

Residential Street-Dirt Accumulation Rates and Chemical Composition, and Removal Efficiencies by Mechanical- and Vacuum-Type Sweepers, New Bedford, Massachusetts, 2003–04

By Robert F. Breault, Kirk P. Smith, and Jason R. Sorenson

In cooperation with the
U.S. Environmental Protection Agency,
Massachusetts Department of Environmental Protection, and the
City of New Bedford Department of Public Works

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Conversion Factors, Datum, and Abbreviations

Multiply	By	To obtain
micrometer (μm)	0.0000328	foot (ft)
millimeter (mm)	0.00328	foot (ft)
grams (g)	0.0022	pounds (lb)
liter (L)	0.234	gallons (gal)
square meters (m^2)	10.8	square foot (ft^2)
milliliter (mL)	0.00026	gallons (gal)
kilometers per hour (km/hr)	0.62137	miles per hour (mph)
cubic meter (m^3)	35.31	cubic foot (ft^3)
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)
kilograms (kg)	2.205	pound avoirdupois (lb)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Sediment-Quality Units

Concentrations are given in percent (%), parts per million (ppm), and parts per billion (ppb).

Street-Dirt Accumulation Rates

Street-dirt accumulation rates are given in grams per curb meter per day (g/curb-m/d). Intuitively, accumulation rates should be reported in units of mass per unit area per unit time. Street dirt accumulates along curbs, however, and therefore accumulation rates are reported in units of mass per unit curb length per unit time as has been the practice in other investigations reporting street-dirt accumulation. For example, one kilogram of street dirt accumulated on a street surface that is one kilometer in length over one day would be equal to 0.5 grams per curb meter per day; one kilometer of street has two kilometers of curb length or 2000 curb meters.

Abbreviations

BMPs	best management practices
DIW	deionized water
HEPA	high-efficiency particulate air filter
ICPES	inductively coupled plasma-emission spectroscopy
MDEP	Massachusetts Department of Environmental Protection
NWQL	National Water Quality Laboratory
PAHs	polyaromatic hydrocarbons
PEC	probable-effect concentration
PES	performance-evaluation sample
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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Abstract

The U.S. Geological Survey, in cooperation with the U.S. Environmental Protection Agency, Massachusetts Department of Environmental Protection, and the city of New Bedford Department of Public Works, examined accumulation rates and chemical composition of street dirt in residential areas in 2003 and 2004 and analyzed the effectiveness of two types of street sweepers. Street-dirt accumulation rates were determined on two streets within an area of predominantly multifamily homes in the city of New Bedford, Massachusetts. Accumulation rates were determined for 1-, 2-, or 3-day intervals; street dirt with particle sizes larger than 125 micrometers was collected; and finer material was flow-proportionally sampled. Chemical composition of street dirt was determined at the two residential locations from a handheld vacuum equipped with a 0.2-micrometer high-efficiency particulate air filter. Vacuumed material was analyzed for elements (including trace metals) and polyaromatic hydrocarbons (PAHs), which are contaminants typical of urban environments. Street-sweeper efficiencies were determined by applying a known mass of dirt to a street and measuring the mass of dirt swept by mechanical- and vacuum-type sweepers. Street dirt swept by the city in routine sweeping by both types of sweepers was analyzed for particle-size distribution, elements, and organic compounds, and these data were used to estimate the mass of contaminants removed from the city's streets.

Street-dirt accumulation rates ranged from about 2.1 to 41 grams/curb-meter/day with an average of 14 grams/curb-meter/day; about 56 percent of the material collected was

coarse sand (gravel, fine sand, silts and clays combine to make up the remaining 44 percent). Residential street dirt had substantial concentrations of trace metals and PAHs. Trace metal and PAH (sum of parent PAHs) concentrations were generally greatest on fine-grained particles (less than 63 microns in size). Coarse-grained particles, however, generally accounted for the largest mass of the trace metals—cadmium, chromium, copper, lead, nickel, and zinc (about 30 percent)—and sum of parent PAHs (about 27 percent), because of the greater mass of coarse-grained particles. Ratios of some PAHs measured in street dirt collected during this study were similar to those measured in other studies elsewhere and closely resemble those measured in asphalt and used motor oil. Street-sweeper efficiencies ranged from about 20 to 31 percent for the mechanical sweeper and from about 60 to 92 percent for the vacuum sweeper for the particle-size range tested. Efficiencies for particle sizes between 2 millimeters and 250 micrometers (or coarse sand) were at least 1.5 to 5 times greater for the vacuum sweeper compared to the mechanical sweeper. Data collected in this study indicate that New Bedford's street-sweeping program has successfully removed about 3.8 million kilograms of street dirt, which contains potentially toxic chemicals such as trace metals and PAHs that may otherwise end up in the city's catch basins, treatment plants, and rivers and streams that receive urban runoff. Results of this study can also be used in simulation models to analyze the effects of street contaminants and street sweeping on the quality of receiving water in other cities throughout the northeastern United States.

Introduction

Protection or restoration of urban water resources often includes the control of contaminant sources by the implementation of best management practices (BMPs). BMPs include structural controls such as infiltration trenches and basins, grassy swales, detention ponds and wetlands, and nonstructural controls such as maximizing vegetation, minimizing impervious area, street sweeping, and educating residents about how their personal habits may affect their environment. Both types of BMPs focus mostly on reducing the loads of trash, leaves, solids, and associated contaminants that tend to accumulate on streets, parking lots, and rooftops, because these contaminants are commonly washed from these surfaces by rainwater into urban rivers, lakes, and streams.

The choice of one or more BMPs depends on many factors, such as the goals of restoration, construction and maintenance costs, existing infrastructure, and available space. The use of structural BMPs often is limited in cities, however, due to lack of usable space needed to implement these types of controls. Cities commonly invest in street-sweeping programs as a nonstructural BMP measure for several reasons. First, the benefits of street sweeping are readily apparent to citizens, improving the overall cleanliness and the aesthetic quality of city streets by removing trash, leaves, and other debris. Cities also invest in street-sweeping efforts to reduce contaminant loads to urban water resources. The effectiveness of street sweeping in reducing contaminant loads to urban water resources, however, is not well understood. Therefore, benefits achieved by different types of sweepers and strategies for meeting water-quality objectives are difficult to quantify.

At the watershed scale, computer models have been used to estimate the benefits of street sweeping (Sutherland and Jelen, 1997; Zarriello and others, 2002). These models require accurate information about the rate at which street dirt accumulates on impervious surfaces, the chemical composition of the street dirt, and the efficiency of different types of sweepers at removing solids and associated contaminants. (For this study, street dirt is defined as an amorphous mixture of natural and anthropogenic particulate matter including soil, plant debris, asphalt, concrete, and trash, that is less than a few millimeters in size.) Most of the data concerning sweeper efficiencies come from studies done in the late 1970s and early 1980s, when street sweepers were nearly all mechanical and inefficient, or the data were from manufacturers' reports, most often published in trade journals. Similarly, data concerning street-dirt-accumulation rates also come from these earlier studies, which include few done in the northeastern United States and none in the city of New Bedford (fig. 1), a city of about 100,000 people, in southeastern Massachusetts.

Like many older cities, New Bedford has limited space for the construction of new structural BMPs. The city owns and operates two different types of street sweepers, however, and is interested in evaluating the effectiveness of its sweeping program as a water-quality management tool. To assist city managers in achieving this goal, the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), Massachusetts Department of Environmental Protection (MDEP), and the city of New Bedford Department of Public Works undertook a study in 2003 and 2004 to evaluate street-dirt-accumulation rates, the chemical composition of street dirt, and street-sweeping efficiencies of different types of sweepers. The results of this study can be used by the city of New Bedford to tailor its street-sweeping program to maximize its water-quality benefits. These study results can also be used in simulation models to analyze the effects of street contaminants and street sweeping on the quality of receiving water in other cities throughout the northeastern United States.

