis and others, 2000). Average concentrations of copper (Cu), Pb, and zinc (Zn) in samples of bulk rainfall collected from a rubberized roof in Ipswich, Mass., were 2.8, 5.9, and 7.9 micrograms per liter ($\mu\text{g/L}$), respectively (Zimmerman and others, 2010). The concentrations of total P in bulk rainfall were 0.01 milligrams per liter (mg/L). Average concentrations of Cu, Pb, and Zn in samples of rainfall runoff from the rubberized roof were about 53, 692, and 514 $\mu\text{g/L}$, respectively, and about 0.10 mg/L was reported for total P. In addition, roofing and siding materials from buildings has been associated with substantial concentrations of Cd, Cu, Pb, and Zn (Davis and others, 2000).

Smith (2010) conducted an extensive study of stormwater runoff from Massachusetts highways of various traffic densities. In addition to exhaustive stormwater sampling, samples of maintenance sand, maintenance salt (sodium chloride), liquid calcium chloride, berm soil, and grass clippings were submitted for analysis of elements, polyaromatic hydrocarbons, and phthalates. Grasses were determined to possess relatively high concentrations of Ca, K, and P. Washed off solids greater than 0.250 mm in diameter, including sands and gravels, but consisting mostly of leaves, were also relatively high in these elements (Smith, 2010). Average concentrations of P, other elements, and suspended sediments in composite samples of highway runoff were reported to be 3 to 11 times greater in winter runoff compared to runoff during warmer months (Smith, 2010). The large difference between winter and nonwinter runoff concentrations in highway runoff was attributed primarily to the application of maintenance sand. Although maintenance sand constituent concentrations were small, the large amount of sand applied during the winter resulted in large increases of many elements in runoff, including a 94-percent increase in winter P concentrations (Smith, 2010). Low temperatures, increased vehicle component wear, and entrained material in snowbanks are all additional sources of increased winter loading. Smith (2010) reported exhaust emissions from gasoline engines at highway speeds represented less than 3 percent of P concentrations in stormwater runoff, background soils accounted for about 37 percent of the median P concentration, and that erosion or presence of soils onto the paved surface could be a large source of P and other elements in stormwater runoff.

Urban and suburban traffic patterns have more frequent stops and accelerations. This type of vehicle operation is associated with less efficient combustion by gasoline engines and increased vehicle component and road wear. These conditions in urban and suburban areas may result in greater concentrations of Cu and Zn associated with brake and tire wear (Davis and others, 2000). Average emission rates of Cr, Cu, Nickel (Ni), and Pb were similar to major particulate-associated polyaromatic hydrocarbon (PAH) emission rates, but P, Fe, and Zn were about 6 to 38 times greater than their respective PAH emission rates (Cadde and others, 2001).

Median concentrations of organic carbon, P, and 31 other elements in street-solid composite samples from multifamily and commercial streets in Cambridge, Mass., were normalized by the mass of the respective grain-size fraction. Median total-recoverable concentrations and respective standard deviations of all CTC composite samples of street solids for each grain-size fraction for the two land-use types are listed in table 9 (in back of report). Concentrations of organic carbon and 12 elements were greater in composite samples collected from multifamily streets than in composite samples collected from commercial streets. Median concentrations of organic carbon and total P were about 35 and 29 percent greater than the median concentrations calculated for composite samples collected from commercial streets. Individual total-recoverable concentrations of street-solid composite samples for streets in

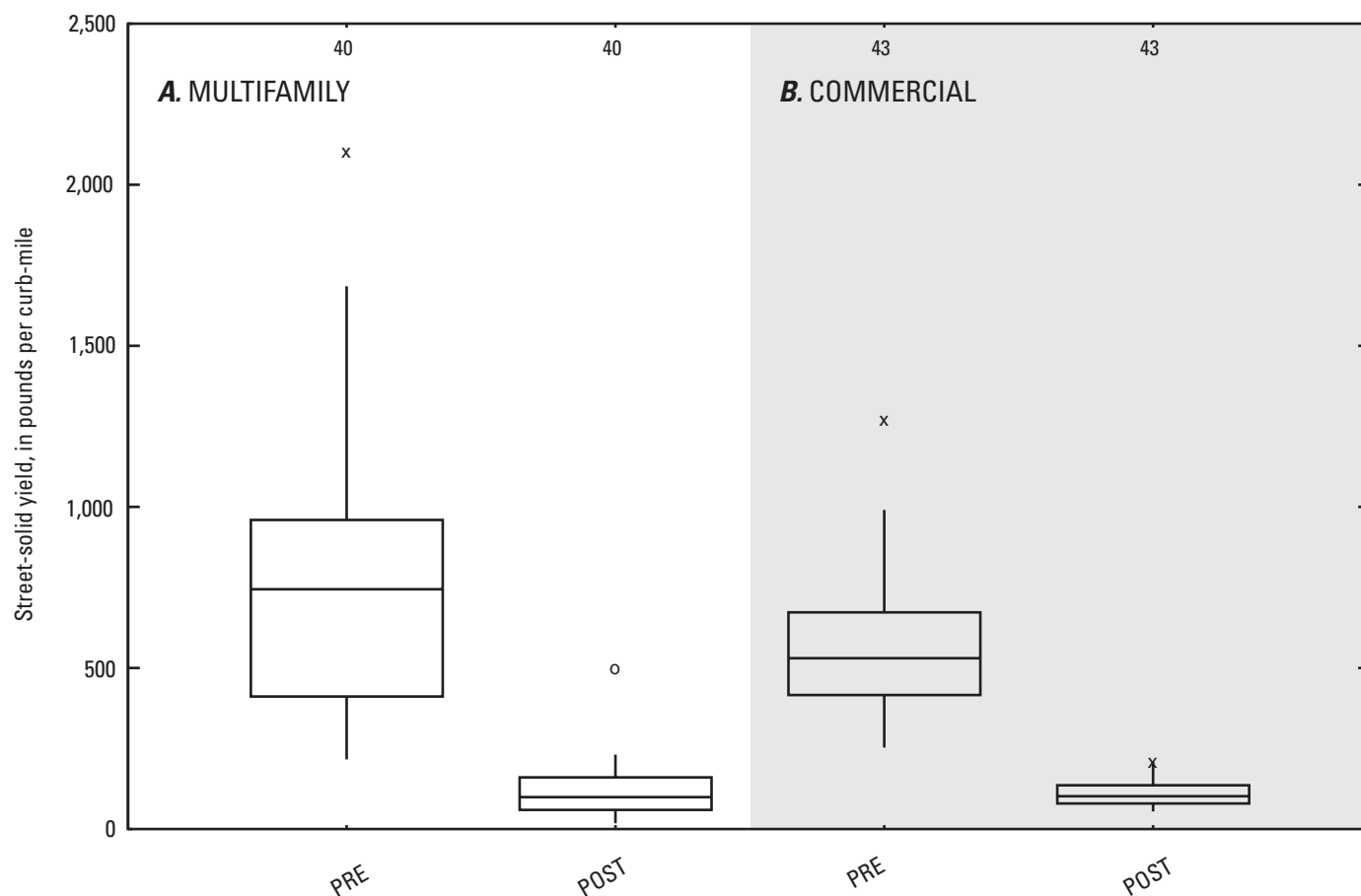


Figure 13. Street-solid yields before (PRE) and after (POST) a single pass of a regenerative-air street cleaner on streets in A, multifamily and B, commercial land-use types, Cambridge, Massachusetts.

both multifamily and commercial land-use types are seen in appendix tables 1–17 and 1–18, respectively (on CD-ROM at back of report).

The total mass of constituents in composite samples collected from multifamily streets also were somewhat greater than the total mass of constituents in composite samples collected from commercial streets (table 9, in back of report). The total mass of constituents generally increased with decreasing grain size, except for organic carbon, Ca, K, Mg, P, and strontium (Sr), in samples from streets in both land-use types. These constituents had higher concentrations in the coarse size fraction.

Concentrations of organic carbon, Ca, and K, from the medium fraction also were greater than concentrations in the fine fraction, although the difference was slightly greater in the multifamily street solid composite samples. Concentrations of organic carbon, Ca, K, P in samples of unwashed leaves collected from residential streets were higher than finer grain-size fractions of street solids. Similar concentrations of these constituents also were found in

bulk samples greater than 0.250 mm in diameter, consisting predominantly of leaves, collected at the outlet of a catch basin along Massachusetts highways (Smith, 2010). About 13.3 and 1.5 percent of the total P mass is within the finest fraction (less than 0.125 mm) for multifamily and commercial land-use types, respectively. The total mass of organic carbon and P in composite samples of street solids from multifamily streets was about 68 and 75 percent greater than the mass of the constituents in composite samples collected from commercial land-use streets, respectively. The mass of P on multifamily streets was greater than that on commercial streets by about 1.4 and 11.5 times in the medium and fine grain-size fractions, respectively. Total P on commercial streets was about 0.8 times (or about 20 percent) greater than total P on multifamily streets within the coarse grain-size fraction. About 87 and 98 percent of the total P mass was observed within material greater than very fine sand (greater than 0.125 mm in diameter), for streets in multifamily and commercial, land-uses, respectively.

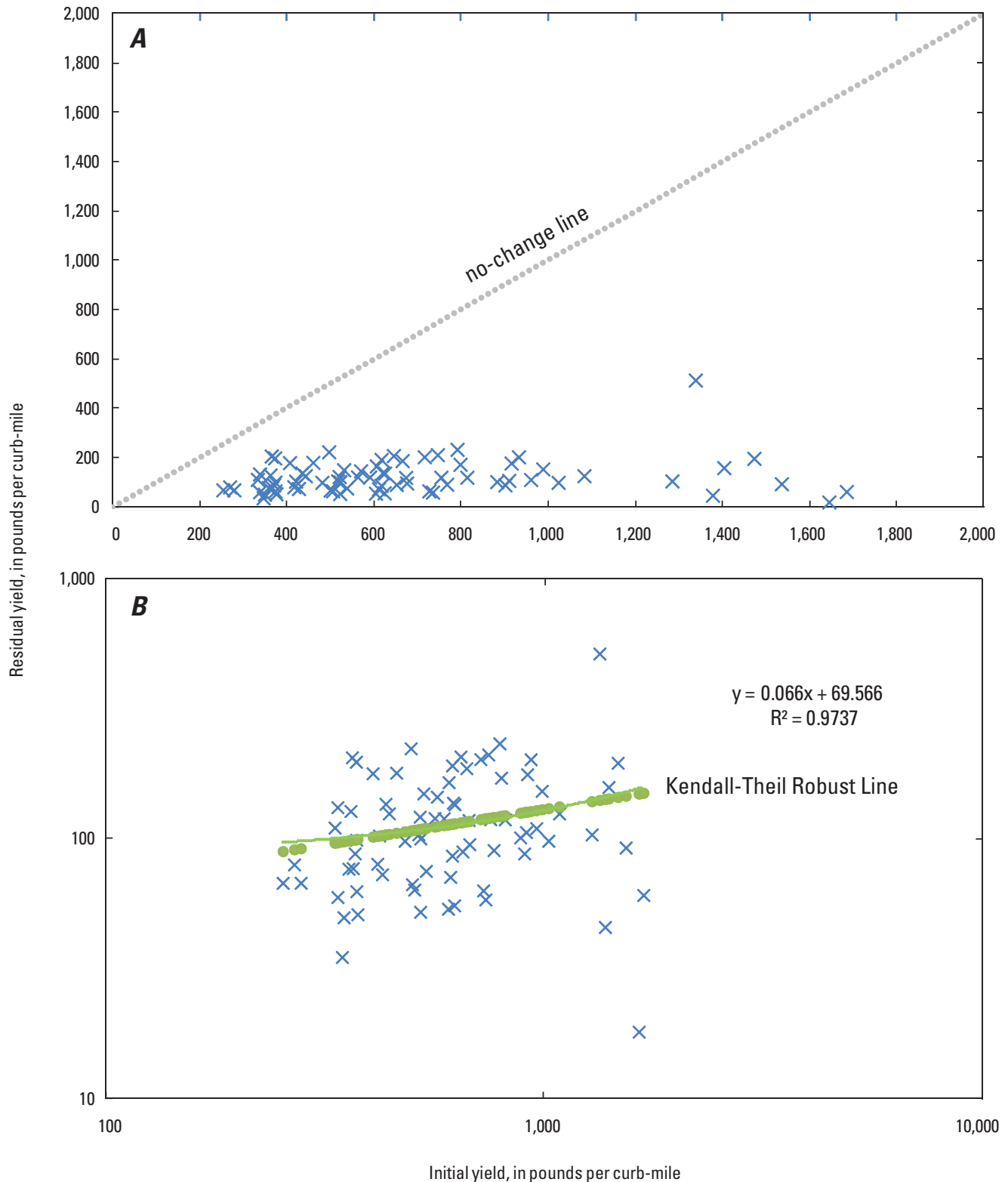


Figure 14. A, Removal efficiency plot of a regenerative-air street cleaner making a single pass on streets with smooth to rough street-surface conditions and heavy on-street parking with monthly parking controls, in multifamily and commercial land-use types Cambridge, Massachusetts. All data below the 1:1 no-change line represent reductions in street-solid yields. B, Productivity function (green dotted line) of the regenerative-air street cleaner using the Kendall-Theil Robust Line (KTRLine version 1.0), where 0.066 is the slope and 69.566 is the y-intercept.

Total P yields (fig. 15, table 10) generally follow the pattern of street solid yields (fig. 8, table 10). Following spring cleaning, P yields are reduced to low levels by street cleaning and washoff events during the spring and summer. Yields of P increase in autumn during leaf-fall season and maximum yields of P were measured on streets in both land-use areas at this time (fig. 15, table 10); however, median yields of P were highest at the EOW in March 2011 (fig. 15).

Accumulation Rate Estimates of Organic Carbon and Elements

Accumulation rate estimates were calculated for concentrations of organic carbon, total P, and 31 elements by first normalizing by mass to determine the load of constituents in grams. The resulting mass was then used to determine the yield of each constituent in lbs/curb-mi using the process described in the “Street-Solid Mass” section. Resulting yields were divided by the total number of days between sampling events to further obtain estimates of constituent accumulation rates in lbs/curb-mi/day. Average, median, maximum, and minimum accumulation rates for each constituent in street-solid samples were estimated for each grain-size fraction by land-use type (table 11, in back of report). Sample concentrations from commercial streets do not include Mount Auburn Street data. Median concentrations of organic carbon and element accumulation rates for the multifamily land-use type are greater than those observed on commercial land-use streets for 24 of the 33 constituents for the coarse and fine fractions, and for 14 of the 33 constituents for the medium fraction. Median accumulation rates from coarse to fine in samples from the multifamily land-use type were greater than those from streets in the commercial land use for 31, 24, and 16 of the 33 constituents, respectively (table 9, in back of report).

Accumulation rates of most constituents were generally smallest within the coarse grain-size fraction, except for yields of organic carbon. The largest accumulation rates for most constituents appear to vary between the medium and fine grain-size fractions (table 10). Accumulation rates from streets in multifamily land-use areas were generally greater than streets in commercial land-use areas. In particular, the median accumulation rates of Cr, Cu, P and Pb in total solids from streets in multifamily areas were about 1.9, 1.4, 5.0, and 12.7 times greater than those from streets in commercial areas, respectively; however, median accumulation rates of Cd, Ni, and Zn from streets in commercial areas were greater than the those from multifamily streets by about 2.0, 1.9, and 1.5 times, respectively. Kaufman and others (2011) also reported high concentrations of metals including Pb in residential as compared to commercial land-use types in urban areas.

The median accumulation rate estimated for organic carbon for all grain-size fractions from multifamily streets was 1.4 lbs/curb-mi/day and ranged between about -10 to 17 lbs/curb-mi/day. The median accumulation rate and range for organic carbon for all grain-size fractions in commercial

data was 0.067 lbs/curb-mi/day, and ranged between about -12 to 4 lbs/curb-mi/day. Accumulation rates of organic carbon were highest within the medium grain-size fraction, followed by the coarse grain-size fraction for both land-use types reflecting the dominant effect of larger organic debris within the coarser fractions.

The median total P accumulation rate for total solids in multifamily data was 0.002 lbs/curb-mi/day and ranged between about -0.017 and 2.36 lbs/curb-mi/day. Accumulation rates of P increased from coarse to fine grain-size fractions. From coarse to fine, multifamily median accumulation rates of P are about 0.001, 0.004, and 0.010 lbs/curb-mi/day, respectively. The median accumulation rate for total P for total solids in commercial data was 0.0004 lbs/curb-mi/day, or about 5 times less than the multifamily accumulation rate, and ranged between about -0.003 to 0.030 lbs/curb-mi/day. Median commercial accumulation rates of total P in the coarse to fine grain-size fractions are about 0.0001, 0.004, and 0.0001 lbs/curb-mi/day, respectively. Although the accumulation rate of total P for the medium size fraction was nearly the same on streets in both land-use types, the accumulation rate on multifamily streets in the coarse and fine size fractions were about 11 and 82 times greater than those on commercial streets.

Washoff Estimates of Organic Carbon and Elements

The amount of washoff for each constituent was determined by multiplying the element concentrations by their respective mass of each grain-size fraction from the six composite sample pairs. Table 12 (in back of report) shows the average, median, maximum, and minimum percent washoff of organic carbon and 32 elements for each grain-size fraction within the multifamily and commercial land-use types. Median percent washoff for organic carbon and elements on streets in multifamily land-use areas was greater than those on commercial land-use streets for 24 of the 33 constituents in the coarse and fine grain-size fractions, and for 14 of the 33 constituents in the medium grain-size fraction. Negative washoff was observed for several rainstorms in all grain-size fractions, but was most common in the coarse and fine grain-size fractions. These rainstorms likely are associated with organic debris and “washon” from other source areas onto the streets.

Median total washoff for total P on streets in multifamily areas was 58 percent and ranged between about -1,120 to 93 percent. Median percent washoff of total P from streets in multifamily areas was about 39 percent for the two coarser fractions greater than 0.125 mm, and about 76 percent for the fine grain-size fraction. Median washoff of total P from streets in commercial areas was about 48 percent and ranged between about -214 to 99 percent. Median washoff of P from coarse to fine grain-size fractions are about 34, 51, and 77 percent, respectively.

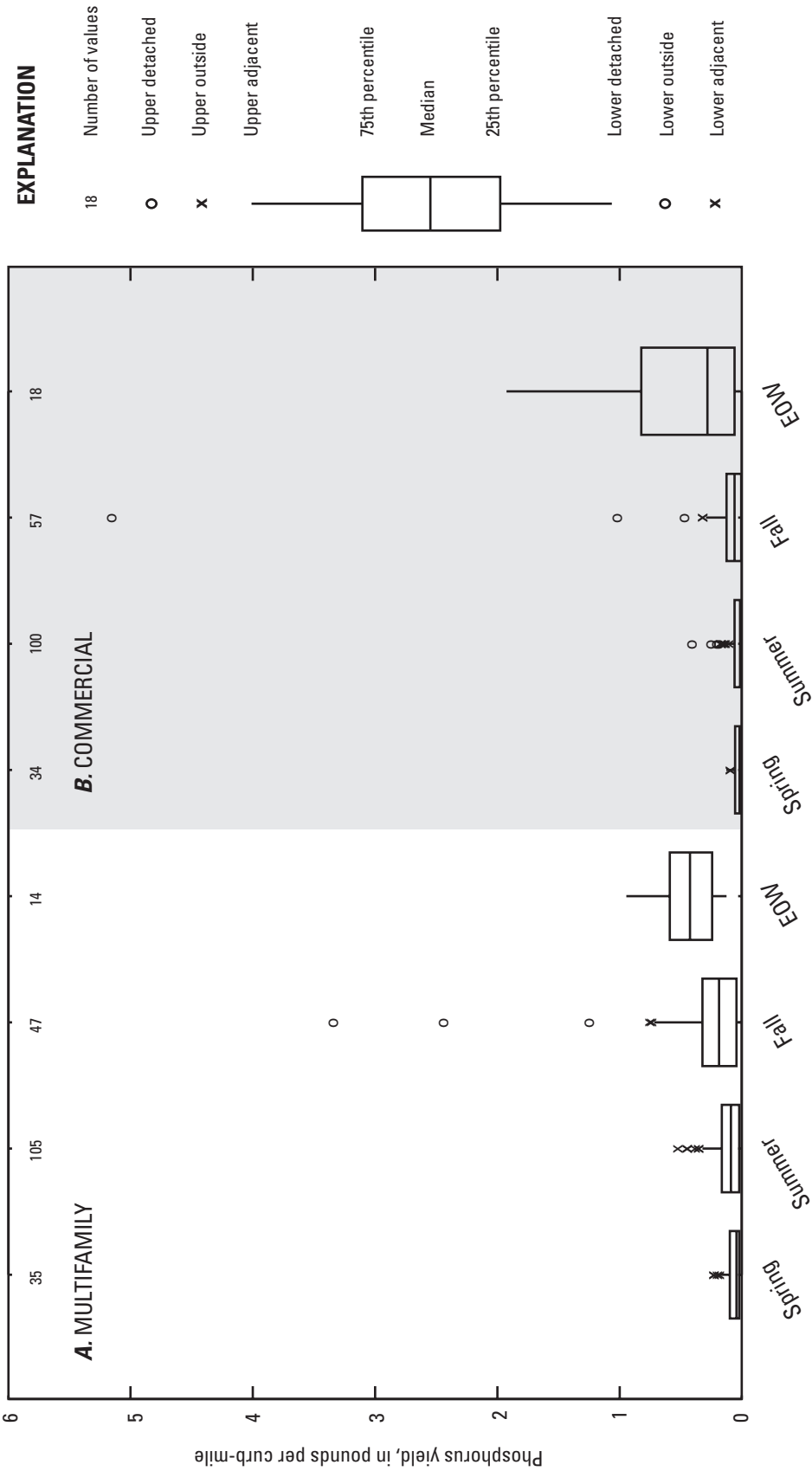


Figure 15. Total phosphorus yields, in pounds per curb-mile, by season from streets representing predominantly *A*, multifamily and *B*, commercial land-use types in Cambridge, Massachusetts. Time periods represent composite samples collected during: SPRING, May to June 2010; SUMMER, July to September, 2010; FALL, October to December, 2010, and EOW, March 2011.

Table 10. Street-solid composite sample collection dates, sample type, antecedent rain conditions, sampled storm volume, street-solid yield, and total phosphorus yields from streets in Cambridge, Massachusetts.

[Street-solid yields from single-side (SS) sample composites are estimated; in, inches; lb/curb-mi, pounds per curb-mile; P, phosphorus; SS, single side; CTC, curb-to-curb; --, no data]

Sample date	Sample type	24-hour precipitation depth (in)	48-hour precipitation depth (in)	72-hour precipitation depth (in)	Sampled storm depth (in)	Multifamily	Commercial	Multifamily	Commercial
						Street-solid yield (lb/curb-mi)	Street-solid yield (lb/curb-mi)	Total P yield (lb/curb-mi)	Total P yield (lb/curb-mi)
05/11/10	SS	0.00	0.00	0.00	0.00	1,077.6	--	--	--
05/12/10	SS	0.00	0.00	0.00	0.00	286.2	--	--	--
05/13/10	SS	0.00	0.00	0.00	0.00	--	529.9	--	--
05/14/10	SS	0.45	0.00	0.00	0.00	--	198.2	--	--
05/18/10	CTC	0.00	0.00	0.00	0.00	476.1	388.8	--	--
05/19/10	CTC	1.48	0.00	0.00	1.54	233.0	198.6	--	--
06/08/10	SS	0.00	0.00	1.38	0.00	630.2	--	--	--
06/09/10	SS	0.05	0.00	0.00	0.00	220.0	--	--	--
06/11/10	SS	0.00	0.13	0.05	0.00	--	529.2	--	--
06/12/10	SS	0.33	0.00	0.13	0.00	--	162.1	--	--
06/24/10	CTC	0.21	0.11	0.00	0.00	504.4	466.2	0.28	0.14
06/24/10	CTC	0.21	0.11	0.00	0.32	298.8	306.1	0.21	0.12
07/07/10	CTC	0.00	0.00	0.00	0.00	819.7	565.3	0.57	0.21
07/08/10	SS	0.00	0.00	0.00	0.00	--	553.0	--	--
07/09/10	SS	0.00	0.00	0.00	0.00	--	182.2	--	--
07/13/10	SS	0.14	0.01	0.05	0.00	568.4	--	--	--
07/14/10	SS	0.01	0.05	0.14	0.00	179.3	--	--	--
07/28/10	CTC	0.00	0.00	0.00	0.00	839.4	628.2	0.54	0.23
07/29/10	CTC	0.05	0.00	0.00	0.05	637.3	419.2	0.37	0.12
08/10/10	SS	0.06	0.00	0.00	0.00	760.1	--	--	--
08/11/10	SS	0.00	0.06	0.00	0.00	185.0	--	--	--
08/12/10	SS	0.00	0.00	0.06	0.00	--	692.8	--	--
08/13/10	SS	0.00	0.00	0.00	0.00	--	195.4	--	--
08/26/10	CTC	0.00	3.38	1.01	0.00	379.6	542.0	0.02	0.02
08/27/10	CTC	0.00	0.00	3.38	0.00	268.6	274.9	0.01	0.01
08/30/10	CTC	0.00	0.00	2.39	0.00	613.1	664.7	0.03	0.03
09/01/10	CTC	0.00	0.00	0.00	0.00	697.8	635.7	0.04	0.03
09/03/10	CTC	0.00	0.00	0.00	0.00	752.7	937.5	0.47	0.37
09/05/10	CTC	0.00	0.54	0.00	0.54	747.6	720.3	0.46	0.30
09/08/10	SS	0.48	0.00	0.00	0.00	410.2	--	--	--
09/09/10	SS	0.00	0.48	0.00	0.00	98.2	667.6	--	--
09/10/10	SS	0.00	0.00	0.48	0.00	--	160.6	--	--
09/27/10	CTC	0.12	0.00	0.00	0.00	618.9	356.3	0.49	0.19
09/29/10	CTC	0.98	0.12	0.00	1.10	542.8	248.7	0.35	0.11
10/02/10	CTC	0.95	0.02	0.00	0.95	667.6	387.7	0.42	0.21
10/08/10	SS	0.00	0.00	1.66	0.00	--	639.0	--	--
10/09/10	SS	0.00	0.00	0.00	0.00	--	138.7	--	--
10/12/10	SS	0.06	0.00	0.00	0.00	1,264.9	--	--	--
10/13/10	SS	0.00	0.06	0.00	0.00	213.9	--	--	--
11/04/10	CTC	1.07	0.00	0.00	0.00	2,433.6	1,015.9	2.96	2.39
11/06/10	CTC	0.00	0.64	1.07	0.00	1,445.4	567.3	0.98	0.29
11/16/10	CTC	0.05	0.00	0.00	0.00	505.3	508.9	0.48	0.22
11/18/10	CTC	0.03	1.23	0.05	1.28	727.2	489.2	0.76	0.25
11/30/10	CTC	0.00	0.00	0.00	0.00	871.3	716.1	0.92	0.32
12/02/10	CTC	0.57	0.00	0.00	0.57	666.6	289.1	0.53	0.10
12/08/10	SS	0.00	0.00	0.00	0.00	808.6	652.2	--	--
12/09/10	SS	0.00	0.00	0.00	0.00	127.7	146.8	--	--
03/04/11	CTC	0.00	0.00	0.00	0.00	2,588.1	4,310.1	1.24	1.24
03/08/11	CTC	0.00	0.71	0.00	0.71	2,639.4	5,266.7	1.52	1.61

Estimates of Regenerative-Air Street Cleaner Removal of Organic Carbon and Elements

Percent reductions of constituent load on streets, as a result of a single pass from the RA street cleaner, were estimated by using the median values of each constituent measured in 48 to 72 pre- and post-RA street cleaner composite samples of street solids formulated to represent the constituent mass for spring, summer, and fall street-solids (table 9, in back of report). The median percent reduction in total yields and three grain-size fractions for organic carbon and 32 elements from seasonal samples of pre- and post-street cleaner operation composite samples for multifamily and commercial, respectively, is shown in table 13 (in back of report). Percent reductions generally decrease with decreasing grain size, with slightly less removal of constituent mass during the spring and summer months. This likely is a reflection of lower street-solid yields available for removal during the summer compared to the larger EOW cleanup and autumn leaf-fall yields. Percent reductions for total samples are greater on multifamily streets in all seasons for all or nearly all constituents. Percent reductions from multifamily streets were greater than those on commercial streets in all seasons for nearly all constituents in coarse and medium grain-size fractions with the exception of the coarse size fraction in the spring and the medium size fraction in the fall where about one-half of constituent reductions are greater on commercial streets. Nearly all constituent reductions are greater on commercial streets in the fine grain-size fraction for summer and fall composites, and for about two-thirds of constituents in the spring fine fraction. Negative values indicate an increase in the mass of a constituent following street cleaner use, and are seen almost entirely in the less than 0.125 mm grain-size fraction from multifamily streets in the fall composite results (table 13, in back of report). Net increases within the fine grain-size fraction are seen for tin (Sn), Pb, Ni, Cu, chromium (Cr) and arsenic (As). The range of reductions on multifamily streets for all constituents is between 50 and 98 percent during the spring, -37 and 100 percent for the summer, and -1,050 and 99 percent for the fall. Commercial street reductions indicated one negative value for cobalt (Co) within the coarse grain-size fraction for the spring. Spring, summer, and fall reductions of all constituents ranged between -8 to 98, 14 to 99, and 60 to 99 percent, respectively.

Median total P reductions for total samples were 82 and 62 percent on streets in multifamily and commercial land-use types, respectively. Percent reductions generally increased with increasing grain size for both land-use types. Multifamily street reductions from coarse to fine were about 94, 86, and 64 percent in spring composites, 100, 99, and 97 percent in summer composites, and 96, 93, and 66 percent in fall composites. Reductions of total P on commercial streets from coarse to fine grain-size fractions were 96, 73, and 63 percent, respectively, in the spring, and 99, 97, and 98 and 97, 89, and 79 percent, respectively, in summer and fall. Total-recoverable concentrations for pre- and post-street cleaner seasonal

composite samples for streets in both multifamily and commercial land-use types are seen in appendix tables 1–19 and 1–20, respectively (on CD-ROM at back of report).

Potential Reductions of Street Solids and Phosphorus Achievable by Street Cleaning

Potential reductions in P associated with various street cleaning practices were simulated for a predominantly commercial land-use subcatchment in Cambridge, Mass., that ultimately drains to the lower Charles River. Street-solid data collected as part of this study and geographic information provided by the city of Cambridge and other sources were used to develop the model specifically for the study area. Street-solid washoff and total P concentration data collected as part of this study were not used in the model.

The Source Loading and Management Model for Microsoft Windows (WinSLAMM, referred to as SLAMM) version 9.4.0 (Pitt and Voorhees, 2002) is capable of continuously simulating stormwater runoff volume, loads of suspended sediments and other constituents, and the effects of stormwater-control measures. SLAMM has been successfully used to evaluate the performance of many types of stormwater control measures, including street cleaning, in locations across the United States and Canada. A more complete description of SLAMM and the input data used for the following simulations are in appendix 1 (included in accompanying CD-ROM).

Version 9.4.0 of SLAMM does have several limitations, including the inability to simulate base flow or snowmelt conditions, evaluate in-stream processes that affect constituent mass, or model erosion from pervious areas and construction sites. The model also uses simplified drainage system routing compared to the detailed water routing through certain stormwater control measures such as grass swales or detention ponds, and it cannot currently (ver 9.4.0) simulate rural areas effectively or run design storm analyses. The model has limited particle size information representing leaf matter and other organic debris and model runs appeared insensitive to seasonal effects such as leaf-fall.

Description of Commercial Land-Use Subcatchment

The subcatchment representing mostly commercial land use was selected for this study because of the existing level, flow, and constituent loading data at its outfall that was available from previous USGS studies (Breault and others, 2002; Zarriello and others, 2002) and is shown in figure 16. In addition, street-solid data were collected from streets in and around this subcatchment (fig. 2). Massachusetts Avenue and Mount Auburn Street are the two major routes that cross the basin,



Figure 16. Predominantly commercial land-use subcatchment in Cambridge, Massachusetts, and U.S. Geological Survey flow and water-quality monitoring station (USGS ID: 01104677), over a 0.5-meter color orthophoto obtained from MassGIS.

and 24-hour traffic counts from 2002 were 11,670 and 9,860, respectively (city of Cambridge, written commun., 2009). Areas of Massachusetts Avenue are swept daily and weekly. The southern side of Mount Auburn Street has a dedicated bicycle lane that is typically swept weekly, while the northern side is swept monthly following the schedule for Street-cleaning district E (fig. 2). The street-cleaning schedule for both sides of Mount Auburn Street was changed to monthly between May and December 2010.

The outfall monitoring location for the commercial land-use station (USGS ID: 01104677) was a 3-ft diameter concrete storm drain located on Mount Auburn Street near Banks Street representing about 77 percent commercial land use and about 24 percent multifamily land use (fig. 16). During 1999 and 2000, 14 dry- and 10 wet-weather sample events were collected from the 14.6 acre (0.023 mi²) subbasin (Breault and others, 2002); however, other areas may have contributed additional runoff to the monitoring location during some storm events and the resulting total area increased to 21.8 acres (Zarriello and Barlow, 2002). Zarriello and Barlow (2002) also determined the commercial subbasin contained about 86 percent effective impervious area (EIA). Multifamily and institutional land-use types also are present in the 21.8 acre subcatchment; however, the model treats commercial and institutional land-uses similarly, therefore the effective commercial land-use area is about 64 percent (appendix 2, table 2–1).

Several limitations need to be considered when using the previous data: (1) level and velocity records from the site were incomplete, and estimation techniques were needed to fill these data gaps (Zarriello and Barlow, 2002); (2) Zarriello and Barlow (2002) used the limited level and discharge data from the commercial subbasins to develop rainfall-runoff relations from low-intensity storms with rainfall-runoff coefficients less than 1.0; (3) water-quality samples were collected in a flow proportional manner from a fixed location pointing downstream on the bottom of the drainage pipe. Under these conditions sand-sized particles (greater than 0.063 mm) generally form a vertical gradient (Smith, 2002; Bent and others, 2000), and sampling in this manner potentially resulted in a large positive bias in total suspended-sediment concentrations and other constituents associated with high concentrations of coarse-grained sediment concentrations, such as P, also were potentially affected by the vertical gradient formed within the water column at the time of sampling.

Source Loading and Management Model

The general order of calibration begins with runoff, followed by particulate solids, and then constituents. Initial SLAMM simulations were evaluated using the special *.RAN file to guide modifications to the *.RSV file to match existing runoff data from 2000 (appendix 2, table 2–2). Only after acceptable agreement between simulated and observed runoff was achieved, were evaluations of simulated and observed street-solid yields from 2009–2011 possible.

Relative Contributions of Source Areas

The special *.RAN file based on 62 years of precipitation record at Boston Logan Airport (COOP ID: 190770, appendix 2, table 2–2) yielded relative runoff contribution data seen graphically as cumulative columns for each of the three land-use types in the subcatchment in figure 17A–C. Multifamily (fig. 17A) runoff is dominated by roof source areas, which contribute about 35 to 55 percent of the total runoff for this land-use type. Paved parking areas represent the next largest fraction of runoff (25 to 30 percent), followed by streets (20 to 15 percent), sidewalks and walkways (about 15 percent), and landscaped areas (about 7 percent). Landscaped areas, and to a much lesser extent, roof runoff disconnected from the drainage system (draining onto about 20 ft or more of pervious area), contribute small amounts of runoff during small storms, but contribute substantially more runoff when storms are greater than 1 inch.

The relative contribution of institutional land-use runoff (fig. 17B), although treated in the same manner as commercial land use by the model, has a runoff distribution similar to multifamily land use; however, the overall contribution of paved parking areas is greater and they are the dominant runoff source area for storm less than 0.3 inches. Walkways and landscaped areas contribute less to institutional runoff as compared to runoff in multifamily land use. Disconnected roof runoff is also much lower compared to runoff from multifamily land use.

The commercial land-use percent contribution is seen in figure 17C. Rooftops contributed between about 23 to 48 percent, street surfaces and paved parking areas contribute similar amounts of runoff, but both source areas contribute greater volumes in storms less than 0.3 inches. Walkway percent contribution was similar to that in multifamily land use. Commercial land use contained only a small amount of landscaped area and such pervious surfaces do not appear to contribute any runoff. Disconnected rooftops also are not a contributor of runoff.

Available runoff data were collected for storm depths between 0.25 and 2.0 in., and model runoff estimates outside of this range are associated with greater uncertainty. Modifications to runoff coefficients were, therefore, based only on simulation results between these precipitation depths. Modifications were made in a stepwise manner beginning with runoff coefficients from source areas with the greatest relative contribution and ending with those areas contributing the least.

Model Output Compared to 1999–2000 Runoff and Water-Quality Data

The 13 runoff observations from 2000 were first evaluated to determine the quality of the data for comparisons with simulated runoff. Plots of rainfall depth as compared to runoff depth and runoff coefficient as compared to rainfall depth, respectively, are shown in figures 18A and B. Although

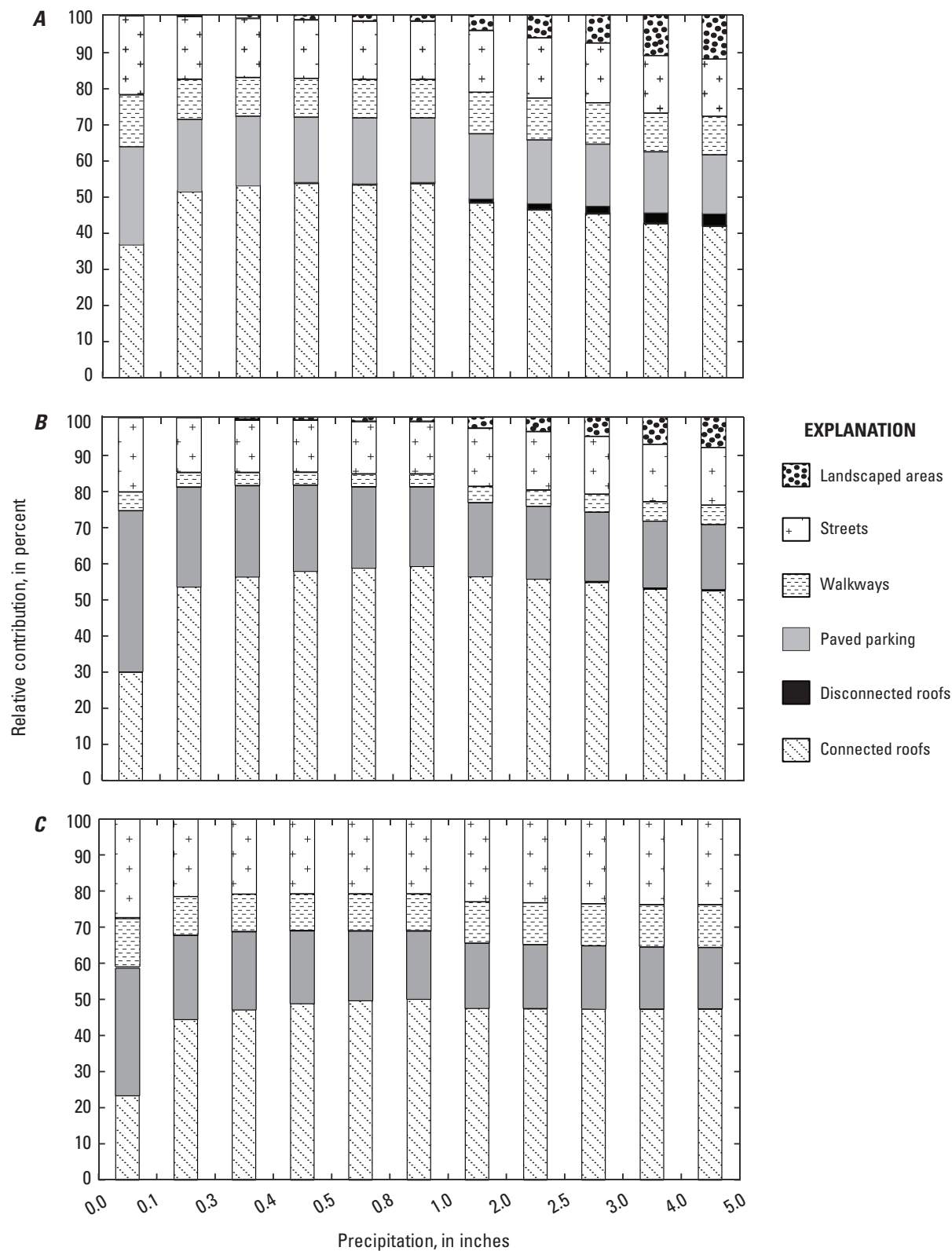


Figure 17. Cumulative relative percent contributions of major source areas within the *A*, multifamily, *B*, institutional, and *C*, commercial land-use types contained in the modeled commercial subcatchment, Cambridge, Massachusetts.