Purpose and Scope

This report provides information on street dirt, associated chemical-accumulation rates, and the effectiveness of two types of street sweepers (mechanical and vacuum) at removing street contaminants. Specifically, this report provides information on street-dirt-accumulation rates and chemistry for two streets in a predominantly multifamily area of New Bedford (fig. 1). Concentrations of elements and polyaromatic hydrocarbons (PAHs), PAH-concentration ratios, and likely sources of the PAHs for the two streets in New Bedford are discussed. Results of efficiency tests are reported for two types of sweepers: a Pelican Series P mechanical sweeper, the most commonly used mechanical sweeper, and a Johnston 605 series vacuum sweeper.

This study included measurement of street-dirt accumulation from two residential areas, the collection of street dirt for analysis of chemical composition, and the controlled measurement of street-sweeper efficiency. The scope of the study was limited; the objective was to provide preliminary order-of-magnitude estimates for the initial assessment of environmental issues. Reduction of the uncertainty of the results would have required a substantial increase in the sampling and analysis effort.



Figure 1. Location of Query and Central Streets, street-dirt accumulation and chemical-composition study areas, in the city of New Bedford, Massachusetts.

Previous Studies

Most studies of street-sweeping efficiency as a water-quality control were published in the late 1970s and early 1980s, when brush-style mechanical sweepers were used. These studies commonly suggest that brush-style sweepers tested at the time were ineffective. For example, Sartor and Gaboury (1984) reported that the removal efficiencies generally ranged from 10 to 30 percent for all particle-size ranges of solids tested. Removal efficiencies for specific particle-size ranges were about 79 percent for gravel, 63 percent for coarse sand, 48 percent for fine sand, 20 percent for very fine sand, and 15 percent for silt and clay or 50 percent overall (Sartor and Gaboury, 1984). Bender and Rice (1982) measured removal efficiencies of about 42 percent for brush-style sweepers. Shoemaker and others (2000) reported removal efficiencies of about 55 percent for a brush-style sweeper, but several passes were required to attain this removal rate. During the past 20 years, sweeper technologies have developed that are reportedly much more efficient in sweeping solids from streets. Shoemaker and others (2000) reported an efficiency of about 93 percent for vacuum-assisted sweepers. Other studies have reported efficiencies of about 90 percent, with a maximum of 98 percent, for the newer sweeper technologies, even for the finest particles (Sutherland and Jelen, 1997; Terrene Institute, 1998; Bannerman, 1999).

Other factors, in addition to sweeper type, that affect the effectiveness of street sweeping include land use, roadway maintenance, patterns in automotive traffic, weather, sweeping frequency and strategy, street condition and material, or curbing (Pitt, 1985; Smith and Lord, 1990; Northern Virginia Planning District Commission, 1992; Camp, Dresser, and McKee and others, 1993; Washington State Department of Ecology, 1999; Washington State Department of Transportation, 1995; Shoemaker and others, 2000). Most of these factors affect the availability of street dirt to be swept, and consequently, the reported street-sweeper efficiencies. These studies have reported accumulation rates of solids in the range of about 1 to 40 g/curb-m/d, averaging about 9 g/curb-m/d, for streets with smooth to intermediate surfaces, and 6 to 34 g/curb-m/d, averaging about 15 g/curb-m/d, for streets with rougher surfaces (Pitt and others, 2004). Most studies of street-dirt accumulation and associated chemical-contaminant accumulation rates were done in Midwest and West Coast cities of the United States.

The chemistry of street dirt as a water-quality contaminant has been the focus of several studies. Sartor and Gaboury (1984) summarized average concentrations of arsenic

(15 ppm), cadmium (3 ppm), chromium (200 ppm), copper (100 ppm), lead (1,000), nickel (20 ppm), and zinc (300 ppm) measured in vacuumed street dirt; concentrations tended to increase with decreasing particle size. Modeling studies also indicate the importance of controlling contaminant loads from street runoff to achieve desired water-quality objectives (for example, Zarriello and others, 2002).

Field Methods and Laboratory Analysis

This study entailed three field efforts: (1) measurement of street-dirt accumulation from two residential areas, after specific time intervals; (2) collection of street dirt for analysis of chemical composition; and (3) controlled measurement of street-sweeper efficiency.

Street-Dirt Accumulation Rates

Two New Bedford streets, Query and Central, were chosen in consultation with the city of New Bedford Department of Public Works (fig. 2) on the basis of land use (multifamily), curbing, and catch basins at the terminus of each study section. Those same two streets were washed before and after the measurement period for accumulation, and wash water was sampled. The total mass of street dirt larger than 125 μm was collected, and finer material was flow-proportionally sampled. Particles smaller than 125 μm remained suspended during washing—determined by trial and error—whereas particles larger than about 125 μm did not.

Sample collectors were installed in each catch basin (fig. 3A). Each sampler was constructed of high density polyethylene and consisted of a v-notch thin-plate weir cut from the polyethylene. The collection chamber had a 125- μm nylon screen and two ports, one for a pressure transducer and one for a polyethylene sampling tube. Each sampling area was power-washed with municipal water (fig. 3B). As wash water passed through the sampler, a submersible pressure transducer measured the height of water in the sampler, and the data were sent to a datalogger. The datalogger was programmed to calculate discharge and the total volume of water (Rantz, 1982) and to trigger an ISCO automated sampler to collect flow-proportional samples (fig. 3C). These samples, consisting of wash water and street-dirt particles smaller than 125 μm , were collected in 1-L precleaned polyethylene bottles. Particles larger than 125 μm were collected on the nylon screen (fig. 3D).

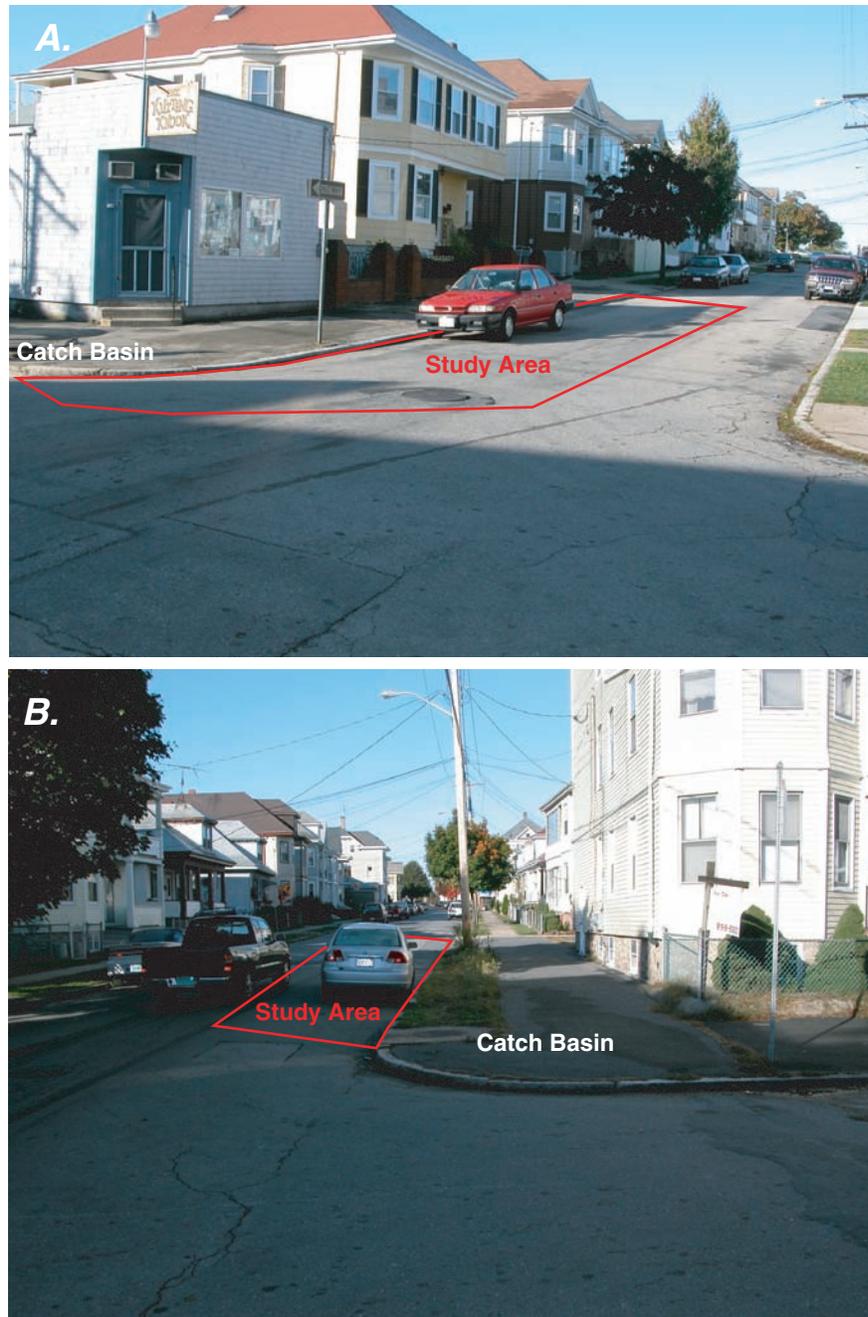


Figure 2. A, Query Street and B, Central Street, street-dirt accumulation and chemical-composition study areas, New Bedford, Massachusetts.



Figure 3. A, Street-dirt collection device installed in the Query Street catch basin; B, Query Street washing with the Vector machine; C, collection of wash water with entrained street dirt as part of the street-dirt accumulation experiments; and D, equipment used to measure discharge and sample wash water, New Bedford, Massachusetts.

Synoptic storm-event studies indicate that the time between storms has an approximate exponential distribution with many short periods and relatively few long periods. Estimates indicate that the average time between storms is about 3.5 d in northeastern Massachusetts (Zarriello and others, 2002). Moreover, street-dirt accumulation rates appear to increase quickly following removal by wind, rain, or human activity, and reach maxima within a few days (Sartor and Boyd, 1972). The experiment, therefore, was designed to examine street-dirt accumulation rates for one-, two-, and three-day dry periods. Weekly weather forecasts were used to select dry period sampling dates during the summer of 2004.

At the beginning of each street-dirt-accumulation experiment interval, the street was washed clean by using high-pressure water supplied from the city's Vactor Machine to remove any accumulated street dirt. After dirt had accumulated on the street for the chosen interval, catch basins were cleaned and a large area of each street (larger than 700 ft²) was washed again with 46 to 91 gal of water from the Vactor (fig. 3B). Washing was done for each experiment by starting at the street centerline and moving towards the curb, then along the curb in a down-slope direction. The Vactor was a negligible source of dirt. Particles in the wash water were determined to be 0.2 percent of the total solids measured in the dirt on the street, and 10 percent of the silt and clay particles, on average.

Wash water with entrained dirt was allowed to run along the street gutter into the catch basin, through the 125- μ m nylon screen, and into the sampler (fig. 3C-D). After each 4-gal volume of wash water had passed through the weir, a 250-mL sample of wash water with particles smaller than 125 μ m was collected until washing was completed. After the street had been completely washed, the total volume of water used to wash the street was recorded, and dirt captured by the screen and in the sample bottles was labeled, stored, and brought back to the USGS laboratory in Northborough, MA. In the laboratory, dirt was washed from the screen by using deionized water (DIW), and this large-grained dirt was collected in 1-L precleaned polyethylene bottles; grass clippings, intact leaves, and other large pieces of debris were rinsed and removed from

each sample. The dirt samples and wash water were shipped to the USGS Sediment Laboratory for particle-size analysis and dry-mass weighing. The total mass of dirt accumulated on each street was determined by adding the mass of particles smaller than 125 μ m, measured as the sediment concentration in g/L multiplied by the total volume in L of wash water, to the mass of particles larger than 125 μ m (collected on the screen). Street-dirt accumulation rates were then calculated by dividing the total mass (g) by the length (curb-m) of street washed and the length of time of each experiment (1, 2, or 3 days).

Street-Dirt Chemistry

Two street-dirt samples were collected from Central and Query Streets, New Bedford, for chemical analysis by using a hand-held vacuum equipped with a 0.2- μ m high-efficiency particulate air (HEPA) filter; one sample was analyzed for elements and the other for organic compounds. These samples were wet-sieved with deionized water into several particle-size ranges, including gravel (larger than 2 mm), coarse sand (2 mm to 250 μ m), fine sand (250 to 125 μ m), very fine sand (125 to 63 μ m), and silt and clay (smaller than 63 μ m) by using precleaned polyethylene, nylon, or stainless-steel sieves, depending on the chemical analysis. Wet sieving was chosen over dry sieving as the means of separating street dirt into different particle sizes to ensure complete separation of the particle-size ranges and to prevent disaggregation of larger particles by the violent shaking that is part of the process of dry sieving.

Samples sieved through polyethylene or nylon sieves were analyzed for elements (including trace metals), and samples sieved through stainless-steel sieves were analyzed for PAHs. The XRAL Laboratory of Ontario, Canada, analyzed street-dirt samples for 32 total and total recoverable elements by inductively coupled plasma emission spectroscopy (ICPES). Total concentrations are determined by using a strong acid digestion, which dissolves the mineral matrix; therefore, total concentrations include those elements that

compose the minerals in the sample. Total recoverable concentrations are determined by using a weak acid digestion, which generally does not dissolve the mineral matrix; therefore, total recoverable concentrations include only those elements that are sorbed to the surface of particles in the sample. Elements measured by means of total recoverable methods are generally considered the result of human activities and are commonly considered to be the geochemically or biologically available fraction. The USGS National Water-Quality Laboratory (NWQL) in Denver, CO, analyzed street-dirt samples for PAHs by gas chromatography with mass spectrometry (Wang and others, 1994).

Twelve street-dirt samples also were collected (randomly during the study period) and analyzed from each type of sweeper after routine operation or street sweeping throughout the city of New Bedford. Samples from each sweeper type were homogenized into one sample in a precleaned Teflon bag and analyzed for total recoverable elements and PAHs by NETLAB of North Providence, Rhode Island, by using methods consistent with those used by XRAL and the NWQL, respectively. Samples of this material were also analyzed by the USGS Sediment Laboratory, Louisville, Kentucky, for particle-size distribution.

Street-Sweeper Efficiencies

The efficiencies of a Pelican Series P mechanical sweeper and a Johnston 605 Series vacuum sweeper were tested (fig. 4). The effectiveness of each sweeper type was determined by (1) precleaning sweeper hoppers, conveyer systems, or both (fig. 5A); (2) applying a known amount of dirt with a known particle-size distribution to a prewashed street (fig. 5B); (3) sweeping the street at normal operating speeds (about 5 mph) or slower (sweeping at speeds slower than normal may bias sweeper efficiencies high) and spraying water as normally done during routine sweeping (fig. 5C); and (4) collecting the swept dirt (fig. 5D). The applied dirt was obtained from catch basins in the study area after trash, leaves, and other debris had been removed. The sediments were then dry sieved, and reconstituted into proportions similar to those measured in vacuumed street dirt, as previously discussed. This reconstituted dirt composed of gravel (about 22 percent), coarse sand

(about 44 percent), fine sand (about 20 percent), very fine sand (about 9 percent), and silt and clay (about 6 percent) was laid down by using a calibrated drop spreader over a 3-ft by about 200-ft stretch of curbed road in amounts that could be expected to accumulate on a street surface within about 1 or 2 days (3,500 g or about 18 g/curb-m/d), so this amount of dirt is consistent with a 1- to 2-day antecedent dry period. Depositing more street dirt than would normally accumulate over a 1- to 2-day period may affect calculated street-sweeper efficiencies. Pitt and Amy (1973) showed that more than 90 percent of street dirt was found to accumulate within 30 cm of the curb.