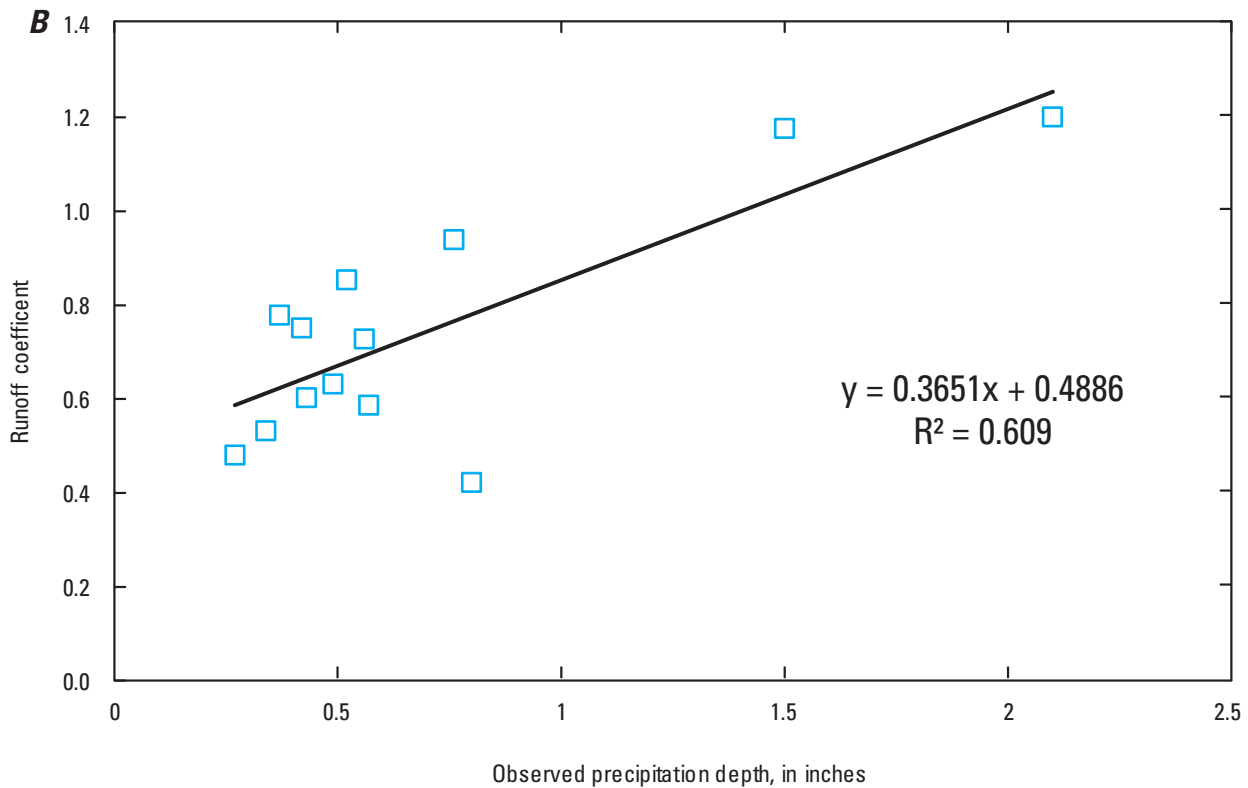
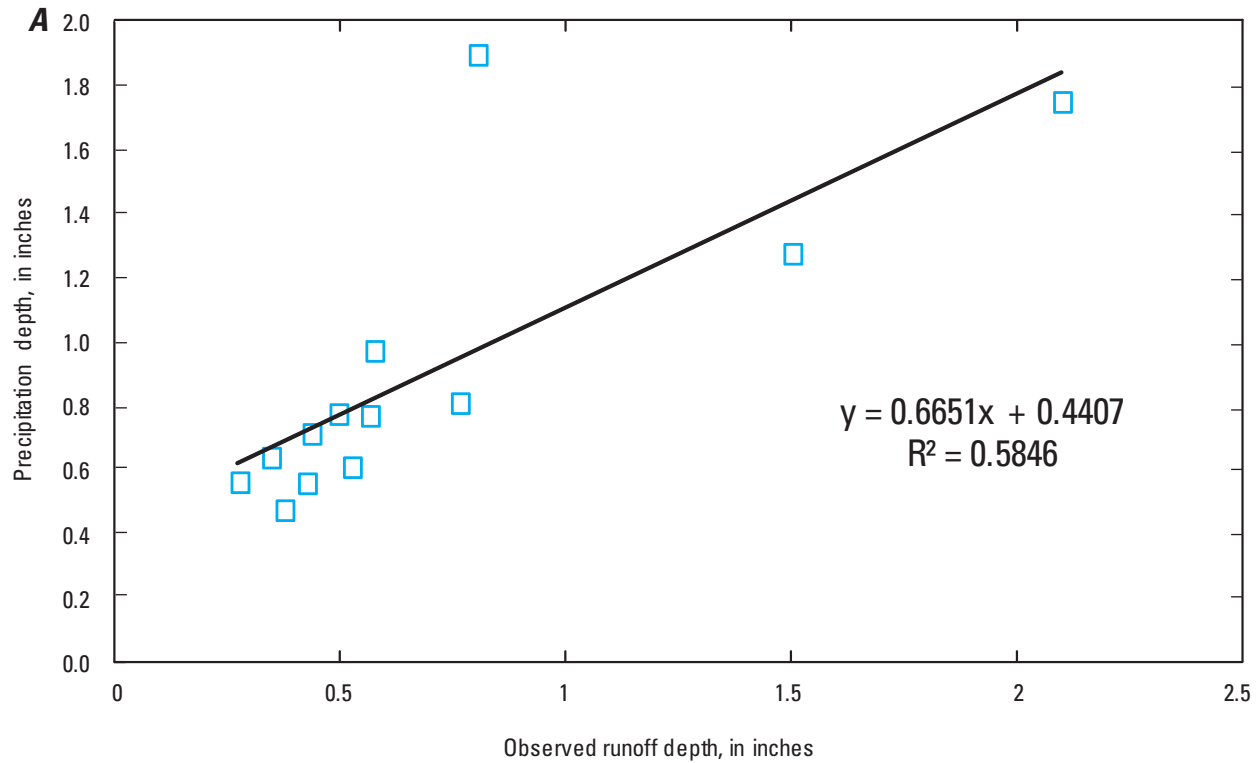


Figure 18. Plots of *A*, rainfall depth as compared to runoff depth, and *B*, runoff coefficient as compared to rainfall depth from commercial subcatchment observations, March to December 2000, Cambridge, Massachusetts (USGS ID: 01104677).

there is some scatter, the general trend appears reasonable for mostly directly connected areas associated with the subcatchment.

Initial SLAMM simulations were run using the parameter files provided with SLAMM and 10 years of Boston Logan Airport data, and resulted in a mean runoff depth percent error between simulated and observed runoff of about 33 percent and the sum of the percent differences was about 28 percent. Following examination of the relative contribution plots seen in figure 17, the selected *.RSV file was modified in a stepwise manner until an acceptable agreement was obtained between simulated runoff and the 13 observations from 1999–2000.

The observed runoff as compared to simulated runoff of commercial subcatchment is shown in figure 19. Despite the scatter about the 1:1 line, the mean runoff depth percent error improved to about -11 percent and the sum of the percent differences was -2.31 percent. The comparison of simulated runoff data to observed runoff data is shown in figure 20.

Initial simulations of particulate solid concentrations and loads resulted in mean percent error between simulated and measured total suspended solids (TSS) of about -43 and -140 percent, respectively. Simulations using the modified *.RSV file resulted in a minor improvement in particulate solid concentrations to about -40 percent and further decreased in particulate solids loads to about -163 percent. Because of the potential high bias in the measured TSS values, and the high number and quality of the particulate solids concentration data contained in the WI_AVG01.PSC (Roger Bannerman, Wisconsin Department of Natural Resources, oral commun., 2011), there was little support for modifications to the *.PSC file to further improve the particulate solid simulation results.

In terms of particulate P, the initial model resulted in mean percent error between simulated and observed particulate P loads of about 54 percent. Simulations using the modified *.RSV file resulted in an improved mean percent error between simulated and observed particulate P loads of about 16 percent.

Model Output Compared to 2009–2011 Street-Solid Yield Data

The base model equipped with the modified *.RSV file was run using 3 years of precipitation data from the Cambridge DPW and the USGS to match street-solid sampling between August 2009 to March 2011. Resulting simulated street-solid output data were compared to street-solid observations as a form of verification of model performance. Productivity function coefficients $M = 0.07$ and $B = 70$ corresponding to the RA street cleaner were input and the model was run. A plot of simulated street-solid yields compared to observed street-solid yields for streets in areas characterized as multifamily and commercial land use with the 2010 data only is shown in figure 21. Average percent error

between simulated and measured yields of street-solids for the multifamily land-use streets is about 22 percent, and for the commercial land-use streets is about -13 percent. The sum of the percent differences between simulated and measured was about -7 and 11 percent for multifamily and commercial streets, respectively. Removal of data collected in November during the highest periods of leaf-fall from both land-use types improved the mean percent error for multifamily and commercial streets to about 6.4 and 6.5 percent, respectively. However, the sum of the percent differences between simulated and observed street-solid loads for multifamily streets increased to about -19 percent, although commercial streets decreased to less than -2 percent. A time series plot of multifamily and commercial/institutional land use street-solid yield simulations compared with their respective field observations is shown in figure 22. Gaps in simulated data correspond to street-solid sampling dates not simulated by the model. These plots show reasonable agreement between some simulated and observed points. However, the model under simulates the autumn period of leaf-fall, which is associated with some of the largest street-solid loadings. Elevated street-solid loadings under simulated by the model during summer months are perhaps associated with construction track out, deposition of organic material, the highly variable nature of the street material, or some combination of these.

Model Simulations

The SLAMM model was used to estimate potential reductions of total solids and total P resulting from various street-cleaning technologies and frequencies. Mechanical-brush and vacuum-assisted street cleaners were simulated using productivity function coefficients supplied with SLAMM. Simulations using a second “vacuum-assisted” street cleaner using productivity function coefficients developed from the removal efficiency experiments described in the Regenerative-Air Street Cleaner Removal Efficiency section represented the regenerative-air street cleaner.

Street-Cleaning Program Performance

The five average years *.RAN file was used to simulate mechanical-brush, vacuum-assist, and regenerative-air street cleaners at the following frequencies: monthly, bi-monthly, weekly, and 3 days per week. Mechanical-brush and vacuum-assist productivity function coefficients were generated by SLAMM based on long-term, on-street parking conditions with parking controls specified. Mechanical-brush street cleaner productivity function coefficients were $M = 0.73$ and $B = 310$. Vacuum-assist coefficients were $M = 0.70$ and $B = 41$. Coefficients for the RA street cleaner evaluated on Cambridge streets were the same as those used to match simulated street solids to observed street solids: $M = 0.07$ and $B = 70$.

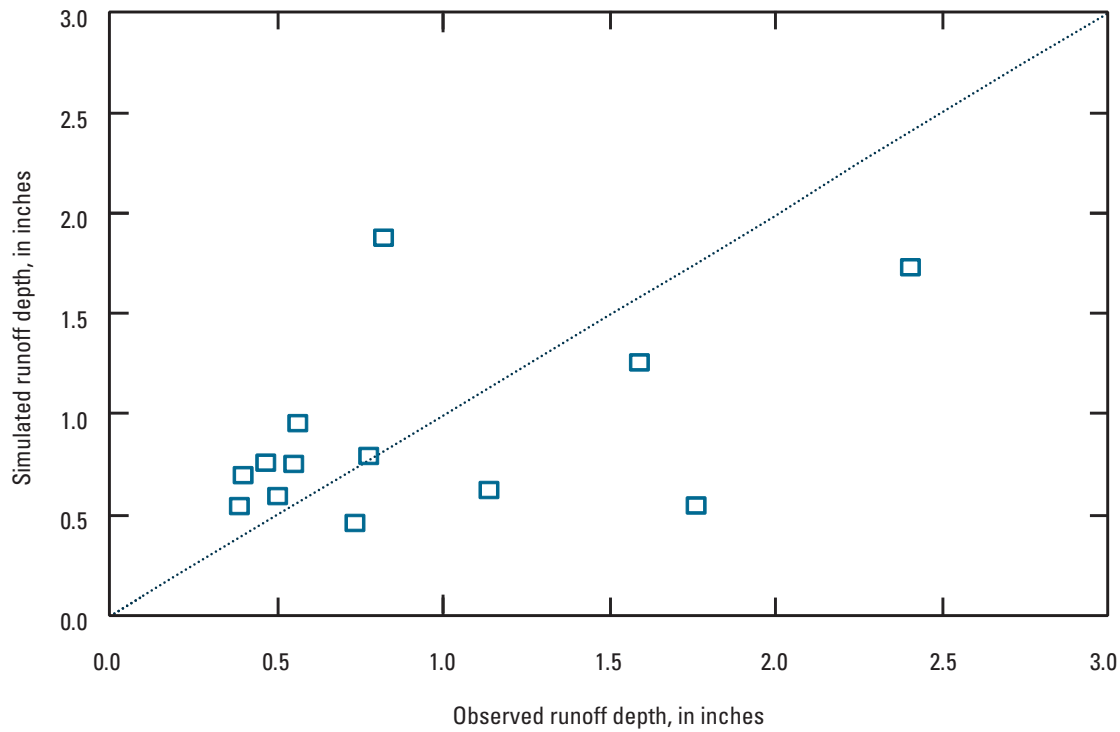


Figure 19. Simulated runoff depth as compared to observed runoff depth, March to December 2000, Cambridge, Massachusetts (USGS ID: 01104677).

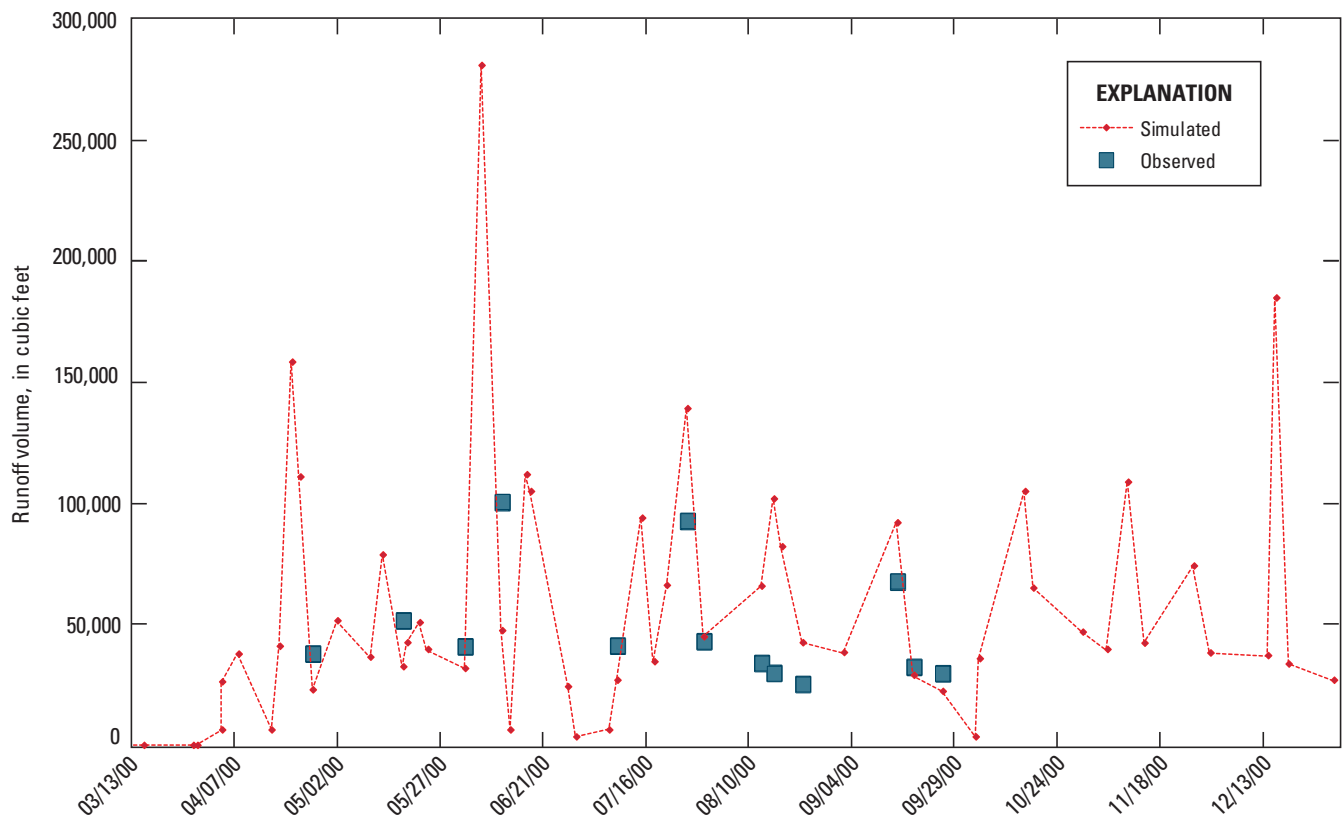
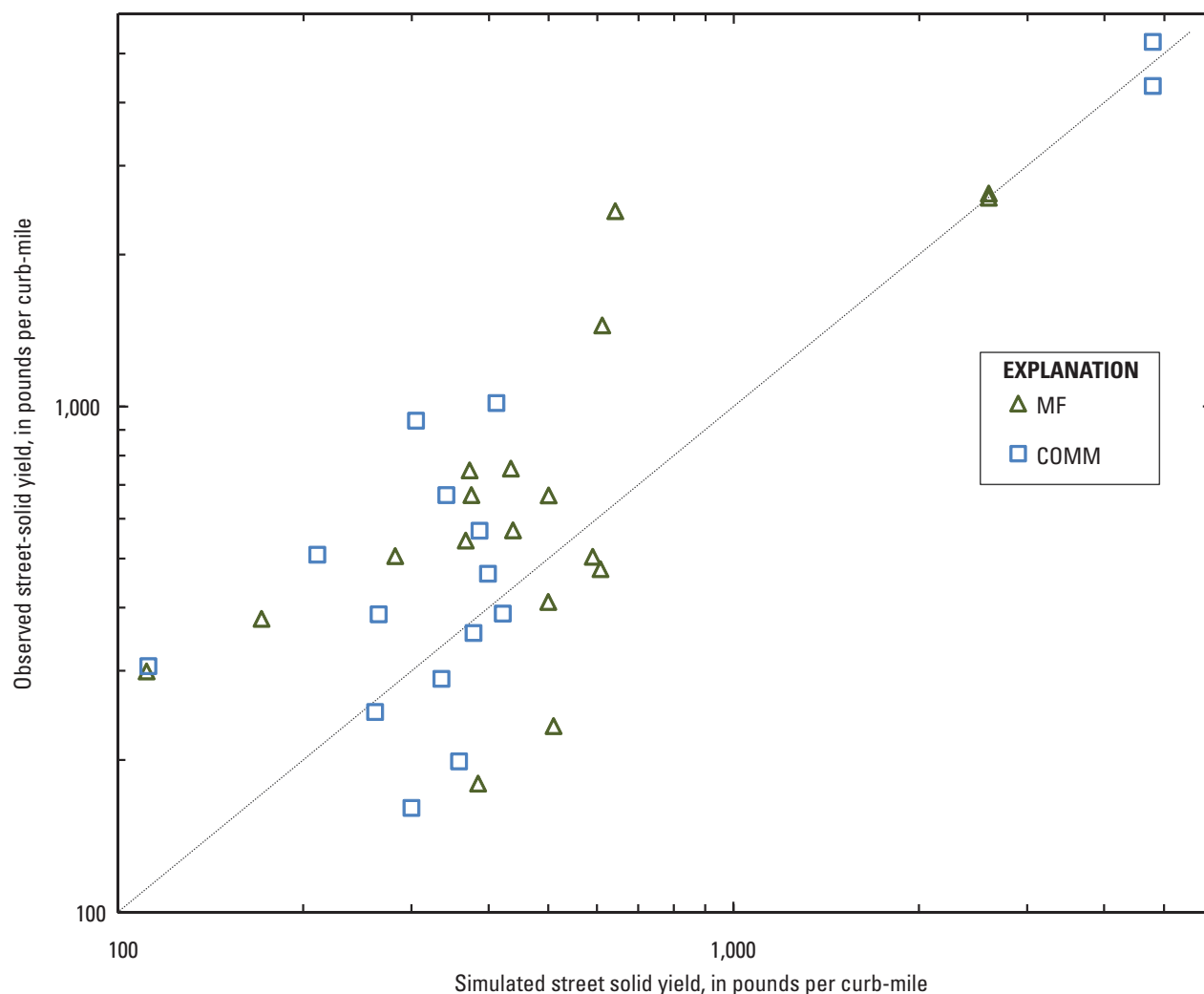


Figure 20. Time series of simulated outfall discharge from the commercial land-use subcatchment as compared to observed runoff volume, March to December 2000, Cambridge, Massachusetts (USGS ID: 01104677).