Dirt from each sweeper hopper, conveyor system, or both, was collected and analyzed by the USGS Sediment Laboratory, Louisville, KY, for total mass and particle-size distribution. Sweeper efficiencies were determined by dividing the total mass of swept dirt by the total mass of applied dirt. Sweeper efficiencies were also determined for the individual particle-size ranges—gravel (larger than 2 mm), coarse sand (2 mm to 250 μm), fine sand (250 to 125 μm), very fine sand (125 to 63 μm), and silt and clay (smaller than 63 μm).

Bias and Variability

Results from environmental sampling efforts may be subject to bias (or systematic error) and variability (or random error) during sample collection, processing, and analysis. The nature and magnitude of bias and variability can be determined by analysis of quality-control samples, including blanks, field duplicates, laboratory duplicates, matrix spikes, matrix-spike duplicates, and performance-evaluation samples (PES). With a few exceptions, bias and variability in this study were generally within acceptable limits; the difference was about 50 percent for field duplicates and 25 percent for laboratory duplicates. The most notable exceptions were for copper and silver total recoverable concentrations and the total lead concentration measured in the duplicate gravel samples. For these constituents, concentrations in duplicate and environmental samples were about 100 percent different. Small metal objects such as brake-pad particulates could explain the observed variability in these metal concentrations (Armstrong, 1994).



Figure 4. A, Pelican Series P mechanical sweeper and B, Johnston 605 Series vacuum sweeper, used in the evaluation of sweeper efficiencies.

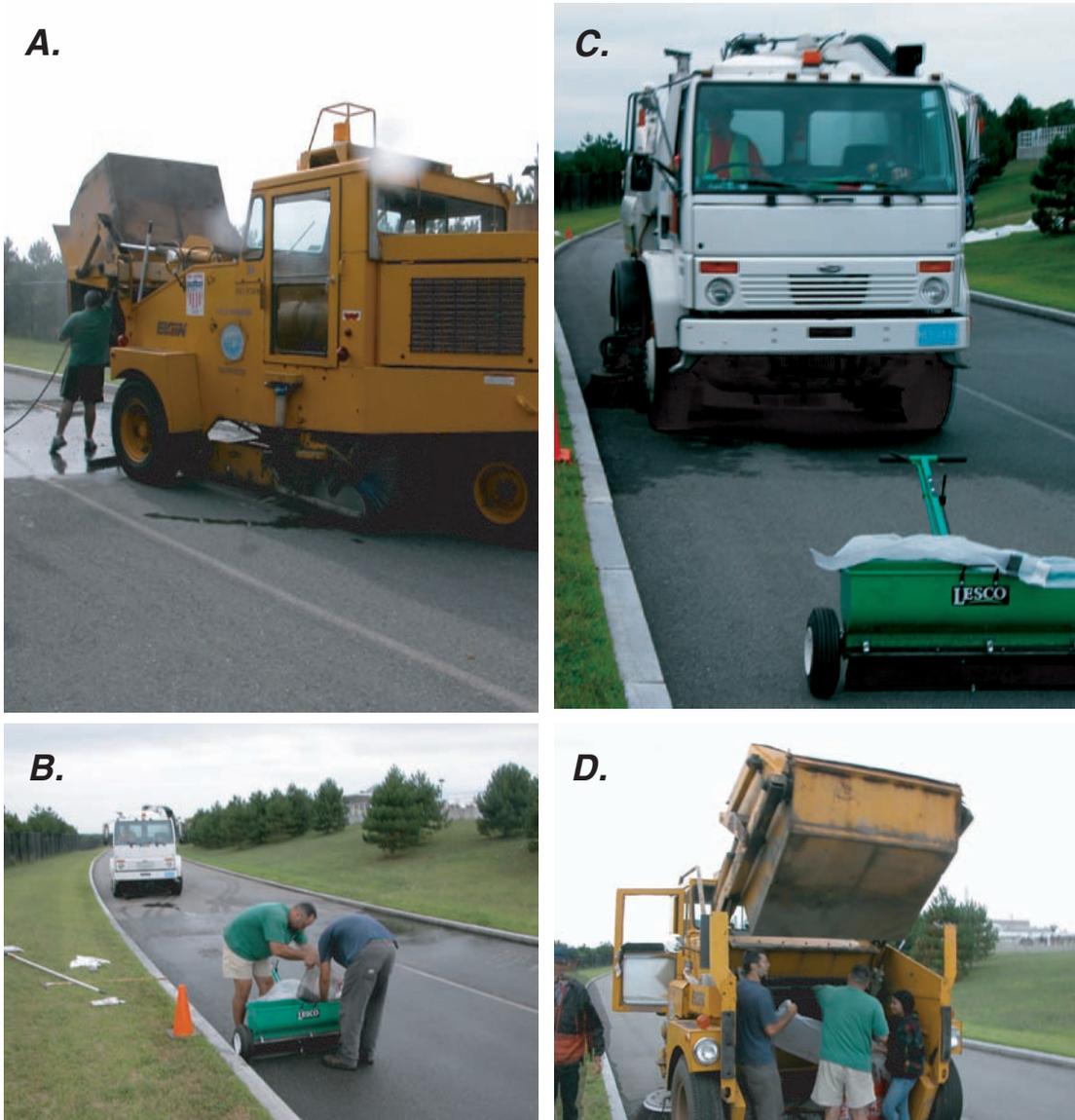


Figure 5. Street-sweeper efficiency tests. The process here was carried out on both types of sweepers. *A*, Precleaning of sweeper, *B*, dirt application, *C*, sweeping, and *D*, collection of swept dirt, as part of the street sweeping-efficiency experiments, New Bedford, Massachusetts.

Street-Dirt Accumulation Rates

Accumulation rates for all particle sizes tested ranged from about 2.1 to 41 g/curb-m/d and averaged about 14 g/curb-m/d (table 1) for both streets for the 1-, 2-, and 3-day experiments. Accumulation rates for individual particle-size fractions were: gravel (0.3 to 10.3 g/curb-m/d); coarse sand (1.1 to 23 g/curb-m/d); fine sand (0.4 to 4.0 g/curb-m/d); very fine sand (0.2 to 2.4 g/curb-m/d); and silt and clay (0.1 to 1.9 g/curb-m/d). Accumulation rates measured for Central Street were greater (by 1.6 to 20 times) than those measured for Query Street for the same time interval (1, 2, or 3 d). This result was unexpected because Central Street has a smoother surface than Query Street; rough streets generally have larger accumulation rates than smooth streets in the same land-use area (Pitt and others, 2004). Although the total mass of dirt measured from the two streets differed substantially, the dirt samples were similar in terms of particle-size distribution (table 1).

Observed differences in street-dirt-accumulation rates for the three time periods are difficult to explain because so few experiments were completed; however, plots of measured accumulation rates in relation to average daily wind speed measured at the New Bedford Airport indicate that wind may be a factor in the observed variability (fig. 6). Higher average daily wind speed corresponds to lower street-dirt-accumulation rates measured for Central Street, whereas the rates measured for Query Street appear to remain constant. Pitt (1979) reported that wind has little effect if accumulation rates are low, as they were for Query Street, but wind is effective at removing solids from smooth streets if accumulation rates are high, like those measured for Central Street. If average daily wind speed exceeds 12 mph (experiment 2), the street-dirt-accumulation rates measured for the two streets may be similar.