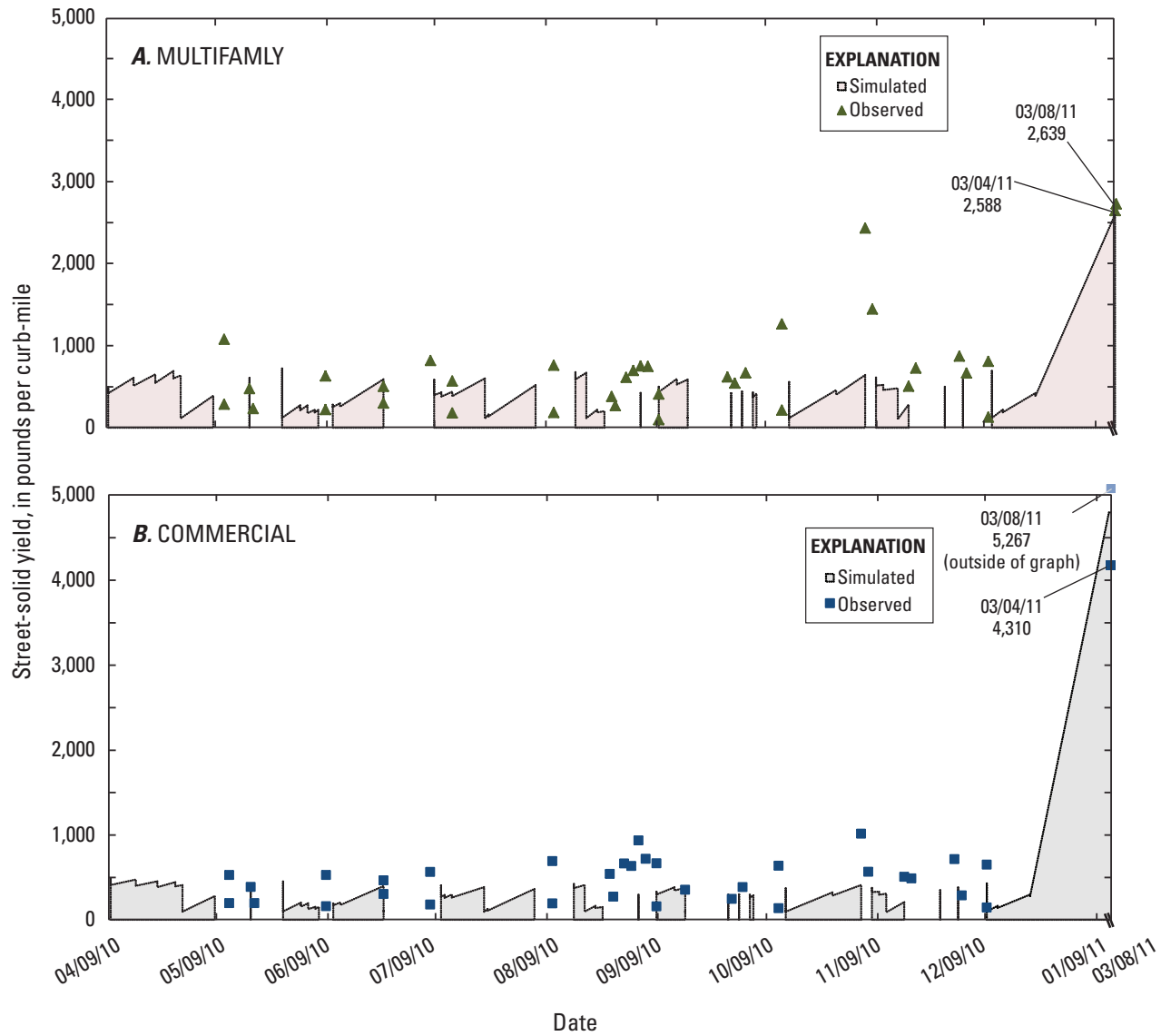


Figure 22. Simulated and observed street-solid yields, April 2010 to March 2011 for A, multifamily and B, commercial land-use types within the modeled subcatchment, Cambridge, Massachusetts.

The estimated percent reduction of total and particulate solids, and total and particulate P following single passes from each street cleaner type under each operational frequency are summarized in table 14. The percent reduction of total and particulate solids, and P as estimated by SLAMM is for the entire subcatchment at its outfall rather than a percent reduction of solids and P as measured specifically on only street surfaces. The model appears insensitive to leaf-fall effects and could be underestimating the total P load reductions from street cleaning programs, particularly in multifamily areas where tree density was greatest. Simulations of monthly mechanical-brush street cleaning resulted in reductions of total and total particulate solids and of about 2.7 and 4.2 percent, respectively. Total and particulate P reductions were about 1.4 and 2 percent, respectively. Estimated reductions

resulting from mechanical-brush street cleaning 3-times per week resulted in total and particulate solids of about 6 and 9.5 percent, respectively, and total and particulate P reduction estimates of about 3.0 and 4.5 percent, respectively.

Simulated reductions of total and particulate solids associated with monthly use of vacuum-assist street cleaning technology were about 5.2 and 8.2, respectively. Total and particulate P reductions were about 2.7 and 4.0 percent, respectively. Simulated reductions in total and particulate solids and total and particulate P associated with a vacuum-assist street cleaner with 3-times per week frequency were about 14 and 24, and 7.4 and 11 percent, respectively.

Estimated reductions of total and particulate solids using RA street cleaning technology at a monthly frequency were about 16 and 27 percent, respectively. Monthly total and particulate P estimated monthly reductions were about 8 and 12 percent, respectively. RA street cleaning three-days per week resulted in estimated reductions of total and particulate solids of about 19 and 32 percent, respectively. Total and particulate P percent reductions were about 9.3 and 14 percent, respectively.

Table 14. Source Loading and Management Model (SLAMM) estimated percent reductions of total and particulate solids and phosphorus using single passes by three different street-cleaning technologies at various frequencies in a predominantly commercial subcatchment, Cambridge, Massachusetts.

Constituent	Mechanical brush street-cleaning percent reduction	Vacuum-assist street-cleaning percent reduction	Regenerative-air street-cleaning percent reduction
Monthly street cleaning			
Total solids	2.7	5.2	16
Total particulate solids	4.2	8.2	27
Total phosphorus	1.4	2.7	8.0
Total particulate phosphorus	2.0	4.0	12
Bimonthly street cleaning			
Total solids	3.3	7.0	18
Total particulate solids	5.1	11	30
Total phosphorus	1.7	3.7	8.3
Total particulate phosphorus	2.5	5.4	12
Weekly street cleaning			
Total solids	4.2	9.6	18
Total particulate solids	6.6	15	31
Total phosphorus	2.1	5.0	8.7
Total particulate phosphorus	3.1	7.5	13
Street cleaning three times per week			
Total solids	6.0	14	19
Total particulate solids	9.5	24	32
Total phosphorus	3.0	7.4	9.3
Total particulate phosphorus	4.5	11	14

Summary and Conclusions

In 2009, the U.S. Geological Survey, in cooperation with the city of Cambridge, Massachusetts, the Massachusetts Department of Environmental Protection, and the U.S. Environmental Protection Agency, conducted a study to better understand the physical and chemical nature of the material on street surfaces, evaluate the performance of a regenerative-air street cleaner, and estimate potential reductions of total particulate solid and total phosphorus loading to the Lower Charles River expected from various street cleaning practices.

Street-solid composite samples from the three streets within each land-use type provided an average value for Cambridge, Mass., asphalt streets characterized by heavy on-street parking, monthly parking controls, intermediate surface texture, and fair surface condition within multifamily and commercial land-use areas. Street-solid samples included gravel and asphalt, and all organic material up to about 50 millimeters in diameter.

The median yield of street solids on multifamily and commercial streets between May and December 2010, was about 602 and 467 pounds per curb-mile, respectively. Including the large amounts observed in March 2011, following the winter season, median yields increased to about 616 and 498 lbs/curb-mi, respectively. Average street-solid yields on multifamily and commercial land-use streets between May and December 2010, were about 1.9 and 1.7 times the national average, respectively, and about 2 to 3 times the national average when including large end-of-winter street-solid yields in March 2011. Street-solid yields were greatest during leaf-fall and end-of-winter for multifamily and commercial streets, respectively.

Street-solid samples were separated into three grain-size fractions: (1) coarse, (2) medium, and (3) fine. About 86 percent of all street-solids were greater than the fine grain-size fraction (or very fine sand) for each land-use type. The coarse solid fraction was higher on multifamily streets and likely from increased tree density on these streets. Routine on-street parking in Cambridge likely causes a more even distribution of material on the streets compared to areas without on-street parking, and as much as 96 percent of the material was measured within 9 feet of the curb.

Median accumulation rate estimates of total street solids were about 33 and 23 pounds per curb-mile per day for multifamily and commercial land-use streets, respectively, but ranged widely from -43 to 308 lbs/curb-mi/day. Median accumulation rates by grain-size fraction were also similar between land-use types, and the medium grain-size fraction accumulated the most rapidly. Accumulation was also slightly greater on multifamily streets for the two coarser grain-size fractions. Results indicate that street solids in Cambridge, Mass., can recover within 1 to 3 days after a rainstorm or street cleaning.

Washoff sample pairs were collected for storms between 0.32 and 1.71 inches and rainfall intensities between 0.027 and 0.185 in/hr. Median average washoff from streets in multifamily and commercial land-use types were similar at about 35 and 40 percent, respectively. The distribution of street solids in the washoff also was similar for all streets in magnitude. Washoff generally increased with decreasing grain size; however, observed net increases of street solids were attributed to overland flow and transport of organic debris from source areas other than streets. Net increases of street solids following rainfall events were largest in the coarse grain-size fraction on multifamily streets and in the fine grain-size fraction on commercial streets.

Median concentrations of organic carbon and total P on multifamily streets were determined to be 35 and 29 percent greater, respectively, than those commercial streets. Median concentrations of organic carbon and total P were highest within the fine grain-size fraction on streets in both land-use types, followed by the coarse and medium grain-size fractions. Median total masses of organic carbon and total P on multifamily streets were determined to be 68 and 75 percent greater, respectively, than those on commercial streets. About 87 and 98 percent of the mass of total P was determined to be within the two larger grain-size fractions for multifamily and commercial streets, respectively. The median total accumulation rate of total P on streets in multifamily land use was about 5 times greater than on commercial streets. The largest total P accumulation rate by grain-size fraction was within the medium grain-size fraction and was the same for streets within both land-use types at 0.004 lbs/curb-mi/day. Accumulation rates within the coarse and fine grain-size fractions on multifamily streets were about 11 and 82 times greater than those on the commercial streets, respectively. Multifamily and commercial median washoff of total P was 58 and 39 percent, respectively, and ranged widely from -1,120 to 99 percent.

Median washoff of total P by grain-size fraction was also similar between both land-use types.

Median street-solid removal efficiencies of a regenerative-air street cleaner were 82 and 78 percent for multifamily and commercial land-use types, respectively. Removal efficiency decreased with decreasing grain size of the street solids. Median removal efficiency of solids by the regenerative-air street cleaner by grain-size fraction was also similar between land-use types. Negative values, or net increases in material, were occasionally observed within the fine grain-size fraction, and typically occurred on streets with rough and damaged surfaces. Increases in street solids following a street cleaner pass is likely the result of the wet gutter broom of the cleaner dislodging coarser material from inside cracks and holes within the street surface and exposing finer materials, as well as pasting fine materials back onto the street surface, which would then be available for washoff. The regenerative-air street cleaner tested left a consistent median residual yield regardless of the initial yield on the streets of both land-use types of about 100 lbs/curb-mi. Total P median reductions resulting from a single pass of a regenerative-air street cleaner on streets in multifamily and commercial land-use types were about 82 and 62 percent, respectively, decreased with decreasing grain-size, and were similar in magnitude for the three grain-size fractions on streets in both land-use types. Constituent mass reductions as a result of regenerative-air street cleaning generally decreased with decreasing grain size, and reductions were slightly less during the spring and summer months, likely a result of lower available street-solid yields. Net increases of some constituent masses following a single regenerative-air street cleaner pass were seen almost entirely in the fine grain-size fraction results from multifamily streets.

A Source Loading and Management Model for Microsoft Windows version 9.4.0 was applied to a 21.8 acre subcatchment in Cambridge, Mass., consisting of commercial, institutional and multifamily land-use types to evaluate the potential reductions of phosphorus as a result of street-cleaning practices. The model results were calibrated to runoff and water-quality data collected at the subcatchment outfall in 2000 and street-solid yield data collected in 2010. Rooftop runoff was the dominant source of the total runoff simulated at the subcatchment outfall. Street surfaces in the subcatchment contributed about 20 percent of the total runoff at the outfall in the model.

Productivity function coefficients for mechanical-brush and vacuum-assisted street cleaners were generated by SLAMM based on long-term (24-hour), on-street parking with parking controls. Regenerative-air street cleaner productivity function coefficients were developed from field data under the same conditions. Simulations based on 5 years of average climatic conditions resulted in potential reductions of total solids of about 3 and 5 percent for monthly mechanical-brush and vacuum-assist street cleaner operation, respectively, and about 16 percent for the regenerative-air street cleaner. Estimated total P reductions for monthly use of mechanical-brush and vacuum-assisted street cleaners were about 1 and 3 percent,

respectively, and 8 percent for the regenerative-air machine. An operational frequency of three times per week increased potential reductions of total solids for mechanical-brush, vacuum-assist and regenerative-air street cleaners to about 6, 14 and 19 percent, respectively. Simulated percent reductions of total P were about 3, 7, and 9 percent, respectively, when streets were cleaned 3 times per week.

References Cited

- Bannerman, R., Baun, K.M., Bohn, P.E., and Graczyk, D.A., 1983, Evaluation of urban nonpoint source pollution management in Milwaukee County, Wisconsin: Chicago, Ill., U.S. Environmental Protection Agency, PB 84-114164.
- Bender, G.M., and Terstriep, M.L., 1984, Effectiveness of street sweeping in urban runoff pollution control: *Science of the Total Environment*, v. 33, p. 185–192.
- Bent, G.C., Gray, J.R., Smith, K.P., and Glysson, G.D., 2000, A synopsis of technical issues for monitoring sediment in highway and urban runoff: U.S. Geological Survey Open-File Report 00-497, 51 p.
- Bent, G.C., Socolow, R.S., and Comeau, L.Y., 2009, Water Resources Data Report, Massachusetts and Rhode Island, Water Year 2009: U.S. Geological Survey Water-Data Report MA-RI-09-1, accessed September 5, 2011, at <http://wdr.water.usgs.gov/wy2009/search.jsp>.
- Breault, R.F., Smith, K.P., and Sorenson, J.R., 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. Geological Survey Scientific Investigations Report 2005-5184, 27 p.
- Breault, R.F., Sorenson, J.R., and Weiskel, P.K., 2002, Streamflow, water-quality, and contaminant loads in the Lower Charles River watershed, Massachusetts, 1999–2000: U.S. Geological Survey Scientific Investigations Report 2002-4137, 139 p.
- Burton, G.A., Jr., and Pitt, R., 2002, Stormwater effects handbook: A tool box for watershed managers, scientists, and engineers: CRC Press, Inc., Boca Raton, Fla., 911 p.
- Cadle, S.H., Mulawa, P., Groblicki, P., Laroo, C., Ragazzi, R.A., Nelson, K., Gallagher, G., and Zielinska, B., 2001, In-use light-duty gasoline vehicle particulate matter emissions on three driving cycles: *Environmental Science and Technology*, v. 35, no. 1, p. 26–32.
- Clausen, J.C., and Spooner, J., 1993, Paired basin watershed study design: U.S. Environmental Protection Agency, Office of Water, EPA-841-F-93-009, 8 p.
- County and City Data Book: 2000, Washington, D.C.: U.S. Department of Commerce, Bureau of the Census, Table C-1.
- Davis, A.P., Shokouhian, M., and Ni, S., 2000, Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources, *Chemosphere*, v. 44, p. 997–1009.
- Granato, G.E., 2006, Kendall-Theil Robust Line (KTRLine—version 1.0)—A visual basic program for calculating and graphing robust nonparametric estimates of linear-regression coefficients between two continuous variables: *Techniques and Methods of the U.S. Geological Survey*, book 4, chap. A7, 31 p.
- Hansen, J., Sasing, M., Hughes, P., and Graczyk, D., 1984, Evaluation of urban nonpoint source pollution management in Milwaukee County, Wisconsin—Vol III—Study site characteristics, Experimental Methods and Quality Assurance Program: Wisconsin Department of Natural Resources, PB 84-114180, variously paginated.
- Helsel, D.R., and Hirsch, R.M., 2002, Statistical methods in water resources—Hydrologic analysis and interpretation: U.S. Geological Survey Techniques of Water-Resources Investigations, chap. A3, book 4, 510 p.
- Kaufman, M.M., Rogers, D.T., and Murray, K.S., 2011, Urban watersheds: geology, contamination, and sustainable development, Boca Raton, Fla., CRC press, 583 p.
- Law, N.L., DiBlasi, K., and Upal, G., 2008, Deriving reliable pollutant removal rates for municipal street sweeping and stormdrain cleanout programs in the Chesapeake Bay Basin: Center for Watershed Protection, 73 p.
- Maestre, A., and Pitt, R., 2005, The National Stormwater Quality Database, Version 1.1, A compilation and analysis of NPDES stormwater monitoring information: Washington D.C., U.S. Environmental Protection Agency, Water Planning Division, variously paginated.
- Massachusetts Department of Environmental Protection and the U.S. Environmental Protection Agency, 2007, Total maximum daily load for nutrients in the Lower Charles River Basin: Massachusetts, CN 301.0, with support from Tetra Tech, 196 p.
- Massachusetts Office of Geographic Information (MassGIS), 2011, 1-meter impervious surface raster and metadata: Accessed February 12, 2011, at <http://www.mass.gov/mgis/imp.htm>.