Table 1. Street-dirt accumulation rates and particle-size distribution for two streets in a predominantly multifamily area of the city of New Bedford, Massachusetts.

[**Experiment 1:** Lasted 24 hours and was done between 8-9-04 and 8-10-04; **Experiment 2:** Lasted 48 hours and was done between 8-10-04 and 8-12-04; **Experiment 3:** Lasted 72 hours and was done between 8-6-04 and 8-9-04. g/curb-m/d, grams per curb-meter per day. Particle-size distribution is given as percent retained.]

Particle size	Experiment 1	Experiment 2	Experiment 3
Accumulation rates (g/curb-m/d)			
Central Street			
Gravel ¹	3.8	1.5	10.3
Coarse sand ²	13	5.2	23
Fine sand ³	4.0	1.6	3.6
Very fine sand ⁴	.8	.3	2.4
Silt and clay ⁵	.4	.2	1.9
Total ⁶	22	9	41
Query Street			
Gravel ¹	.6	.5	.3
Coarse sand ²	2.8	3.0	1.1
Fine sand ³	1.4	1.3	.4
Very fine sand ⁴	.4	.4	.2
Silt and clay ⁵	.3	.3	.1
Total ⁶	5.4	5.4	2.1
Particle-size distribution (percent)			
Central Street			
Gravel ¹	18	17	25
Coarse sand ²	59	59	56
Fine sand ³	18	18	9
Very fine sand ⁴	4	4	6
Silt and clay ⁵	2	2	5
Query Street			
Gravel ¹	11	9	15
Coarse sand ²	51	55	53
Fine sand ³	26	25	18
Very fine sand ⁴	7	7	10
Silt and clay ⁵	5	5	4

¹Gravel: Larger than 2.0 millimeters.

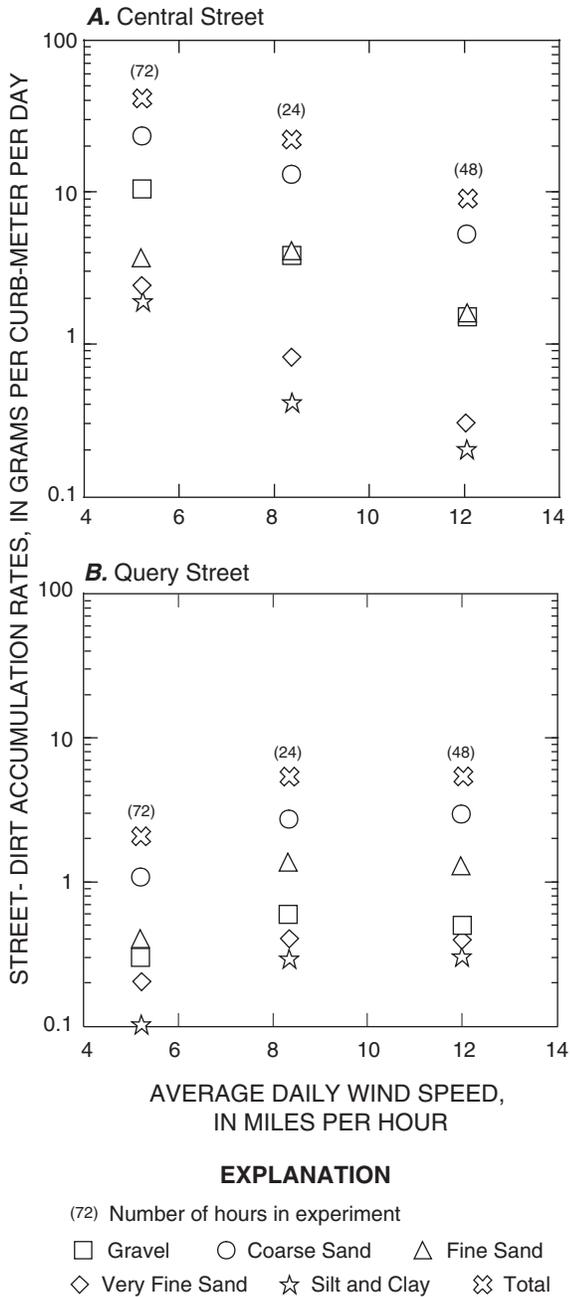
²Coarse sand: Smaller than 2.0 millimeters, larger than or equal to 250 micrometers.

³Fine sand: Smaller than 250 micrometers, larger than or equal to 125 micrometers.

⁴Very fine sand: Smaller than 125 micrometers, larger than or equal to 63 micrometers.

⁵Silt and clay: Smaller than 63 micrometers.

⁶Total: The total accumulation rate for all particle sizes.



Street-Dirt Chemistry

Street dirt vacuumed by hand from Central and Query Streets was wet-sieved into five particle-size ranges, and each range was analyzed for 32 elements (including trace metals) and PAHs. Most of the metals were detected in every particle-size range and generally increased in concentration with decreasing particle size (table 2; fig. 7). This result was expected, because fine-grained particles have a larger surface area per unit weight to which contaminants can adhere than do coarse-grained particles. One notable exception to this result was the total recoverable concentration of copper measured in the gravel fraction.

Some elements, however, may have transferred from the solid phase to the aqueous phase during wet-sieving, and were either washed away or redistributed to other particle-size ranges. This problem likely affects only the most soluble elements; therefore, it is minor because the focus of this study is on trace metals and PAHs, which have relatively low solubilities in relation to contaminants such as nutrients. More rigorous testing would be needed to determine the elements affected and the magnitude of this potential problem. Pitt and others (1994), for example, showed that most metals in urban runoff (street dirt suspended in rainwater) were associated with the solid phase, with the exception of zinc. The relative solubilities determined in other studies for some common trace metals are shown in table 3.

Figure 6. Relation between street-dirt accumulation rates and average daily wind speed, New Bedford, Massachusetts.

Table 2. Inorganic element concentrations by particle size measured in street dirt collected in an area of predominantly multifamily homes in the city of New Bedford, Massachusetts.

[**Gravel:** Larger than 2.0 millimeters. **Coarse sand:** Smaller than 2.0 millimeters, larger than or equal to 250 micrometers. **Fine sand:** Smaller than 250 micrometers, larger than or equal to 125 micrometers. **Very fine sand:** Smaller than 125 micrometers, larger than or equal to 63 micrometers. **Silt and clay:** Smaller than 63 micrometers. D, duplicate; LD, laboratory duplicate; ppm, parts per million; <, actual value is less than value shown, --, not done]

Element	Gravel	Coarse sand	Fine sand	Very fine sand	Silt and clay	Gravel (D)	Silt and clay (LD)
Total recoverable concentrations							
Calcium, in percent	1.2	0.49	0.55	0.76	0.95	1.2	--
Magnesium, in percent	.93	.33	.42	.61	.89	.95	--
Sodium, in percent	.11	.05	.05	.06	.05	.11	--
Potassium, in percent	.26	.16	.14	.15	.20	.26	--
Phosphorus, in percent	.06	.03	.04	.07	.16	.06	--
Aluminum, in percent	1.3	.67	.76	.98	1.8	1.3	--
Antimony, in ppm	<5	<5	6	<5	6	6	--
Arsenic, in ppm	<3	3	6	5	9	<3	--
Barium, in ppm	82	84	98	110	210	81	--
Beryllium, in ppm	.7	<.5	.5	.6	.9	.6	--
Bismuth, in ppm	<5	<5	<5	<5	<5	<5	--
Cadmium, in ppm	<1	<1	1	2	3	<1	--
Chromium, in ppm	200	260	350	300	200	202	--
Cobalt, in ppm	10	6	6	9	11	9	--
Copper, in ppm	1,510	69	91	140	250	6,240	--
Iron, in percent	3.1	3.0	3.3	3.4	3.3	3.2	--
Lanthanum, in ppm	11	10	12	18	24	11	--
Lead, in ppm	82	270	420	490	1,240	84	--
Lithium, in ppm	18	8	9	12	22	18	--
Manganese, in ppm	400	290	350	400	440	400	--
Molybdenum, in ppm	2	4	4	4	5	<1	--
Nickel, in ppm	30	23	35	44	55	31	--
Scandium, in ppm	4.8	2.3	2.7	3.8	3.9	5.0	--
Silver, in ppm	.8	.6	.4	1.0	1.2	.2	--
Strontium, in ppm	470	32	30	36	46	500	--
Tin, in ppm	<10	<10	<10	12	19	220	--
Titanium, in percent	.12	.06	.08	.10	.13	.12	--
Tungsten, in ppm	<10	<10	<10	<10	<10	<10	--
Vanadium, in ppm	52	26	36	49	75	52	--
Yttrium, in ppm	10	8.5	11	13	15	10	--
Zinc, in ppm	130	230	270	320	810	140	--
Zirconium, in ppm	29	19	13	10	7.1	29	--
Total concentrations							
Calcium, in percent	0.99	1.1	1.8	2.0	5.7	2.4	5.9
Magnesium, in percent	.47	.55	.86	1.2	.73	1.1	.75
Sodium, in percent	1.2	1.2	1.5	1.4	.41	1.8	.44
Potassium, in percent	1.6	1.4	1.4	1.4	.91	1.8	.95
Phosphorus, in percent	.03	.04	.07	.18	.85	.06	.88
Aluminum, in percent	3.9	3.8	5.1	5.9	3.2	5.9	3.3
Antimony, in ppm	8	12	12	18	45	8	45
Arsenic, in ppm	3	5	5	7	120	<3	120
Barium, in ppm	370	340	380	470	450	580	480
Beryllium, in ppm	1.3	1.1	1.5	1.6	1.9	1.5	2.0
Bismuth, in ppm	<5	7	9	7	16	6	13
Cadmium, in ppm	<1	<1	<1	2	69	<1	72
Chromium, in ppm	330	370	280	210	130	350	130
Cobalt, in ppm	6	7	10	12	15	10	15
Copper, in ppm	52	110	140	240	560	36	580

Table 2. Inorganic element concentrations by particle size measured in street dirt collected in an area of predominantly multifamily homes in the city of New Bedford, Massachusetts.—Continued

[Gravel: Larger than 2.0 millimeters. Coarse sand: Smaller than 2.0 millimeters, larger than or equal to 250 micrometers. Fine sand: Smaller than 250 micrometers, larger than or equal to 125 micrometers. Very fine sand: Smaller than 125 micrometers, larger than or equal to 63 micrometers. Silt and clay: Smaller than 63 micrometers. D, duplicate; LD, laboratory duplicate; ppm, parts per million; <, actual value is less than value shown, --, not done]

Element	Gravel	Coarse sand	Fine sand	Very fine sand	Silt and clay	Gravel (D)	Silt and clay (LD)
Iron, in percent	3.5	3.6	4.0	3.9	3.7	3.5	3.8
Lanthanum, in ppm	13	16	28	36	38	21	39
Lead, in ppm	230	380	490	1,230	5,960	87	6,150
Lithium, in ppm	10	10	13	23	20	18	20
Manganese, in ppm	390	490	650	660	780	520	790
Molybdenum, in ppm	8	8	6	6	16	7	16
Nickel, in ppm	30	44	47	60	74	46	76
Scandium, in ppm	5.4	6.0	9.4	13	5.9	9.7	6.2
Silver, in ppm	<.2	.4	.9	1.5	6.4	.9	6.3
Strontium, in ppm	113	112	170	179	200	210	200
Tin, in ppm	<10	<10	16	20	90	<10	95
Titanium, in percent	.14	.26	.35	.36	.31	.22	.32
Tungsten, in ppm	<10	<10	<10	10	<10	<10	<10
Vanadium, in ppm	46	58	84	120	140	78	140
Yttrium, in ppm	11	14	19	24	14	18	15
Zinc, in ppm	190	260	320	810	4,330	110	4,480
Zirconium, in ppm	30	32	80	88	72	39	73

Metals

Concentrations of metals measured in street dirt collected in this study were similar to the concentrations of the same metals measured in earlier studies (Sartor and Gaboury, 1984), with the notable exception of lead. The lower lead concentrations measured in street dirt from New Bedford are probably a result of regulation to phase out leaded gasoline between the early 1970s and mid-1980s.

Many sources of trace metals in the urban environment can contribute substantial amounts of these metals to street dirt. Consequently, metal concentrations in street dirt may be classified as toxic by human-health standards. Exposure-based guidelines, guidelines that relate contaminant concentrations to human health, do not explicitly exist for street dirt, but they do exist for contaminated soil. In the absence of street-dirt guidelines, comparison with direct-contact, exposure-based soil standards may suffice (Massachusetts Department of Environmental Protection, 1996; method 2, soil category S-1). These guidelines exist for some of the elements tested, including antimony (10 ppm), arsenic (30 ppm), barium (1,000 ppm), beryllium (0.7 ppm), cadmium (30 ppm), chromium (1,000 ppm), lead (300 ppm), nickel (300 ppm), silver (100 ppm), vanadium (400 ppm), and zinc (2,500 ppm). Of these contaminants, beryllium and lead had total recoverable

concentrations associated with the silt and clay particle-size range (or less than 63 μm) greater than the exposure-based guidelines by 1.3 and 4.1 times, respectively. Lead concentrations also were greater than the exposure-based guideline for all particle sizes less than 250 μm (fine sand). Calculation of whole-sample concentrations [the sum of measured total recoverable concentrations for each particle-size range tested multiplied by the weight percentage of each particle-size range in street dirt collected with the hand-held vacuum composed of gravel (22 percent), coarse sand (44 percent), fine sand (20 percent), very fine sand (9 percent), and silt and clay (6 percent)], indicates that only lead was greater than its exposure-based guideline (1.1 times). Total recoverable concentrations of antimony, arsenic, barium, cadmium, chromium, nickel, silver, vanadium, and zinc measured in street dirt were all less than exposure-based guidelines in every particle-size range tested and for the whole sample.

Metal concentrations in street dirt are of concern for aquatic life in receiving waters as well as for human health. For example, a literature review (Buckler and Granato, 1999) indicates (qualitatively) that road runoff (even from roads with high traffic volume) may not usually be acutely toxic. Tissue analysis and ecological community assessments, however, indicate adverse effects from street dirt near discharge points