- Massachusetts Office of Geographic Information (MassGIS), 2011, 0.5-meter color ortho mosaic and metadata: Accessed February 12, 2011, at <http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/massgis-data-download-usgs-color-ortho-imagery-2008-2009.html>
- National Climatic Data Center, accessed February 12, 2011, at <http://cdo.ncdc.noaa.gov/dlyp/DLYP>.
- National Oceanic and Atmospheric Administration, National Weather Service, accessed July 6, 2011, at <http://www.erh.noaa.gov/box/AveragesTotals.shtml>
- Novotny, V., and Chesters, G., 1981, Handbook of nonpoint pollution sources and management, New York, New York, Van Nostrand Reinhold Company.
- Pitt, R.E., 1979, Demonstration of nonpoint pollution abatement through improved street cleaning practices: Washington, D.C., U.S. Environmental Protection Agency, EPA-600/2-79/161, 269 p.
- Pitt, R.E., 1982, Urban bacteria sources and control in the lower Rideau River watershed: Ottawa Ontario, Ontario Ministry of the Environment, variously paginated.
- Pitt, R.E., 1985, Characterizing and controlling urban runoff through street and sewerage cleaning: U.S. Environmental Protection Agency, Storm and Combined Sewer Program, Cincinnati, Ohio, Risk Reduction Engineering Laboratory, EPA/600/S2-85/038, PB 85-186500, variously paginated.
- Pitt, R.E., 1987, Small storm urban flow and particulate washoff contributions to outfall discharges: Department of Civil and Environmental Engineering, University of Wisconsin, Madison, Ph.D. dissertation 187 p.
- Pitt, R.E., 2008, Calibration of WinSLAMM: PV & Associates, Madison, Wis., 38 p.
- Pitt, R.E., and Amy, G., 1973, Toxic materials analysis of street surface constituents: Washington, D.C., U.S. Environmental Protection Agency, EPA-R2-73-283, 143 p. (Also available from National Technical Information Service, Springfield, VA 22161 and <http://www.ntis.gov>, item PB 224-677)
- Pitt, R.E., Bannerman, R., Clark, S., and Williamson, D., 2005a, Sources of pollutants in urban areas (part I)—older monitoring projects, *in* Effective modeling of urban water systems: Monograph 13, James, W., Irvine, K.N., McBean, E.A., and Pitt, R.E., eds., CHI, Guelph, Ontario, 465-484 and 507-530 p.
- Pitt, R.E., Bannerman, R., Clark, S., and Williamson, D., 2005b, Sources of pollutants in urban areas (part II)—recent sheetflow monitoring results, *in* Effective modeling of urban water systems: Monograph 13, James, W., Irvine, K.N., McBean, E.A., and Pitt, R.E., eds., CHI, Guelph, Ontario, 485-530 p.
- Pitt, R.E., and Bozeman, M., 1982, Sources of urban runoff pollution and its effects on an urban creek: Cincinnati, Ohio, U.S. Environmental Protection Agency, EPA-600/S2-82-090, variously paginated.
- Pitt, R.E., Chen, S., Clark, S.E., Swenson, J., and Ong, C.K., 2008, Compaction's impacts on urban storm-water infiltration: Journal of Irrigation and Drainage Engineering, p. 652-658.
- Pitt, R.E., and McLean, J., 1984, Humber River pilot watershed project: Toronto, Ontario, Ontario Ministry of the Environment, variously paginated.
- Pitt, R.E., and Shawley, G., 1981, Demonstration of nonpoint pollution management on Castro Valley Creek: Washington, D.C., U.S. Environmental Protection Agency, Water Planning Division, variously paginated.
- Pitt, R.E., and Voorhees, J., 2000, The source loading and management model (SLAMM): A water quality planning management model for urban storm water runoff, PV & Associates, Madison, Wis., 587 p.
- Pitt, R.E., and Voorhees, J., 2002, Field, R., and Sullivan, D., eds., *in* Wet-weather flow in the urban watershed—Technology and Management: Boca Raton, Fla., CRC Press, p. 103-139.
- Pitt, R.E., Williamson, D., and Voorhees, J., 2005c, Review of historical street dust and dirt accumulation and washoff data, *in* Effective modeling of urban water systems: Monograph 13, James, W., Irvine, K.N., McBean, E.A., and Pitt, R.E., ed., CHI, Guelph, Ontario, 203-246 pp.
- Pitt, R.E., Williamson, D., Voorhees, J., and Clark, S., 2004, Review of historical street dust and dirt accumulation and washoff data, chap. 12 *of*, James, W., Irvine, K.N., McBean, E.A., and Pitt, R.E., eds., Effective modeling of urban water systems: CHI Publishing, Ontario, Canada, 44 p.
- Sartor, J.D., and Boyd, G.B., 1972, Water pollution aspects of street surface constituents: Washington, D.C., U.S. Environmental Protection Agency, EPA-R2-72-081, p. 458-467.
- Seattle Public Utilities and Department of Transportation, 2009, Seattle streetsweeping pilot study: monitoring report, Herrera Environmental Consultants, 266 p.

- Selbig, W.R., and Bannerman, R.T., 2007, Evaluation of street sweeping as a stormwater-quality-management tool in three residential basins in Madison, Wisconsin: U.S. Geological Survey Scientific Investigations Report 2007–5156, 103 p.
- Shelley, P.E., and Gaboury, D.R., 1986, Estimation of pollution from highway runoff-initial results: Conference on urban runoff quality-impact and quality enhancement technology, Henniker, New Hampshire: Urbonas, B., and Roesner, L.A., eds., *in* Proceedings published by the American Society of Civil Engineering, New York, variously paginated.
- Skeehan, J.W., 2001, Roadside geology of Massachusetts: Mountain Press Publishing, Missoula, Mont., 379 p.
- Smith, K.P., 2002, Effectiveness of three best management practices for highway runoff quality along the southeast expressway, Boston, Massachusetts: U.S. Geological Survey Scientific Investigations Report 2002–4059, 170 p.
- Smith, K.P., 2010, Quality of stormwater runoff discharged from Massachusetts highways, 2005–07: U.S. Geological Survey Scientific Investigations Report 2009–5269, 198 p.
- Steuer, Jeffrey, Selbig, William, Hornewer, N.J., and Prey, Jeffrey, 1997, Sources of contamination in an urban basin in Marquette, Michigan, and an analysis of concentrations, loads, and data quality: U.S. Geological Survey Water-Resources Investigations Report 97–4242, 25 p.
- Terstriep, M.L., Bender, G.M., and Noel, D.C., 1982, Evaluation of the effectiveness of municipal street cleaning in the control of urban storm pollution: Final report-NURP project, Champaign-Urbana, Illinois, State Water Survey Division, Illinois Department of Energy and Natural Resources, variously paginated.
- U.S. Census Bureau, Census Summary File, 2010, PL94–171 Massachusetts data file, accessed July 6, 2011, at (http://www.census.gov/rdo/data/2010_census_redistricting_data_pl_94-171_summary_files.html).
- U.S. Department of Agriculture, 1995, Soil Survey Geographic (SSURGO) Data Base, Data Use Information: Natural Resources Conservation Service, National Soil Survey Center, Miscellaneous Publication Number 1527, variously paged.
- U.S. Environmental Protection Agency, 1983, Nationwide Urban Runoff Program, Winston-Salem, N.C.—An evaluation of street sweeping as a runoff pollution control: Office of Water Programs, 229 p. (Also available from National Technical Information Service, Springfield, VA 22161 and <http://www.ntis.gov>, item PB85–102507)
- U.S. Environmental Protection Agency, 1986, Quality criteria for water 1986: U.S. Environmental Protection Agency, EPA440/5–86–001, variously paginated.
- U.S. Geological Survey, Fresh Pond streamflow monitoring station (USGS ID: 422302071083801).
- Waschbusch, R.J., Selbig, W.R., and Bannerman, R.T., 1999, Sources of phosphorus in stormwater and street dirt from two urban residential basins in Madison, Wisconsin, 1994–95: U.S. Geological Survey Water-Resources Investigations Report 99–4021, 47 p.
- Weather Underground, accessed September 16, 2011, at <http://www.wunderground.com/US/MA/Cambridge.html>
- Zarriello, P.J., and Barlow, L.K., 2002, Measured and simulated runoff to the Lower Charles River, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 02–4129, 89 p.
- Zarriello, P.J., Breault, R.F., and Weiskel, P.K., 2002, Potential effects of structural controls and street sweeping on stormwater loads to the Lower Charles River, Massachusetts: U.S. Geological Survey Water-Resources Investigations Report 02–4220, 42 p.
- Zimmerman, M.J., Barbaro, J.R., Sorenson, J.R., and Waldron, M.C., 2010, Effects of selected low-impact development (LID) techniques on water quality and quantity in the Ipswich River Basin, Massachusetts—Field and modeling studies: U.S. Geological Survey Scientific Investigations Report 2010–5007, 114 p.

Tables 9, 11, 12, and 13

Table 9A. Total and grain-size fraction median constituent total-recoverable concentrations and masses constituent masses from composite street-solid samples collected from streets representing *A*, multifamily and *B*, commercial land-use types in Cambridge, Massachusetts.

[***Bold italicized*** values indicate less than one-half the detection limit was used to determine concentration and normalized mass. Note: concentrations converted to milligrams per kilogram and in this case are equivalent to concentrations in parts per million (ppm). n, number of samples; mg/kg, milligrams per kilogram; g, grams; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

Total n = 225				Coarse n = 76		Medium n = 74		Fine n = 75	
Multifamily									
Analyte	Detection limit (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)
Organic carbon	500	91,700	126,431	183,500	151,308	59,850	52,671	72,800	28,279
<i>Silver</i>	<i>0.2</i>	<i>0.10</i>	<i>0.25</i>	<i>0.10</i>	<i>0.06</i>	<i>0.10</i>	<i>0.06</i>	<i>0.10</i>	<i>0.40</i>
Aluminum	100	5,200	3,042	2,700	2,696	4,630	1,045	8,900	1,427
Arsenic	3.0	4.0	14	1.5	23	4.0	2.3	10.0	3.9
Barium	1	55	75	31	17	48	27	127	101
<i>Beryllium</i>	<i>0.5</i>	<i>0.25</i>	<i>0.17</i>	<i>0.25</i>	<i>0.14</i>	<i>0.25</i>	<i>0.16</i>	<i>0.25</i>	<i>0.20</i>
<i>Bismuth</i>	<i>5</i>	<i>2.50</i>	<i>0.54</i>	<i>2.50</i>	<i>0.00</i>	<i>2.50</i>	<i>0.57</i>	<i>2.50</i>	<i>0.76</i>
Calcium	100	9,400	7,462	11,732	11,360	8,150	2,906	10,200	3,642
<i>Cadmium</i>	<i>1</i>	<i>0.50</i>	<i>0.41</i>	<i>0.50</i>	<i>0.08</i>	<i>0.50</i>	<i>0.64</i>	<i>0.50</i>	<i>0.31</i>
Cobalt	1	4.0	16	3.0	27	4.0	1.1	8.0	1.6
Chromium	1	41	65	10	8	41	36	140	39
Copper	0.5	47	160	14	128	46	217	176	46
Iron	100	18,600	100,001	5,650	8,010	18,000	5,722	27,800	5,534
Potassium	100	1,700	1,276	2,400	1,751	1,100	552	1,800	522
Lanthanum	0.5	8.5	5.9	4.4	4.5	7.9	2.0	16.3	3.0
Lithium	1	8.0	4.6	5.0	5.0	7.0	1.8	13.0	2.3
Magnesium	0.01	0.34	0.36	0.24	0.61	0.28	0.06	0.44	0.07
Manganese	2	272	131	202	201	247	48	350	39
Molybdenum	1	2.00	2.05	0.50	0.92	2.00	1.39	5.00	1.05
Sodium	0.01	0.03	0.22	0.02	0.23	0.02	0.24	0.04	0.17
Nickel	1	15	21	8	26	14	7	41	8
Phosphorus	100	700	461	800	600	500	241	900	389
Lead	2	111	247	25	37	110	178	436	242
Antimony	5	2.5	3.1	2.5	5.2	2.5	0.3	2.5	0.8
Scandium	0.5	1.2	0.9	0.3	0.9	1.1	0.4	2.1	0.5
Tin	10	10	146	5	65	5	14	20	240
Strontium	0.5	40	21	43	28	34	15	44	12
Titanium	100	500	353	200	216	500	134	1,000	199
Vanadium	2	24	17	12	12	22	6	46	10
<i>Tungsten</i>	<i>10</i>	<i>5.0</i>	<i>1.9</i>	<i>5.0</i>	<i>0.0</i>	<i>5.0</i>	<i>2.9</i>	<i>5.0</i>	<i>1.8</i>
Yttrium	0.5	5.3	2.9	3.0	2.5	4.8	1.1	8.6	1.7
Zinc	0.5	169	185	76	79	160	97	427	137
Zirconium	0.5	2.7	2.8	1.2	1.9	2.7	1.5	5.9	2.8

Table 9A. Total and grain-size fraction median constituent total-recoverable concentrations and masses constituent masses from composite street-solid samples collected from streets representing *A*, multifamily and *B*, commercial land-use types in Cambridge, Massachusetts.—Continued

[***Bold italicized*** values indicate less than one-half the detection limit was used to determine concentration and normalized mass. Note: concentrations converted to milligrams per kilogram and in this case are equivalent to concentrations in parts per million (ppm). n, number of samples; mg/kg, milligrams per kilogram; g, grams; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

		Total n = 225		Coarse n = 76		Medium n = 74		Fine n = 75	
Multifamily									
Analyte	Detection limit (mg/kg)	Median mass (g)	Standard deviation (g)	Median mass (g)	Standard deviation (g)	Median mass (g)	Standard deviation (g)	Median mass (g)	Standard deviation (g)
Organic carbon	500	13	92	22	148	19	15	2.9	5.9
<i>Silver</i>	<i>0.2</i>	<i>0.02</i>	<i>0.05</i>	<i>0.01</i>	<i>0.05</i>	<i>0.03</i>	<i>0.04</i>	<i>0.01</i>	<i>0.06</i>
Aluminum	100	0.59	1.41	0.35	1.11	1.25	1.78	0.37	0.80
Arsenic	3	0.43	5.9	0.30	9.9	1.1	1.8	0.40	0.93
Barium	1	7.9	17	3.6	19	12	18	5.6	9.4
<i>Beryllium</i>	<i>0.5</i>	<i>0.03</i>	<i>0.09</i>	<i>0.03</i>	<i>0.10</i>	<i>0.07</i>	<i>0.09</i>	<i>0.01</i>	<i>0.04</i>
<i>Bismuth</i>	<i>5</i>	<i>0.31</i>	<i>1.16</i>	<i>0.28</i>	<i>0.98</i>	<i>0.67</i>	<i>1.6</i>	<i>0.10</i>	<i>0.22</i>
Calcium	100	1.2	4.2	1.2	6.0	2.1	3.2	0.37	1.6
<i>Cadmium</i>	<i>1</i>	<i>0.06</i>	<i>0.20</i>	<i>0.06</i>	<i>0.20</i>	<i>0.13</i>	<i>0.25</i>	<i>0.02</i>	<i>0.05</i>
Cobalt	1	0.5	6.6	0.3	11	1.0	1.4	0.3	0.7
Chromium	1	4.1	15	1.1	4.0	12	21	6.0	11
Copper	0.5	6.5	48	1.5	53	13	62	7.6	13
Iron	100	1.8	5.4	0.7	2.6	4.4	7.5	1.1	2.4
Potassium	100	0.16	1.1	0.31	1.8	0.33	0.30	0.01	0.01
Lanthanum	0.5	0.91	2.5	0.45	1.6	2.03	3.3	0.66	1.3
Lithium	1	0.91	2.4	0.50	1.7	2.02	3.2	0.57	1.5
Magnesium	0.01	0.38	0.96	0.33	1.0	0.76	1.1	0.20	0.47
Manganese	2	33	88	28	113	67	85	13	28
Molybdenum	1	0.17	0.65	0.07	0.49	0.47	0.84	0.20	0.37
Sodium	0.01	0.03	2.3	0.02	1.5	0.05	3.6	0.02	0.77
Nickel	1	2.0	7.8	1.1	11	4.0	6.5	1.8	3.6
Phosphorus	100	0.08	0.29	0.08	0.45	0.14	0.15	0.03	0.08
Lead	2	16	29	2.1	17	28	34	20	25
Antimony	5	0.31	1.25	0.28	1.8	0.67	0.89	0.12	0.34
Scandium	0.5	0.13	0.33	0.06	0.24	0.30	0.43	0.08	0.21
Tin	10	1.6	5.7	1.4	5.1	2.7	5.7	0.71	6.2
Strontium	0.5	5.0	19	4.8	28	8.5	15	1.7	5.6
Titanium	100	0.05	0.16	0.02	0.08	0.12	0.22	0.04	0.09
Vanadium	2	2.72	8.2	1.31	6.6	5.5	10	1.9	5.3
<i>Tungsten</i>	<i>10</i>	<i>0.60</i>	<i>1.7</i>	<i>0.55</i>	<i>2.0</i>	<i>1.3</i>	<i>1.8</i>	<i>0.20</i>	<i>0.37</i>
Yttrium	0.5	0.54	1.67	0.35	1.52	1.23	2.09	0.37	0.80
Zinc	0.5	23	45	6.5	44	47	47	17	37
Zirconium	0.5	0.31	1.3	0.15	0.61	0.74	1.8	0.26	0.76

Table 9B. Total and grain-size fraction median constituent total-recoverable concentrations and masses constituent masses from composite street-solid samples collected from streets representing *A*, multifamily and *B*, commercial land-use types in Cambridge, Massachusetts.

[***Bold italicized*** values indicate less than one-half the detection limit was used to determine concentration and normalized mass. Note: concentrations converted to milligrams per kilogram and in this case are equivalent to concentrations in parts per million (ppm). n, number of samples; mg/kg, milligrams per kilogram; g, grams; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

Total n = 221				Coarse n = 75		Medium n = 73		Fine n = 73	
				Commercial					
Analyte	Detection limit (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)	Median concentration (mg/kg)	Standard deviation (mg/kg)
Organic carbon	500	60,100	113,171	160,000	142,140	27,100	18,274	59,100	17,275
<i>Silver</i>	<i>0.2</i>	<i>0.10</i>	<i>0.67</i>	<i>0.10</i>	<i>0.10</i>	<i>0.10</i>	<i>0.10</i>	<i>0.50</i>	<i>0.99</i>
Aluminum	100	5,000	2,528	4,100	778	4,100	778	7,800	986
Arsenic	3	5.00	4.66	4.00	2.17	4.00	2.17	11.00	4.19
Barium	1	54	53	42	28	42	28	128	36
<i>Beryllium</i>	<i>0.5</i>	<i>0.25</i>	<i>0.15</i>	<i>0.25</i>	<i>0.04</i>	<i>0.25</i>	<i>0.04</i>	<i>0.25</i>	<i>0.17</i>
<i>Bismuth</i>	<i>5</i>	<i>2.5</i>	<i>0.0</i>	<i>2.5</i>	<i>0.0</i>	<i>2.5</i>	<i>0.0</i>	<i>2.5</i>	<i>0.0</i>
Calcium	100	8,600	5,613	6,100	1,631	6,100	1,631	10,000	3,237
<i>Cadmium</i>	<i>1</i>	<i>0.50</i>	<i>0.21</i>	<i>0.50</i>	<i>0.26</i>	<i>0.50</i>	<i>0.26</i>	<i>0.50</i>	<i>0.26</i>
Cobalt	1	5.0	29	4.0	4.6	4.0	4.6	8.0	49
Chromium	1	51	205	47	58	47	58	166	56
Copper	0.5	71.78	125.30	66	99	66	99	250	96
Iron	100	23,000	12,239	21,700	6,797	21,700	6,797	34,200	6,005
Potassium	100	1,100	878	700	254	700	254	1,400	296
Lanthanum	0.5	9.30	5.44	7.80	1.51	7.80	1.51	16.60	2.91
Lithium	1	8.00	4.19	7.00	1.95	7.00	1.95	11.00	3.09
Magnesium	0.01	0.33	0.20	0.26	0.07	0.26	0.07	0.40	0.07
Manganese	2	270	271	237	64	237	64	358	43
Molybdenum	1	3.0	3.0	2.0	1.7	2.0	1.7	7.0	1.9
Sodium	0.01	300	3,544	200	1,943	200	1,943	500	2,671
Nickel	1	18	25	15.00	31.58	15.00	31.58	48.00	9.08
Phosphorus	100	500	656	400	166	400	166	800	288
Lead	2	62	214	61	226	61	226	241	231
Antimony	5	2.50	0.92	2.50	0.00	2.50	0.00	2.50	0.67
Scandium	0.5	1.10	0.68	0.96	0.24	0.96	0.24	1.80	0.39
Tin	10	10	210	5.0	11	5.0	11	20	361
Strontium	0.5	33.30	24.34	22.40	6.68	22.40	6.68	40.10	10.42
Titanium	100	500	331	400	110	400	110	900	222
Vanadium	2	23	18	21	3.5	21	3.5	48	8.2
<i>Tungsten</i>	<i>10</i>	<i>5.0</i>	<i>2.9</i>	<i>5.0</i>	<i>4.1</i>	<i>5.0</i>	<i>4.1</i>	<i>5.0</i>	<i>2.9</i>
Yttrium	0.5	5.6	3.1	4.7	0.9	4.7	0.9	9.0	1.5
Zinc	0.5	146	219	132	56	132	56	521	147
Zirconium	0.5	3.9	4.0	3.5	1.0	3.5	1.0	8.7	2.3