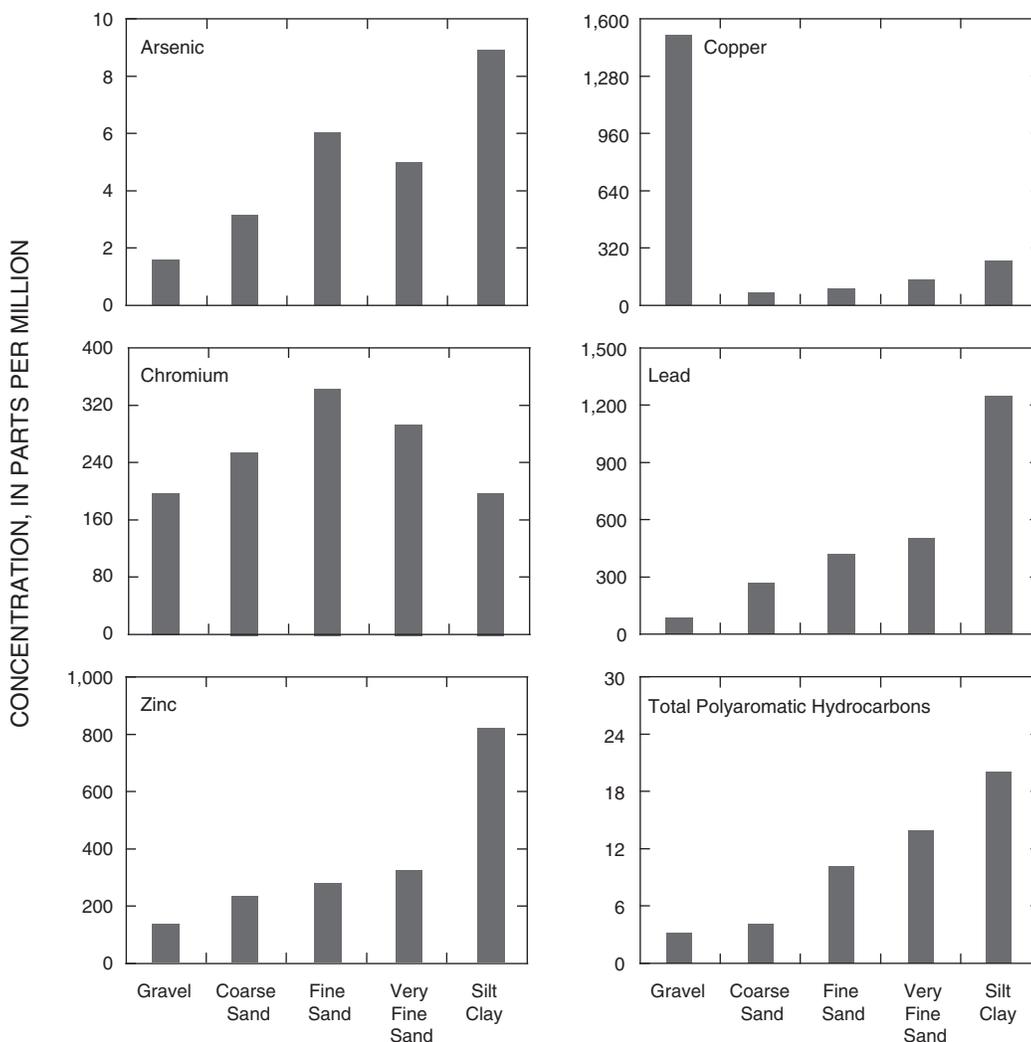


Figure 7. Total recoverable concentration of selected metals and total polyaromatic hydrocarbons (sum of parent polyaromatic hydrocarbons) measured in street dirt, by particle-size range, New Bedford, Massachusetts.

(even from sites near highways with relatively low traffic volumes). At many sites, elevated concentrations of street-dirt constituents were measured in tissues of species associated with aquatic sediments. It is useful, therefore, to compare these concentrations to aquatic-sediment guidelines, known as probable effects concentrations (PEC), above which adverse biological effects are likely to occur (Ingersoll, 2000). These guidelines exist for some of the elements tested, including cadmium (PEC equal to 4.98 ppm), chromium (111 ppm), copper (149 ppm), lead (128 ppm), nickel (22 ppm), and zinc

(459 ppm). Of these contaminants, total recoverable concentrations of chromium and nickel were greater than PECs for all particle-size ranges; concentrations of lead were greater than the PEC for all particle-size ranges with the exception of the largest (gravel); and concentrations of the other elements—cadmium, copper, and zinc—were higher in only the smallest particle-size range (silt and clay), with the exception of copper. Copper concentrations in the gravel fraction were also greater than the PEC for copper.

Table 3. Hierarchy of the relative solubility of trace elements commonly studied in highway runoff.

[From Breault and Granato, 2000. The percent dissolved of each constituent's total concentration decreases from left to right; the greater than symbol (>) indicates a difference of at least 10 percent between adjacent constituents; ≈ indicates a difference that is less than 10 percent. Cd, cadmium; Cr, Chromium; Cu, Copper; Ni, nickel; Pb, lead; Zn, zinc]

Highway-runoff study	Relative solubility
Dupuis and others, 1985	Cu>Cd≈Ni>Cr>Zn>Pb
Ellis and Revitt, 1982	Cd>Zn≈Cu>Pb
Gupta and others, 1981	Zn>Pb
Harrison and Wilson, 1985	Cd>Cu>Pb
Laxen and Harrison, 1977	Cd>Zn>Pb
Legret and Paggoto, 1999	Zn≈Cu>Cd>Pb
Legret and others, 1995	Zn>Ni>Cd>Cu>Cr>Pb
Marsalek and others, 1997	Ni≈Zn>Cu
Morrison and others, 1990	Cd>Zn>Cu>Pb
Morrison and Florence, 1990	Cd>Zn>Cu>Pb
Morrison and others, 1987	Cd>Zn>Cu>Pb
Morrison and others, 1984	Zn>Cd>Cu>Pb
Revitt and others, 1990	Cu>Zn>Cd>Pb
Revitt and Morrison, 1987	Cd≈Zn>Cu>Pb
Sansalone and Buchberger, 1997	Zn>Cu>Cd>Pb
Sansalone and others, 1995	Cr>Cd>Cu≈Zn>Pb
Schiffer, 1989	Ni≈Zn>Cu>Pb
Speiran, 1998	Zn>Cu>Pb
Yousef and others, 1985 (runoff)	Cd≈Cu>Cr>Zn≈Ni>Pb
Yousef and others, 1985 (pond)	Zn≈Cu>Cd≈Ni>Pb≈Cr
Yousef and others, 1984	Ni>Zn>Cu>Cd>Cr>Pb

Polyaromatic Hydrocarbons

A total of 30 parent PAHs were tested, and 27 parent PAHs were detected in street-dirt samples (table 4). Only a few parent PAHs and alkyl homologs (C1 and C2 isomers) were not detected, including 1,2-dimethylnaphthalene, 2,3,6-trimethylnaphthalene, and 2-ethylnaphthalene. The C3, C4, and C5 isomers were not detected, with the exception of C3-alkylated naphthalenes. PAH concentrations also increased with decreasing particle size, with a few exceptions. Redistribution during wet-sieving of PAHs between phases and particle-size ranges is unlikely because of the hydrophobic nature of most PAHs.

A total of four PAHs had measured concentrations greater than their respective exposure-based guidelines, all of which are 700 ppb (Massachusetts Department of Environmental Protection, 1996; method 2, soil category S-1). In particular, benzo[*a*]anthracene and indeno[1,2,3-*cd*]pyrene concentrations associated with the silt and clay particle-size range (or smaller than 63 μm) were greater than the exposure-based guidelines by 1.5 times and 1.9 times, respectively. Benzo[*a*]pyrene concentrations associated with the silt and clay and very fine sand fractions (125 to 63 μm) were greater than exposure-based guidelines by 1.4 times and 2.0 times, respectively. Benzo[*b*]fluoranthene concentrations associated with silt and clay, very fine sand, and fine sand (250 to 125 μm) were greater than exposure-based guidelines by 1.2, 1.8, and 2.7 times, respectively. Estimated PAH concentrations for the whole sample composed of gravel (22 percent), coarse sand (44 percent), fine sand (20 percent), very fine sand (9 percent), and silt and clay (6 percent) indicate that only one PAH, benzo[*b*]fluoranthene, is likely to be present in concentrations that approximate its exposure-based guideline (about 80 percent). Concentrations of all other individual PAHs tested are likely to be less than their respective exposure-based guidelines. These data indicate that, when taken as a whole, direct contact with or incidental ingestion of PAHs from street dirt may present little risk to human health, whereas contact with or ingestion of dirt within specific particle-size ranges, especially silts and clays, may represent a threat to human health. Moreover, silts and clays are most likely to pass through structural BMPs and be deposited in rivers, streams, and estuaries, where PAHs associated with silts and clays may pose a threat to aquatic organisms, or enter the food chain, where they may be concentrated by bioaccumulation. Total PAH concentrations (sum of acenaphthylene, acenaphthene, dibenzo[*a,h*]anthracene, anthracene, benzo[*a*]anthracene, benzo[*a*]pyrene, chrysene, fluoranthene, fluorene, naphthalene, phenanthrene, and pyrene) were all below the PEC for total PAHs (22.8 ppm) for all particle-size ranges tested.