Table 9B. Total and grain-size fraction median constituent total-recoverable concentrations and masses constituent masses from composite street-solid samples collected from streets representing *A*, multifamily and *B*, commercial land-use types in Cambridge, Massachusetts.—Continued

[***Bold italicized*** values indicate less than one-half the detection limit was used to determine concentration and normalized mass. Note: concentrations converted to milligrams per kilogram and in this case are equivalent to concentrations in parts per million (ppm). n, number of samples; mg/kg, milligrams per kilogram; g, grams; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

		Total n = 221		Coarse n = 75		Medium n = 73		Fine n = 73	
		Commercial							
Analyte	Detection limit (mg/kg)	Median mass (g)	Standard deviation (g)	Median mass (g)	Standard deviation (g)	Median mass (g)	Standard deviation (g)	Median mass (g)	Standard deviation (g)
Organic carbon	500	4.3	33	8.5	12	8.5	12	0.28	0.68
<i>Silver</i>	<i>0.2</i>	<i>0.02</i>	<i>0.08</i>	<i>0.03</i>	<i>0.08</i>	<i>0.03</i>	<i>0.08</i>	<i>0.03</i>	<i>0.11</i>
Aluminum	100	0.19	2.1	1.07	3.20	1.07	3.20	0.04	0.12
Arsenic	3	0.44	2.4	0.99	3.6	0.99	3.6	0.57	1.8
Barium	1	6.55	15	13	19	13	19	7.1	13
<i>Beryllium</i>	<i>0.5</i>	<i>0.02</i>	<i>0.12</i>	<i>0.06</i>	<i>0.20</i>	<i>0.06</i>	<i>0.20</i>	<i>0.01</i>	<i>0.06</i>
<i>Bismuth</i>	<i>5</i>	<i>0.23</i>	<i>1.2</i>	<i>0.64</i>	<i>1.9</i>	<i>0.64</i>	<i>1.9</i>	<i>0.13</i>	<i>0.31</i>
Calcium	100	0.60	3.3	1.8	4.6	1.8	4.6	0.05	0.26
<i>Cadmium</i>	<i>1</i>	<i>0.05</i>	<i>0.25</i>	<i>0.13</i>	<i>0.40</i>	<i>0.13</i>	<i>0.40</i>	<i>0.03</i>	<i>0.06</i>
Cobalt	1	0.52	6.6	1.0	3.6	1.0	3.6	0.47	11
Chromium	1	6.1	19	15	26	15	26	9.3	13
Copper	0.5	8.9	21	20	28	20	28	14	15
Iron	100	0.50	6.6	5.5	9.4	5.5	9.4	0.19	0.33
Potassium	100	0.08	0.46	0.22	0.55	0.22	0.55	0.01	0.03
Lanthanum	0.5	1.0	4.0	2.0	6.2	2.0	6.2	0.89	2.0
Lithium	1	0.78	3.9	2.0	5.8	2.0	5.8	0.58	2.7
Magnesium	0.01	0.19	1.27	0.77	1.91	0.77	1.91	0.02	0.08
Manganese	2	29	83	61	119	61	119	19	41
Molybdenum	1	0.27	0.60	0.66	0.68	0.66	0.68	0.39	0.57
Sodium	0.01	0.01	2.6	0.05	4.4	0.05	4.4	0.002	0.13
Nickel	1	2.1	7.5	4.2	11	4.2	11	2.6	4.5
Phosphorus	100	0.02	0.33	0.09	0.25	0.09	0.25	0.003	0.01
Lead	2	8.3	31	20	46	20	46	13	17
Antimony	5	0.24	1.2	0.64	1.9	0.64	1.9	0.13	0.31
Scandium	0.5	0.12	0.52	0.26	0.77	0.26	0.77	0.10	0.36
Tin	10	1.2	5.9	2.0	5.7	2.0	5.7	1.2	6.2
Strontium	0.5	3.2	12	6.7	14	6.7	14	2.1	9.0
Titanium	100	0.01	0.22	0.11	0.35	0.11	0.35	0.00	0.01
Vanadium	2	2.8	10	5.2	15	5.2	15	2.6	8.1
<i>Tungsten</i>	<i>10</i>	<i>0.46</i>	<i>2.6</i>	<i>1.3</i>	<i>4.2</i>	<i>1.3</i>	<i>4.2</i>	<i>0.26</i>	<i>1.0</i>
Yttrium	0.5	0.59	2.3	1.2	3.4	1.2	3.4	0.47	1.3
Zinc	0.5	23	51	38	66	38	66	26	48
Zirconium	0.5	0.49	2.0	0.83	3.0	0.83	3.0	0.45	1.4

Table 11. Accumulation rates for constituents measured in street-solid composite samples, by grain-size fraction and land-use type collected before and after precipitation events in pounds per curb-mile per day, Cambridge, Massachusetts.

[Negative values indicate a net loss of material. Commercial data does not include Mount Auburn Street; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

Organic carbon	Silver	Aluminum	Arsenic	Barium	Beryllium	Bismuth	Calcium	Cadmium	Cobalt	Chromium	Copper	Iron	Potassium	Lanthanum	Lithium
Multifamily-all grain-size fractions															
Coarse															
Average	1.6	0.006	0.06	0.11	0.94	0.004	0.13	0.01	0.07	0.83	0.93	0.20	0.04	0.11	0.10
Median	1.4	0.002	0.06	0.06	0.43	0.003	0.03	0.004	0.05	0.68	0.43	0.11	0.03	0.09	0.06
Maximum	17	0.128	0.70	1.3	42	0.028	0.23	0.88	0.69	4.21	7.71	1.66	0.24	1.4	1.5
Minimum	-10	-0.006	-0.49	-0.81	-29	-0.014	-0.14	-0.31	-0.51	-10.98	-5.48	-1.22	-0.04	-0.70	-0.86
Medium															
Average	1.3	0.001	-0.016	0.013	0.115	0.001	0.008	0.042	0.002	0.046	0.016	-0.040	0.034	-0.007	-0.031
Median	1.4	0.001	0.012	0.014	0.204	0.001	0.014	0.019	0.003	0.047	0.081	0.029	0.032	0.036	0.024
Maximum	17	0.004	0.220	0.109	1.15	0.009	0.085	0.381	0.017	1.17	0.545	1.49	0.096	0.223	0.183
Minimum	-10	-0.006	-0.489	-0.109	-1.97	-0.014	-0.139	-0.310	-0.028	-1.14	-1.48	-1.22	-0.021	-0.627	-0.860
Fine															
Average	2.6	0.002	0.115	0.122	1.6	0.006	0.060	0.235	0.023	0.091	1.3	0.417	0.048	0.186	0.221
Median	2.9	0.002	0.089	0.176	0.311	0.005	0.049	0.163	0.010	0.076	2.3	0.385	0.049	0.177	0.141
Maximum	8.1	0.009	0.704	0.504	41.7	0.023	0.232	0.884	0.690	0.595	4.2	7.7	0.145	1.35	1.45
Minimum	-1.8	-0.001	-0.289	-0.806	-29.4	-0.001	-0.015	-0.137	-0.508	-0.184	-11	-5.5	-0.037	-0.698	-0.369
Commercial-all grain-size fractions															
Coarse															
Average	0.093	0.008	0.020	0.046	0.718	0.004	0.021	0.057	0.005	0.830	0.688	0.139	0.011	0.127	0.099
Median	0.067	0.003	0.007	0.031	0.506	0.002	0.018	0.010	0.004	0.460	0.315	0.026	0.001	0.069	0.062
Maximum	4.13	0.110	0.476	0.340	3.10	0.030	0.299	0.365	0.060	16.8	5.77	1.86	0.121	1.16	0.647
Minimum	-11.6	-0.027	-0.271	-0.438	-0.874	-0.009	-0.141	-0.180	-0.028	-0.281	-5.08	-0.723	-0.038	-0.516	-0.310
Medium															
Average	-0.436	0.000	-0.003	0.034	0.101	0.002	-0.002	0.063	-0.000	0.002	-0.117	0.027	0.015	0.004	0.036
Median	0.488	0.000	0.003	0.009	-0.016	0.001	0.005	0.054	0.001	0.003	0.072	0.013	0.005	0.004	-0.005
Maximum	3.59	0.006	0.216	0.314	1.60	0.014	0.066	0.292	0.013	0.265	0.413	0.664	0.121	0.238	0.647
Minimum	-11.6	-0.006	-0.271	-0.063	-0.874	-0.009	-0.141	-0.180	-0.028	-0.281	-1.933	-0.723	-0.038	-0.272	-0.310
Fine															
Average	0.334	0.004	0.121	0.027	0.925	0.008	0.082	0.161	0.034	0.593	0.625	0.659	0.026	0.280	0.239
Median	0.592	0.003	0.047	0.031	0.623	0.005	0.047	0.151	0.009	0.074	0.315	0.709	0.007	0.150	0.064
Maximum	4.13	0.037	0.568	0.711	3.10	0.030	0.299	0.365	0.117	4.75	5.77	1.86	0.136	1.24	1.68
Minimum	-5.34	-0.027	-0.177	-0.438	-0.037	-0.007	-0.065	-0.022	-0.017	-0.078	-5.08	-0.594	-0.020	-0.516	-0.377
Commercial-all grain-size fractions															
Coarse															
Average	0.068	0.017	0.011	0.152	1.48	0.006	0.032	0.014	0.009	2.20	2.38	0.038	0.002	0.258	0.153
Median	0.057	0.007	0.007	0.148	1.09	0.003	0.021	0.010	0.004	0.097	2.02	0.030	0.001	0.154	0.110
Maximum	0.179	0.110	0.036	0.340	3.28	0.023	0.094	0.042	0.026	16.8	5.00	0.094	0.008	0.900	0.539
Minimum	-0.011	-0.019	-0.003	-0.070	-0.027	-0.000	-0.004	0.000	0.002	0.002	0.130	-0.003	-0.000	-0.050	0.008

Table 11. Accumulation rates for constituents measured in street-solid composite samples, by grain-size fraction and land-use type collected before and after precipitation events in pounds per curb-mile per day, Cambridge, Massachusetts.—Continued

[Negative values indicate a net loss of material. Commercial data does not include Mount Auburn Street; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

	Magne- sium	Man- ganese	Molyb- denum	Sodium	Nickel	Phospho- rus	Lead	Anti- mony	Scan- dium	Tin	Stron- tium	Tita- nium	Vana- dium	Tung- sten	Yttrium	Zinc	Zirco- nium
Multifamily-all grain-size fractions																	
Coarse																	
Average	-0.008	1.68	-0.001	0.002	-0.009	0.004	-1.28	0.008	-0.002	0.147	0.176	-0.001	-0.059	0.016	-0.009	0.157	0.006
Median	0.021	1.45	0.002	0.001	0.024	0.001	0.070	0.014	0.003	0.069	0.197	0.001	0.063	0.029	0.015	0.463	0.007
Maximum	0.204	28.4	0.017	0.022	0.863	0.025	0.913	0.085	0.034	0.655	1.26	0.020	0.294	0.170	0.174	2.04	0.191
Minimum	-0.377	-25.5	-0.028	-0.010	-0.924	-0.017	-19.2	-0.139	-0.094	-0.278	-1.65	-0.033	-1.51	-0.278	-0.435	-5.63	-0.173
Medium																	
Average	0.075	5.28	0.042	0.010	0.593	0.0145	5.96	0.060	0.026	0.319	0.962	0.011	0.673	0.120	0.100	4.62	0.028
Median	0.041	3.23	0.060	0.012	0.648	0.0036	2.73	0.049	0.028	0.117	0.859	0.012	0.710	0.098	0.096	4.08	0.002
Maximum	0.353	25.2	0.410	0.032	3.89	0.0518	64.1	0.232	0.179	2.30	6.36	0.078	4.07	0.464	0.770	77.6	0.980
Minimum	-0.094	-5.70	-0.537	-0.018	-1.48	-0.0001	-42.8	-0.015	-0.090	-2.69	-3.38	-0.053	-1.631	-0.029	-0.343	-53.4	-0.566
Fine																	
Average	0.429	2.73	0.038	0.039	0.291	0.24515	5.16	0.021	-0.194	-0.008	0.400	0.095	0.449	0.047	0.771	4.63	0.040
Median	0.042	2.68	0.038	0.007	0.261	0.01018	5.44	0.017	0.019	0.365	0.337	0.013	0.459	0.034	0.099	3.49	0.037
Maximum	3.92	8.68	0.139	0.324	1.24	2.3599	9.80	0.060	0.047	5.92	1.43	0.861	1.18	0.120	7.17	14.0	0.193
Minimum	-0.011	-1.41	-0.077	-0.000	-0.650	-0.00004	0.028	-0.002	-2.110	-9.095	-0.012	-0.009	-0.247	-0.004	-0.153	0.145	-0.141
Commercial-all grain-size fractions																	
Coarse																	
Average	0.021	2.28	0.027	0.032	-0.000	0.0038	1.77	0.027	0.015	0.405	0.340	0.002	0.325	0.099	0.074	3.64	0.077
Median	0.003	1.88	0.040	0.001	0.177	0.0004	0.083	0.019	0.013	0.157	0.241	0.001	0.218	0.036	0.061	2.34	0.016
Maximum	0.263	20.5	0.244	0.782	1.397	0.0297	38.6	0.299	0.116	2.60	2.47	0.048	2.32	1.54	0.454	15.8	0.488
Minimum	-0.108	-11.664	-0.445	-0.470	-5.166	-0.0028	-23.0	-0.065	-0.050	-1.98	-0.899	-0.024	-1.280	-0.281	-0.174	-6.21	-0.193
Medium																	
Average	0.019	-0.470	0.004	0.039	-0.004	0.0033	0.004	0.011	0.003	0.063	0.090	-0.000	-0.034	-0.004	0.003	-0.159	0.004
Median	0.004	-0.002	0.002	0.002	0.010	0.0001	0.015	0.006	-0.000	0.009	0.093	-0.000	0.007	0.009	-0.001	0.254	0.003
Maximum	0.156	4.14	0.076	0.365	0.400	0.0237	0.243	0.075	0.065	0.579	0.994	0.015	0.751	0.131	0.144	2.65	0.158
Minimum	-0.108	-11.7	-0.059	-0.014	-0.633	-0.0028	-0.242	-0.054	-0.036	-0.281	-0.899	-0.020	-1.28	-0.281	-0.119	-6.21	-0.148
Fine																	
Average	0.080	7.31	0.032	0.042	0.120	0.015	2.63	0.082	0.029	1.167	0.679	0.011	0.686	0.165	0.158	4.51	0.138
Median	0.052	5.26	0.100	0.010	0.494	0.004	-0.051	0.047	0.017	0.174	0.131	0.007	0.338	0.094	0.073	3.22	0.046
Maximum	0.263	20.5	0.244	0.782	2.14	0.077	38.6	0.299	0.123	5.27	2.70	0.052	2.32	0.597	0.611	10.5	0.574
Minimum	-0.055	-5.00	-0.445	-0.470	-5.17	-0.001	-23.0	-0.065	-0.050	-1.573	-0.799	-0.024	-0.337	-0.131	-0.174	-1.36	-0.193
Coarse																	
Average	0.005	4.65	0.083	0.002	0.613	0.0008	1.85	0.032	0.027	0.455	0.571	0.001	0.641	0.214	0.150	7.18	0.153
Median	0.003	3.29	0.059	0.001	0.423	0.0001	1.79	0.021	0.015	0.253	0.372	0.001	0.450	0.042	0.088	5.82	0.097
Maximum	0.017	12.3	0.173	0.009	1.397	0.0042	7.65	0.094	0.093	1.685	1.93	0.005	1.98	1.54	0.454	15.8	0.467
Minimum	-0.000	-1.74	-0.013	-0.002	0.111	0.0000	-2.87	-0.004	-0.018	-0.241	-0.133	-0.003	-0.259	-0.007	-0.043	-0.152	-0.020

Table 12. Percent washoff of constituent masses in terms of grain-size fraction and land-use type from street-solid composite samples collected before and after 6 storms with a recorded rainfall volume range of 0.32 to 1.71 inches, Cambridge, Massachusetts.

[Negative values indicate a net increase of material; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

Organic carbon	Silver	Aluminum	Arsenic	Barium	Beryllium	Bismuth	Calcium	Cadmium	Cobalt	Chromium	Copper	Iron	Potassium	Lanthanum	Lithium
Multifamily all grain-size fractions															
Average	-25.83	-22.14	-37.64	10.53	-2.37	-138.48	-23.92	-14.53	-1.090	-42.06	-11.17	-27.92	-24.17	19.18	-83.33
Median	59.49	39.29	49.43	62.10	49.96	37.99	39.75	54.02	39.75	59.76	59.83	50.88	54.77	64.86	48.65
Maximum	95.26	97.22	93.96	95.52	94.59	92.53	92.53	95.42	95.84	93.47	97.34	98.25	92.78	94.11	92.86
Minimum	-1,454	-1,120	-1,243	-617	-1,487	-6,730	-1,420	-1,347	-1,120	-1,321	-886	-1,478	-1,082	-1,064	-2,799
Coarse															
Average	-48.33	-28.5	-85.7	4.17	9.05	-1.74	8.02	-25.9	8.02	-85.8	-48.0	-4.62	-60.3	29.8	-222.3
Median	41.86	21.1	42.1	39.7	31.2	21.2	21.2	59.0	21.2	51.7	10.3	21.6	24.8	64.1	-31.80
Maximum	95.26	90.3	82.0	95.0	88.1	83.4	86.8	95.4	86.8	89.7	86.8	88.4	87.9	93.1	92.21
Minimum	-1,196	-633	-966	-286	-339	-286	-286	-628	-286	-1,321	-824	-310	-958	-367	-2,799
Medium															
Average	25.1	17.5	18.4	1.6	34	-11.6	25	27	25	9.95	44	-10.5	26	44	22
Median	44.0	43.2	35.9	47.7	41	33.2	34	30	34	33.7	60	51.6	52	36	40
Maximum	84.6	73.8	71.0	92.2	73	62.7	63	69	63	77.6	97	98.3	79	75	76
Minimum	-106	-114	-122	-226	-27	-413	-64	-67	-64	-311	-38	-433	-81	-6.4	-93
Fine															
Average	-51.25	-54.95	-39.24	26.7	-51.4	-420.4	-109.0	-43.34	-37.44	-44.49	-24.35	-71.76	-33.19	-17.57	-30.65
Median	69.86	83.17	75.60	80.8	75.2	79.16	75.38	76.31	75.38	75.85	77.08	76.80	75.52	76.44	78.56
Maximum	93.53	97.22	93.96	95.5	94.6	92.53	92.53	95.15	95.84	93.47	92.08	93.95	92.78	94.11	92.86
Minimum	-1,454	-1,120	-1,243	-617	-1,487	-6,730	-1,420	-1,347	-1,120	-1,294	-886	-1,478	-1,082	-1,064	-1,094
Commercial all grain-size fractions															
Coarse															
Average	32.8	-3.40	-25.3	-5.13	18.4	13.5	27.9	25.8	27.4	-12.6	-311.1	12.5	-18.8	39.3	-33.13
Median	51.3	52.3	38.0	32.7	50.6	39.5	39.5	50.8	41.8	33.2	43.82	44.4	40.3	57.1	34.01
Maximum	96.4	99.2	96.0	96.0	96.8	96.7	94.8	95.6	94.8	95.5	94.26	96.9	94.6	96.9	95.48
Minimum	-268	-772	-958	-590	-395	-752	-249	-332	-249	-629	-15,130	-354	-731	-323	-1,402
Medium															
Average	17.4	-5.40	-114	-28.2	-0.938	24	25	14.5	27	-85.4	-927.1	-2.86	-107	44	-146.9
Median	41.4	34.8	-17.4	-5.84	26.2	18	20	28.6	20	-56.3	11.54	24.3	-15.4	46	-23.59
Maximum	89.0	90.3	89.4	96.0	90.2	89	89	92.9	89	89.4	83.01	94.2	94.5	97	95.48
Minimum	-268	-772	-958	-405	-281	-31	-31	-118	-31	-629	-15,130	-354	-731	-8.9	-1,402
Fine															
Average	45	-42.0	27.8	24.8	35	29	29	40	29	28	37	8.34	33	43	29
Median	52	21.6	37.9	44.4	47	41	41	51	41	32	55	38.6	40	57	38
Maximum	84	66.8	77.9	92.1	87	67	67	76	67	72	87	96.9	71	83	75
Minimum	-30	-342	-106	-195	-75	-47	-47	-23	-47	-56	-75	-252.1	-24	-31	-36
Coarse															
Average	40.6	34.9	23.1	-7.59	25.5	-12.2	31.3	26.9	27.5	30.6	36.0	34.5	30.6	32.5	35.0
Median	79.1	84.5	70.2	78.0	77.0	73.7	73.7	73.1	73.7	74.1	75.5	79.9	72.3	73.9	71.0
Maximum	96.4	99.2	96.0	93.7	96.8	96.7	94.8	95.6	94.8	95.5	94.3	95.3	94.6	96.9	95.1
Minimum	-253	-330	-389	-590	-395	-752	-249	-332	-249	-298	-197	-182	-259	-323	-236

Table 12. Percent washoff of constituent masses in terms of grain-size fraction and land-use type from street-solid composite samples collected before and after 6 storms with a recorded rainfall volume range of 0.32 to 1.71 inches, Cambridge, Massachusetts.—Continued

[Negative values indicate a net increase of material; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter]

	Magne- sium	Manga- nese	Molybde- num	Sodium	Nickel	Phospho- rus	Lead	Anti- mony	Scan- dium	Tin	Strontium	Titanium	Vana- dium	Tung- sten	Yttrium	Zinc	Zirconium
Multifamily all grain-size fractions																	
Average	-11.03	3.406	5.228	18.71	-7.953	-2.055	-44.70	-7.46	-30.02	-45.71	-6.181	-21.34	-69.38	17.77	-68.53	-42.05	-77.04
Median	60.39	56.31	59.53	68.99	46.58	57.97	48.48	37.99	54.93	50.77	56.85	53.48	51.29	39.75	52.32	43.51	32.72
Maximum	98.09	93.48	93.78	97.05	91.77	93.28	96.44	92.53	95.13	99.12	94.44	92.53	93.99	92.53	93.42	95.43	97.33
Minimum	-1.211	-1.126	-876	-1,120	-1,088	-1,120	-1,913	-1,120	-1,204	-2,339	-1,412	-1,120	-2,884	-375	-2,799	-1,246	-2,725
Coarse																	
Average	-13.6	11.8	-11.8	30.8	-16.0	-9.03	-20.7	-5.74	-57.07	-0.93	4.52	-48.9	-170.7	8.02	-168.3	-96.20	-78.3
Median	70.8	42.3	21.0	49.1	27.7	39.4	33.2	21.0	39.75	39.7	62.4	49.1	14.94	21.2	37.99	33.43	-30.6
Maximum	98.1	91.4	89.7	94.5	86.8	89.7	85.2	91.4	95.13	95.5	89.4	83.4	87.67	86.8	86.12	87.99	97.3
Minimum	-523	-230	-286	-163	-326	-467	-621	-286	-1,204	-358	-395	-468	-2,884	-286	-2,799	-1,020	-636
Medium																	
Average	18.4	29	44.1	44	32	31	-26.2	22	0.605	30.9	25	22.3	22.1	25	14.5	18.2	-23.5
Median	20.3	46	59.5	63	45	39	28.3	33	47.9	43.2	29	43.2	43.9	34	39.4	37.0	22.7
Maximum	71.5	64	93.4	86	89	66	70.0	63	86.7	95.2	63	76.7	69.0	63	75.7	84.6	78.2
Minimum	-106	-86	-110	-64	-85	-39	-467	-64	-426	-114	-64	-119	-128	-64	-248	-289	-558
Fine																	
Average	-37.50	-31.27	-14.3	-20.53	-38.75	-27.32	-90.42	-39.31	-29.98	-173.1	-49.90	-33.72	-46.08	21.7	-38.48	-40.89	-129.2
Median	74.53	75.31	76.0	85.63	76.79	75.59	75.16	75.38	77.28	51.84	76.52	75.31	75.38	75.4	78.55	73.07	84.33
Maximum	94.23	93.48	93.8	97.05	91.77	93.28	96.44	92.53	93.73	99.12	94.44	92.53	93.99	92.5	93.42	95.43	95.82
Minimum	-1,211	-1,126	-876	-1,120	-1,088	-1,120	-1,913	-1,120	-1,120	-2,339	-1,412	-1,120	-1,323	-375	-1,208	-1,246	-2,725
Commercial all grain-size fractions																	
Average	-7.20	-9.65	-1.75	40.9	-0.433	29.9	12.32	27.7	-20.57	-34.49	32.7	-9.2	-10.5	26.3	-15.0	30.6	-31.27
Median	43.1	44.4	63.3	73.9	42.1	48.1	64.33	39.5	42.84	25.87	51.8	40.0	40.2	39.5	33.1	52.0	27.72
Maximum	95.8	95.4	95.5	97.6	94.9	99.3	96.33	96.7	95.64	99.05	95.9	95.1	95.5	94.8	95.1	96.8	95.98
Minimum	-847	-911	-1,338	-365	-637	-214	-1,004	-249	-1,056	-2,360	-289	-557	-401	-249	-892	-410	-1,791
Coarse																	
Average	-71.2	-79.3	-66.70	36.2	-20.7	15.9	26.1	24.6	-96.1	8.33	33	-77.1	-82.9	21	-89.8	31	-122.4
Median	33.4	9.82	44.48	64.7	13.4	34.4	45.5	20.4	27.2	14.2	38	-44.9	-48.1	18	-43.5	42	-0.3969
Maximum	93.8	92.4	89.38	97.6	84.1	99.3	89.9	89.4	89.4	94.4	89	89.4	89.4	89	87.3	92	91.66
Minimum	-847	-911	-1,338	-220	-393	-176	-118	-75	-1,056	-362	-83	-557	-401	-59	-892	-61	-1,791
Medium																	
Average	35	32	39.1	57	-12.9	40	-4.679	29	23	15	38	33	35	29	25	45	12
Median	35	42	72.2	74	29.2	51	72.27	41	36	22	48	41	41	41	40	40	26
Maximum	75	69	89.0	96	77.2	89	96.33	67	76	94	82	78	80	67	71	92	63
Minimum	-5	-40	-103	-13	-637	-18	-1,004	-47	-129	-89	-44	-96	-41	-47	-84	-12	-66
Fine																	
Average	24.3	29.3	33.0	33.4	34.1	38.3	13.5	31.5	22.6	-131.3	29.2	27.0	27.7	31.3	31.2	18.4	28.5
Median	72.8	69.9	80.4	82.5	74.6	77.3	73.1	73.7	72.5	53.7	73.5	67.6	75.6	73.7	71.7	79.1	74.3
Maximum	95.8	95.4	95.5	97.5	94.9	96.3	95.2	96.7	95.6	99.0	95.9	95.1	95.5	94.8	95.1	96.8	96.0
Minimum	-354	-265	-249	-365	-189	-214	-347	-249	-372	-2,360	-289	-336	-315	-249	-278	-410	-264

Table 13. Median percent reductions for total and grain-size fractions of constituents measured in seasonal composite of street-solid yields collected before and after a single pass of a regenerative-air street cleaner on streets representing multifamily and commercial land-use types in Cambridge, Massachusetts.

[*Bold italicized* values indicate less than one-half the detection limit was used to determine concentration and normalized mass. Negative values indicate a potential net increase of a constituent. n, number of samples; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter; spring, May to June, 2010; summer, July to September, 2010; fall, October to December, 2010]

Analyte	Multifamily											
	Spring, n = 12				Summer, n = 17				Fall, n = 12			
	Total	Coarse	Medium	Fine	Total	Coarse	Medium	Fine	Total	Coarse	Medium	Fine
Organic carbon	80	93	87	60	87	93	90	57	94	97	96	81
<i>Silver</i>	<i>78</i>	<i>92</i>	<i>83</i>	<i>55</i>	<i>84</i>	<i>93</i>	<i>93</i>	<i>66</i>	<i>94</i>	<i>98</i>	<i>92</i>	<i>66</i>
Aluminum	78	90	84	60	79	91	87	42	93	98	59	37
Arsenic	70	98	66	55	77	90	83	11	90	94	73	-171
Barium	85	91	85	62	80	90	83	12	93	98	92	46
<i>Beryllium</i>	<i>78</i>	<i>92</i>	<i>83</i>	<i>55</i>	<i>84</i>	<i>93</i>	<i>86</i>	<i>66</i>	<i>94</i>	<i>98</i>	<i>92</i>	<i>66</i>
<i>Bismuth</i>	<i>78</i>	<i>92</i>	<i>83</i>	<i>55</i>	<i>84</i>	<i>93</i>	<i>86</i>	<i>66</i>	<i>94</i>	<i>98</i>	<i>92</i>	<i>66</i>
Calcium	79	90	88	57	89	96	85	48	93	98	94	78
<i>Cadmium</i>	<i>78</i>	<i>92</i>	<i>83</i>	<i>55</i>	<i>84</i>	<i>93</i>	<i>86</i>	<i>66</i>	<i>94</i>	<i>98</i>	<i>92</i>	<i>66</i>
Cobalt	67	85	83	50	84	93	86	31	94	99	59	32
Chromium	55	87	76	60	80	89	82	18	98	97	84	-81
Copper	74	97	78	70	90	88	92	21	97	99	88	-141
Iron	75	89	81	58	80	90	86	48	95	95	49	23
Potassium	86	96	87	66	90	96	88	50	94	98	94	69
Lanthanum	76	88	81	54	71	88	85	23	92	81	4	11
Lithium	75	86	85	65	82	83	90	59	95	97	59	42
Magnesium	70	89	84	57	85	93	87	50	94	98	80	51
Manganese	75	88	84	58	81	88	88	57	94	96	87	51
Molybdenum	67	96	74	55	84	93	86	43	98	95	84	15
Sodium	85	92	83	67	84	93	72	-3	90	91	76	32
Nickel	69	85	77	58	80	90	83	10	95	97	85	-88
Phosphorus	82	94	86	64	99	100	99	97	94	96	93	66
Lead	70	94	62	64	80	85	83	-13	93	97	57	-18
Antimony	78	92	83	55	84	93	86	66	94	98	92	66
Scandium	72	81	84	62	84	88	86	44	95	98	64	32
Tin	94	96	97	70	92	97	44	-37	98	98	92	-1,050
Strontium	80	92	84	60	85	90	88	45	92	98	94	78
Titanium	82	92	86	60	84	91	86	48	94	98	51	24
Vanadium	72	87	81	53	79	91	86	31	95	98	63	26
<i>Tungsten</i>	<i>78</i>	<i>92</i>	<i>83</i>	<i>55</i>	<i>84</i>	<i>93</i>	<i>86</i>	<i>66</i>	<i>94</i>	<i>98</i>	<i>92</i>	<i>66</i>
Yttrium	78	90	84	54	79	88	86	41	94	91	61	27
Zinc	77	94	81	62	76	95	85	22	95	98	86	13
Zirconium	78	74	86	52	79	87	82	59	94	98	82	2

Table 13. Median percent reductions for total and grain-size fractions of constituents measured in seasonal composite of street-solid yields collected before and after a single pass of a regenerative-air street cleaner on streets representing multifamily and commercial land-use types in Cambridge, Massachusetts.—Continued

[***Bold italicized*** values indicate less than one-half the detection limit was used to determine concentration and normalized mass. Negative values indicate a potential net increase of a constituent. n, number of samples; mm, millimeter; coarse, greater than or equal to 2 mm; medium, less than 2 mm greater than or equal to 0.125 mm; fine, less than 0.125 mm in diameter; spring, May to June, 2010; summer, July to September, 2010; fall, October to December, 2010]

Analyte	Commercial											
	Spring, n = 12				Summer, n = 17				Fall, n = 15			
	Total	Coarse	Medium	Fine	Total	Coarse	Medium	Fine	Total	Coarse	Medium	Fine
Organic carbon	70	94	78	59	83	91	79	72	92	96	93	85
<i>Silver</i>	<i>37</i>	<i>85</i>	<i>73</i>	<i>82</i>	<i>37</i>	<i>91</i>	<i>35</i>	<i>61</i>	<i>88</i>	<i>96</i>	<i>89</i>	<i>73</i>
Aluminum	51	47	75	56	74	86	76	68	83	96	87	74
Arsenic	72	97	62	53	79	82	86	56	79	97	88	73
Barium	54	96	60	63	84	88	83	74	84	98	86	76
<i>Beryllium</i>	<i>69</i>	<i>92</i>	<i>73</i>	<i>58</i>	<i>79</i>	<i>91</i>	<i>78</i>	<i>66</i>	<i>88</i>	<i>96</i>	<i>89</i>	<i>73</i>
<i>Bismuth</i>	<i>69</i>	<i>92</i>	<i>73</i>	<i>58</i>	<i>79</i>	<i>91</i>	<i>78</i>	<i>66</i>	<i>88</i>	<i>96</i>	<i>89</i>	<i>73</i>
Calcium	54	92	74	61	71	73	82	70	83	98	93	79
<i>Cadmium</i>	<i>69</i>	<i>92</i>	<i>73</i>	<i>58</i>	<i>79</i>	<i>91</i>	<i>78</i>	<i>66</i>	<i>88</i>	<i>96</i>	<i>89</i>	<i>73</i>
Cobalt	45	-8	66	62	53	85	68	59	86	93	89	73
Chromium	59	80	64	66	66	84	65	68	93	97	87	73
Copper	30	90	11	60	31	84	29	62	90	97	87	60
Iron	64	82	65	61	74	84	73	62	86	93	86	68
Potassium	72	97	79	62	84	94	78	72	84	98	90	79
Lanthanum	68	92	68	60	74	86	73	67	86	87	89	74
Lithium	53	54	73	58	72	85	75	69	83	89	88	73
Magnesium	55	59	75	57	70	83	77	67	85	93	88	76
Manganese	58	94	71	59	76	83	78	64	87	94	85	72
Molybdenum	48	96	31	63	86	91	86	66	94	96	68	73
Sodium	69	96	73	58	79	63	78	81	83	98	89	77
Nickel	64	86	71	66	71	83	70	62	91	95	87	70
Phosphorus	62	96	73	63	97	99	97	98	83	97	89	79
Lead	73	98	76	66	65	90	63	57	93	98	95	78
Antimony	69	92	73	58	79	91	78	66	88	98	89	73
Scandium	53	54	75	58	77	88	74	66	83	88	87	79
Tin	84	92	73	58	58	82	14	66	94	96	89	91
Strontium	66	93	77	64	73	83	75	68	81	97	93	78
Titanium	61	61	73	58	74	77	73	63	80	94	85	77
Vanadium	61	50	70	58	72	87	75	65	87	94	88	76
<i>Tungsten</i>	<i>69</i>	<i>92</i>	<i>73</i>	<i>58</i>	<i>79</i>	<i>91</i>	<i>78</i>	<i>66</i>	<i>88</i>	<i>96</i>	<i>89</i>	<i>73</i>
Yttrium	73	93	77	59	73	87	75	69	86	87	89	75
Zinc	70	96	60	63	75	85	74	73	86	99	88	80
Zirconium	60	90	71	44	79	89	77	70	88	96	84	71

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Appendix 1. Supplemental Data Tables

Tables included on accompanying CD-ROM

Tables

- 1-1. Curb-to-curb street-solid composite sample collection dates, start times, locations, intake nozzle widths and resulting masses and yields
- 1-2. Single-sided street cleaner removal efficiency composite sample pair collection dates, start times, locations, intake nozzle widths and resulting masses and yields
- 1-3. Curb-to-curb street-solid composite sample collection dates, start times, locations, intake nozzle widths and resulting total-recoverable concentrations by grain size for multifamily streets
- 1-4. Curb-to-curb street-solid composite sample collection dates, start times, locations, intake nozzle widths and resulting total-recoverable concentrations by grain size for commercial streets
- 1-5. Seasonal mixtures of single-sided street-solid composite samples, locations, and resulting total-recoverable concentrations by grain-size for multifamily streets before and after regenerative-air street cleaner operation
- 1-6. Seasonal street mixtures of single-sided street-solid composite samples, locations, and resulting total-recoverable concentrations by grain-size for commercial streets before and after regenerative-air street cleaner operation

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Appendix 2. Source Loading and Management Model for Windows (WinSLAMM)

Functional Description of SLAMM

The Source Loading and Management Model for Windows (WinSLAMM) uses a mass balance approach to track particulate and dissolved constituents associated with as many as six different land-use types and their source areas, taking into account a variety of rainfall conditions and source-area control measures. Runoff, constituent mass discharge and effects of selected control practices are the primary model output. SLAMM also can output other types of information such as the relative contribution of source areas within each land-use type and generation of National Resource Conservation Service (NRCS) curve numbers that represent the modeled land-use and control measures.

The model emphasizes the concept of small storm hydrology and particulate washoff to better simulate stormwater quality. This emphasis follows a major finding of the National Urban Runoff Program (NURP)-era work indicating small rainstorms represent the largest proportion of the annual urban runoff discharge quantities (U.S. Environmental Protection Agency, 1983; Pitt, 1987). The model also takes into account the findings of Maestre and Pitt (2005), where log-transformed constituent concentration data in stormwater generally have a lognormal distribution between the 5th and 95th percentiles. A Monte Carlo option in the model provides the means to determine variations in the constituent concentrations in source area runoff and provide median values used for mass balance calculations. This feature can be deactivated and discrete concentration can be used to allow evaluations of extreme concentrations. SLAMM also can be used with other models such as the Hydrologic Simulation Program Fortran (HSPF) and the StormWater Management Model (SWMM) to improve simulations of stormwater and water-quality controls.

Simulations in SLAMM require six input parameter files, which are based on actual data collected from many different studies across the United States and Canada since the late seventies and continue to be modified as new data become available. It is possible to simulate different stormwater control practices using precipitation data from a single year or several decades. SLAMM simulations can yield accurate predictions of stormwater quality for a drainage area with only limited ancillary information.

Local outfall stormwater quantity and quality data from several watersheds with relatively homogeneous land uses should be collected and used to calibrate SLAMM. Ideally, data from one set of watersheds or subcatchments should be used to calibrate the model, and data from the remaining

subcatchments used to verify model performance. Alternatively, a subset of data from a single location can be used for model calibration and any remaining data from the same location used for verification. These approaches assume availability of good quality data. However, available data for this study were limited in number and quality.

Input Data used for Modeling of Land-Use Subcatchments

Land-use types and their respective source areas as input to SLAMM are provided in appendix table 2–1. About 36 percent of the commercial subcatchment is considered multifamily or high-density residential land use (referred to as multifamily), about 17 percent institutional, and about 47 percent commercial land use. The model treats institutional and commercial areas the same, so the effective commercial land use is about 64 percent.

Drainage systems and other control practices must also be identified. SLAMM parameter files (table 2–2) must be input and modified as needed following their general order of calibration. Required information and the data contained in the parameter files used for SLAMM simulations of the commercial subcatchment are discussed in the following sections.

Delineation of Land-Use Types and Source-Areas

Characterization of land-use types and their respective source areas within the model subcatchments were delineated from impervious surface geographic information system (GIS) 2010 coverages generated by the city of Cambridge/MassGIS basemap development project (Cambridge Department of Public Works, written commun., 2011, table 2–1). Using the municipal GIS layers, which provided greater source-area resolution than the 1-meter (m) impervious surface raster layers based on 2005 0.5-m color ortho mosaic index (MassGIS, 2011), all constructed surfaces and areas of man-made compacted soils were considered impervious. All surface waters, wetlands, natural and man-made vegetated areas were considered pervious. Roof, driveway, and other impervious surface drainage were further evaluated in the field to determine connectivity. If runoff drained less than 20 feet of pervious area, the drainage was considered directly connected.

Table 2–1. Source-area designations and respective areas as input to SLAMM model within the commercial subcatchment, Cambridge, Massachusetts (Based on 2010 land-use coverages, city of Cambridge/MassGIS basemap development project).

[--, no data]

Subcatchment source areas	Multifamily and high-density residential land use (acres)	Commercial land use (acres)	Public/urban/institutional land use (acres)	Total area (acres)	Source area proportion of total (percent)
Roofs flat	1.69	3.17	1.37	6.24	28.66
Roofs-flat, disconnected	0.47	--	--	0.47	2.16
Roofs-pitched	0.57	0.56	0.13	1.26	5.80
Roofs-pitched, disconnected	0.01	0.09	0.05	0.15	0.68
Paved parking/storage	0.62	1.73	0.47	2.81	12.93
Driveways	0.61	0.76	0.04	1.41	6.50
Driveways-disconnected	0.04	--	--	0.04	0.18
Sidewalks/walks	0.54	1.22	0.11	1.87	8.59
Sidewalks/walks-disconnected	0.07	--	0.14	0.21	0.98
Street area	0.82	2.23	0.46	3.52	16.15
Large/small landscaped area	2.48	0.40	0.90	3.78	17.37
Total subcatchment area (acres)	7.93	10.16	3.67	21.76	
Proportion of total area (percent)	36.45	46.70	16.86		

Soils

Soils in the subcatchment area (Middlesex County) typically are considered disturbed urban glacio-fluvial outwash (U.S. Department of Agriculture, 1995). Despite highly permeable classifications of parent soils, pervious areas were represented as “silty” rather than “sandy” within the model to account for the effects of compression and buildup of fugitive dust that substantially reduce native soil permeability (Pitt and others, 2008).

Control Practices

The city has a well-defined curb-and-gutter drainage system equipped with about 15-inch (in.) high granite curb-stone set at roughly 90 degrees to the road surface (fig. 4). Catchbasins are incorporated into the drainage system and are cleaned about twice a year. SLAMM version 9.4.0 is unable to simulate catchbasins and street cleaning simultaneously, and catchbasins were not specified. The city uses a monthly street-cleaning program with parking controls between April and December that uses mechanical brush sweepers. The tandem street cleaning approach (mechanical brush followed by vacuum assist) applied during the months of April and November was not simulated. In addition, many commercial areas and city squares that are swept weekly or daily were also not included in the model.

Base model simulations used to compare with flow and water-quality data collected in 1999–2000 were run by specifying monthly mechanical-brush street cleaning in the model. Productivity function coefficients provided with SLAMM for mechanical-brush street cleaners (slope, $M = 0.85$ and y-intercept, $B = 310$) were used. Model performance also was evaluated by comparing simulated street-dirt yield to street-dirt observations from 2009–2011. These simulations specified monthly vacuum-assist street cleaning using productivity function coefficients developed from the regenerative-air street cleaner observations in Cambridge.

Street-Solid Accumulation

The observations of material accumulation on street surfaces in Cambridge collected in 2010–2011 were used to populate SLAMM accumulation coefficients. The average accumulation rate for streets in multifamily areas (M) was set to 30 pounds per curb-mile per day (lbs/curb-mi/day), the intercept load (B) was set to 225 lbs/curb-mi, and the maximum load (C) was set to 3,800 lbs/curb-mi. The end-of-winter (EOW) load for residential land-use streets was set at 2,600 lbs/curb-mi. Commercial and institutional land-use accumulation coefficients M, B, C and EOW were set to 20, 225, 1,400, and 4,800, respectively.

Table 2-2. Parameter files and other model data required to develop SLAMM for the commercial subcatchment Cambridge, Massachusetts.

[SSC; suspended sediment concentrations]

Parameter file name	File type	Description	Initial data source	Regional source data
Rain	*.RAN	Rainfall depths, durations and intervening time periods; Special rain file contains typical rain duration data to determine percent contribution of runoff from each source area for various rain events	National Climatic Data Center, Boston Logan Airport; Cambridge Department of Public Works; U.S. Geological Survey MA-RI WSC	National Climatic Data Center, Boston Logan Airport
Runoff coefficient	*.RSV	Contains volumetric runoff coefficients for each surface type for various rain depths. Must be calibrated before any other parameter files are evaluated.	Bannerman and others, 1983; Pitt and others, 2005a, b, and c; Pitt and Shawley, 1981; Pitt, 1982; Pitt and McLean, 1984; and Shelley and Gadbourey, 1985	Verified runoff coefficients from 8 study sites in Milwaukee and 2 sites in Toronto. Modified verified runoff coefficient file to better match 1999–2000 runoff data and runoff data
Particulate solids concentration	*.PSC	Describes SSC for each source area and land use for several rain categories (except road and highway surfaces)	Bannerman and others, 1983; Pitt and others, 2005a, b, and c; Pitt and Shawley, 1981; Pitt, 1982; Pitt and McLean, 1984; and Shelley and Gadbourey, 1986	No modifications
Particulate residue reduction (Particulate solids delivery)	*.PRR	Calibrates source-area predictions of SSC to outfall observations to account for deposition of particulates within the storm drainage system	Bannerman and others, 1983; Pitt and others, 2005a, b, and c; Pitt and Shawley, 1981; Pitt, 1982; Pitt and McLean, 1984; and Shelley and Gadbourey, 1986	Not used—obsolete file
Street-dirt delivery	*.STD	More accurately accounts for deposition of street-dirt washoff material	Bannerman and others, 1983; Pitt and Shawley, 1981; Pitt, 1982; Pitt and McLean, 1984; and Shelley and Gadbourey, 1986	No modifications
Pollutant probability distribution (Event particulate solids loading)	*.PPD	Particulate pollutant concentrations related to particulate and filterable pollutant concentrations for each source area and land use (optional unless modeling chemical constituents)	Bannerman and others, 1983; Pitt and others, 2005a, b, and c; Pitt and Amy, 1973; Pitt, 1979; Pitt and Shawley, 1981; Pitt, 1982; Pitt and Bozeman, 1982; Pitt, 1985; Pitt and McLean, 1984; Sartor and Boyd, 1972; Shaheen, 1975; Shelley and Gadbourey, 1986; and Terstriep and others, 1982	No modifications
Particle size diameter	*.CPZ	Critical particle size	U.S. Environmental Protection Agency, 1983	Not used for street-cleaning simulations

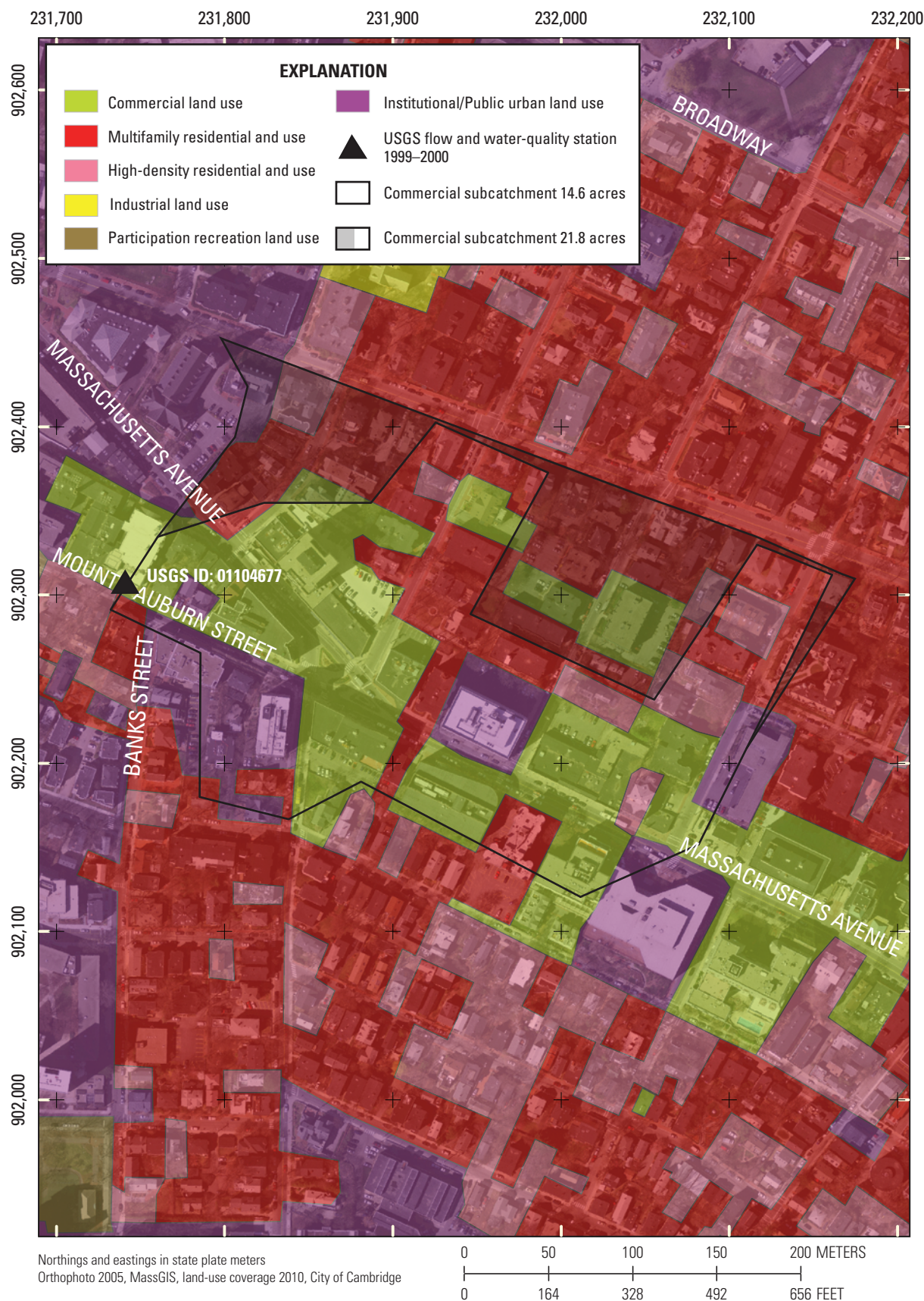


Figure 2–1. Predominantly commercial land-use subcatchment in Cambridge, Massachusetts, and United States Geological Survey flow and water-quality monitoring station (1999–2000; USGS ID: 01104677). Orthophoto 2005, MassGIS, and land-use coverages 2010, based on city of Cambridge/MassGIS basemap development project.

Rainfall

Initial model runs used 62 years of rainfall data from Logan Airport in Boston, Massachusetts (1948–2010 COOP ID: 190770) available through the National Climatic Data Center (NCDC, 2011). Storms with rainfall less than 0.1 inch were omitted from all *.RAN files, (that is, only runoff producing storms were considered). A special *.RAN file was created from the long-term Logan Airport data to determine the average storm duration of storm depths between 0.10 to 5.00 in. SLAMM runs using the special *.RAN file estimated the relative contribution of runoff from each source area through the range of storm volumes and provided the basis for any modifications to runoff coefficient *.RSV parameter files. Logan Airport rainfall data were also used to evaluate simulated outfall runoff and loading compared to water-quality data collected in 1999–2000. Additional *.RAN files developed using precipitation records from the Cambridge Department of Public Works (DPW) Hampshire Street gage supplemented by the USGS Fresh Pond gage (USGS ID: 422302071083801) during winter months were used to evaluate model performance in terms of street-dirt loading observations in 2009–2011.

The base model that provided acceptable estimates of runoff and street-dirt loading was run using 5 years of precipitation data from Logan Airport. The five average years were selected by comparison of annual discharges from the USGS Aberjona River at Winchester, Mass. gage (USGS gage ID: 01102500, located about 7 miles north of Cambridge) with the 70-year mean annual flow of 31 cubic feet per second (ft³/s) reported at the gage (Bent and others, 2009). Years with annual average discharge within 4.5 percent of the 70-year mean annual flow at the USGS Aberjona River at Winchester, Mass. gage were 1948, 1953, 1961, 1986, and 1991. Model runs using a *.RAN file based on these data allowed SLAMM to generate average estimates of street cleaner performance in terms of total and particulate solid and phosphorus (P) reductions.

Runoff

Runoff coefficient (R_v) parameter files (*.RSV) contain ratios of runoff quantity to rainfall volume for all modeled surface types for rain depths measuring from 0.01 to 5 in. The WI_SL06 Dec06.RSV file provided with the model initially was used, and examination of the relative contribution of source areas generated by the model run using the special *.RAN file, runoff coefficients were modified in a stepwise manner to improve agreement between simulated results and runoff data from 1999–2000. Runoff coefficient increases between 0.05 and 0.10 were determined to be sufficient to better match simulated and observed outfall flows.

Particulate Solids Concentration

Suspended solids concentrations (SSCs) associated with source areas from each land use over a range of rain depths is contained in the particulate solids concentrations (*.PSC) file. Build-up and washoff functions directly predict roads and highway surface SSCs, and are not included in the *.PSC file (Pitt and Voorhees, 2000). The WI_AVG01.PSC file (appendix table 2–2) provided with the model is based on data from Madison, Wisconsin, that represents the best average particulate solids information. No new outfall SSC data were collected in Cambridge to support modifications to this *.PSC file, and therefore the WI_AVG01.PSC file was used for calibration and subsequent SLAMM simulations.

Two additional parameter files are used to describe the transport of particulates in SLAMM. The first file is the particulate residue reduction file (*.PRR), and was designed to account for the deposition of particulates in the storm drainage system before the outfall or outfall controls (Pitt, 2008; Pitt and Voorhees, 2000). Particulate deposition in the storm drainage system, however, is now directly calculated, making the *.PRR file obsolete (Pitt, 2008). SLAMM still requires a *.PRR file to be specified, and the file WI_DLV01.PRR, set to zero, was used as a placeholder in the model. The second additional file is the street-dirt delivery file (*.STD). These files account for the fraction reduction in street dirt yield during washoff events measuring from 0.04 to 3.2 in. Fraction washoff is applied to street surfaces with textures ranging from smooth to rough within each land-use type. The files WI_Res and Other Urban Dec06.STD, WI_Com Inst Indust Dec06.STD, and Freeway Dec06.STD were used in the model. These files typically show 100-percent washoff for all surface types for storm depths greater than 0.60 inches. Changes to washoff coefficients are not possible in SLAMM version 9.4. Washoff data calculated as part of this study are not used in the following simulations.

Pollutant Concentrations

The *.PPD file contains particulate and dissolved pollutant concentrations associated with each source area for each land-use type specified in the model. This file only needs to be specified for constituents other than particulate solids. Coefficient of variation (COV) values included for each constituent for Monte Carlo simulations (Pitt, 2008; Pitt and Voorhees, 2000). The WI_GEO01.PPD file (appendix table 2–2) was applied to model the Cambridge commercial subcatchment. The critical particle size file (*.CPZ) is primarily designed to assist evaluations of wet detention ponds and other structural stormwater control measures SCMs. SLAMM comes with several *.CPZ files that describe particle size ranges in areas associated with low to high particulate residue concentrations as well as files that contain the average of the NURP-era studies and a regionally-specific *.CPZ file. The critical particle size parameter file was not necessary for SLAMM simulations of street cleaning in this study, and no *.CPZ file was specified.

References

- Bannerman, R., Baun, K.M., Bohn, P.E., and Graczyk, D.A., 1983, Evaluation of urban nonpoint source pollution management in Milwaukee County, Wisconsin: Chicago, Ill., U.S. Environmental Protection Agency, PB 84–114164.
- Maestre, A., and Pitt, R., 2005, The National Stormwater Quality Database, Version 1.1, A compilation and analysis of NPDES stormwater monitoring information: Washington D.C., U.S. Environmental Protection Agency, Water Planning Division, variously paginated.
- Massachusetts Office of Geographic Information (MassGIS), 2011, 0.5-meter color ortho mosaic and metadata: Accessed February 12, 2011, at <http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/massgis-data-download-usgs-color-ortho-imagery-2008-2009.html>
- National Climatic Data Center, accessed February 12, 2011, at <http://cdo.ncdc.noaa.gov/dlyp/DLYP>.
- Pitt, R.E., 1982, Urban bacteria sources and control in the lower Rideau River watershed: Ottawa Ontario, Ontario Ministry of the Environment, variously paginated.
- Pitt, R.E., 1985, Characterizing and controlling urban runoff through street and sewerage cleaning: U.S. Environmental Protection Agency, Storm and Combined Sewer Program, Cincinnati, Ohio, Risk Reduction Engineering Laboratory, EPA/600/S2-85/038, PB 85-186500, variously paginated.
- Pitt, R.E., 1987, Small storm urban flow and particulate washoff contributions to outfall discharges: Department of Civil and Environmental Engineering, University of Wisconsin, Madison, Ph.D. dissertation, 187 p.
- Pitt, R.E., 2008, Calibration of WinSLAMM, PV & Associates, Madison, Wis., 38 p.
- Pitt, R.E., Bannerman, R., Clark, S., and Williamson, D., 2005a, Sources of pollutants in urban areas (part I)—older monitoring projects, *in* Effective modeling of urban water systems: Monograph 13, James, W., Irvine, K.N., McBean, E.A., and Pitt, R.E., eds., CHI, Guelph, Ontario, 465–484 and 507–530 p.
- Pitt, R.E., Bannerman, R., Clark, S., and Williamson, D., 2005b, Sources of pollutants in urban areas (part II)—recent sheetflow monitoring results, *in* Effective modeling of urban water systems: Monograph 13, James, W., Irvine, K.N., McBean, E.A., and Pitt, R.E., eds., CHI, Guelph, Ontario, 485–530 p.
- Pitt, R.E., and Bozeman, M., 1982, Sources of urban runoff pollution and its effects on an urban creek: Cincinnati, Ohio, U.S. Environmental Protection Agency, EPA-600/S2-82-090, variously paginated.
- Pitt, R.E., Chen, S., Clark, S.E., Swenson, J., and Ong, C.K., 2008, Compaction's impacts on urban storm-water infiltration: *Journal of Irrigation and Drainage Engineering*, p. 652–658.
- Pitt, R.E., and McLean, J., 1984, Humber River pilot watershed project: Toronto, Ontario, Ontario Ministry of the Environment, variously paginated.
- Pitt, R.E., and Shawley, G., 1981, Demonstration of nonpoint pollution management on Castro Valley Creek: Washington, D.C., U.S. Environmental Protection Agency, Water Planning Division, variously paginated.
- Pitt, R.E., and Voorhees, J., 2000, The source loading and management model (SLAMM): A water quality planning management model for urban storm water runoff, PV & Associates, Madison, Wis., 587 p.
- Pitt, R.E., Williamson, D., and Voorhees, J., 2005c, Review of historical street dust and dirt accumulation and washoff data, *in* Effective modeling of urban water systems: Monograph 13, James, W., Irvine, K.N., McBean, E.A., and Pitt, R.E., ed., CHI, Guelph, Ontario, 203–246 pp.
- Shelley, P.E., and Gaboury, D.R., 1986, Estimation of pollution from highway runoff-initial results: Conference on urban runoff quality-impact and quality enhancement technology, Henniker, New Hampshire: Urbonas, B., and Roesner, L.A., eds., *in* Proceedings published by the American Society of Civil Engineering, New York, variously paginated.
- Terstriep, M.L., Bender, G.M., and Noel, D.C., 1982, Evaluation of the effectiveness of municipal street cleaning in the control of urban storm pollution: Final report-NURP project, Champaign-Urbana, Illinois, State Water Survey Division, Illinois Department of Energy and Natural Resources, variously paginated.
- U.S. Department of Agriculture, 1995, Soil Survey Geographic (SSURGO) Data Base, Data Use Information: Natural Resources Conservation Service, National Soil Survey Center, Miscellaneous Publication Number 1527, variously paged.
- U.S. Environmental Protection Agency, 1983, Nationwide Urban Runoff Program, Winston-Salem, N.C.—An evaluation of street sweeping as a runoff pollution control: Office of Water Programs, 229 p. (Also available from National Technical Information Service, Springfield, VA 22161 and <http://www.ntis.gov>, item PB85–102507)

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