Table 4. Polyaromatic hydrocarbon concentrations and ratios of selective parent and alkyl polyaromatic hydrocarbons by particle size measured in street dirt collected in an area of predominantly multifamily homes in the city of New Bedford, Massachusetts.

[Concentrations are in parts per billion. **Gravel:** Larger than 2.0 millimeters. **Coarse sand:** Smaller than 2.0 millimeters, larger than or equal to 250 micrometers. **Fine sand:** Smaller than 250 micrometers, larger than or equal to 125 micrometers. **Very fine sand:** Smaller than 125 micrometers, larger than or equal to 63 micrometers. **Silt and clay:** Smaller than 63 micrometers, An/178, ratio of anthracene to anthracene plus phenanthrene; Fl/Fl+Py ratio of fluoranthene to fluoranthene plus pyrene; BaA/228, ratio of benzo[*a*]anthracene to benzo[*a*]anthracene plus triphenylene (not measured in this study) plus chrysene; IP/IP+Bghi, ratio of indeno[1,2,3-*cd*]pyrene to indeno[1,2,3-*cd*]pyrene plus benzo[*ghi*]perylene; C0/C0+C1 (P/A), ratio of phenanthrene plus anthracene to phenanthrene plus anthracene plus C1-178 isomers; C0/C0+C1 (F/P), ratio of fluoranthene plus pyrene to fluoranthene plus pyrene plus C1-202 isomers; e, estimated; <, actual value is less than value shown; --, not done]

Polyaromatic hydrocarbons and ratios	Gravel	Coarse sand	Fine sand	Very fine sand	Silt and clay	Spike (percent recovery)	Blank
1,2-dimethylnaphthalene	<10	<12	<12	<13	<85	64	< 10
1,6-dimethylnaphthalene	<10	e7.1	e6.6	e11	<85	68	< 10
1-methyl-9 <i>H</i> -fluorene	e6.7	e8.2	e10	17	e30	55	< 10
1-methylphenanthrene	26	33	54	89	100	67	< 10
1-methylpyrene	31	29	43	65	150	78	< 10
2,3,6-trimethylnaphthalene	<10	<12	<12	<13	<85	66	< 10
2,6-dimethylnaphthalene	e9.3	e9.6	e9.4	15	e50	68	< 10
2-ethylnaphthalene	<10	<12	<12	<13	<85	69	< 10
2-methylantracene	17	22	24	39	93	64	< 10
4,5-methylenephenanthrene	36	48	87	140	122	54	< 10
9 <i>H</i> -Fluorene	17	31	46	73	e64	54	< 10
Acenaphthene	e9.1	25	31	52	e33	56	< 10
Acenaphthylene	11	37	45	76	190	59	< 10
Anthracene	49	84	120	200	310	65	e2.8
Benzo[<i>a</i>]anthracene	220	220	450	690	1,020	85	< 10
Benzo[<i>a</i>]pyrene	160	250	580	960	1,400	66	< 10
Benzo[<i>b</i>]fluoranthene	e140	e330	840	1,250	1,870	77	< 10
Benzo[<i>e</i>]pyrene	120	220	490	760	1,400	70	< 10
Benzo[<i>g,h,i</i>]perylene	110	130	390	716	1,230	70	< 10
Benzo[<i>k</i>]fluoranthene	e330	e260	720	1,080	1,700	74	< 10
C1-128 isomers, methylated naphthalenes	e13	e30	e26	e53	e91	--	< 10
C1-178 isomers, methylated phenanthrene/ anthracenes	e160	e200	e310	e520	e640	--	< 10
C1-202 isomers, methylated fluoranthene/pyrenes	e380	e340	e620	e980	e1,520	--	< 10
C1-228 isomers, methylated benzo[<i>a</i>]anthracene/ chrysenes	e240	e190	e360	e620	e1,090	--	< 10
C1-252 isomers, C1-methylated benzopyrene/ perylene	<300	e260	e450	e800	e1,510	--	< 10
C2-128 isomers, C2-alkylated naphthalenes	e31	e47	e42	e74	e190	--	< 10
C2-178 isomers, C2-alkylated phenanthrene/ anthracenes	e160	e140	e210	e360	e600	--	< 10
C2-202 isomers, C2-alkylated fluoranthene/pyrenes	e270	e280	e530	e930	e1,560	--	< 10
C2-228 isomers, C2-alkylated benzo[<i>a</i>]anthracene/ chrysenes	e110	e94	e130	e250	e590	--	< 10
C2-252 isomers, C2-alkylated benzopyrene/ perylene	<240	e190	e320	e630	e1,230	--	< 10
C3-128 isomers, C3-alkylated naphthalenes	e47	e75	e78	e120	e260	--	< 10
C3-178 isomers, C3-alkylated phenanthrene/ anthracenes	<110	<90	<110	<180	<450	--	< 10
C3-202 isomers, C3-alkylated fluoranthene/pyrenes	<180	<160	<260	<480	<900	--	< 10
C3-228 isomers, C3-alkylated benzo[<i>a</i>]anthracene/ chrysenes	<150	<110	<145	<300	<700	--	< 10

Table 4. Polyaromatic hydrocarbon concentrations and ratios of selective parent and alkyl polyaromatic hydrocarbons by particle size measured in street dirt collected in an area of predominantly multifamily homes in the city of New Bedford, Massachusetts.
—Continued

[Concentrations are in parts per billion. **Gravel:** Larger than 2.0 millimeters. **Coarse sand:** Smaller than 2.0 millimeters, larger than or equal to 250 micrometers. **Fine sand:** Smaller than 250 micrometers, larger than or equal to 125 micrometers. **Very fine sand:** Smaller than 125 micrometers, larger than or equal to 63 micrometers. **Silt and clay:** Smaller than 63 micrometers, An/178, ratio of anthracene to anthracene plus phenanthrene; FI/FI+Py ratio of fluoranthene to fluoranthene plus pyrene; BaA/228, ratio of benzo[*a*]anthracene to benzo[*a*]anthracene plus triphenylene (not measured in this study) plus chrysene; IP/IP+Bghi, ratio of indeno[1,2,3-*cd*]pyrene to indeno[1,2,3-*cd*]pyrene plus benzo[*ghi*]perylene; C0/C0+C1 (P/A), ratio of phenanthrene plus anthracene to phenanthrene plus anthracene plus C1-178 isomers; C0/C0+C1 (F/P), ratio of fluoranthene plus pyrene to fluoranthene plus pyrene plus C1-202 isomers; e, estimated; <, actual value is less than value shown; --, not done]

Polyaromatic hydrocarbons and ratios	Gravel	Coarse sand	Fine sand	Very fine sand	Silt and clay	Spike (percent recovery)	Blank
C3-252 isomers, C3-alkylated benzopyrene/ perylenes	<140	<85	<140	<290	<610	--	< 10
C4-128 isomers, C4-alkylated naphthalenes	<25	<30	<50	<75	<165	--	< 10
C4-178 isomers, C4-alkylated phenanthrene/ anthracenes	<55	<45	<55	<95	<230	--	< 10
C4-202 isomers, C4-alkylated fluoranthene/pyrenes	<150	<130	<210	<420	<880	--	< 10
C4-228 isomers, C4-alkylated benzo[<i>a</i>]anthracene/ chrysenes	<85	<60	<120	<210	<450	--	< 10
C4-252 isomers, C4-alkylated benzopyrene/ perylenes	<80	<55	<65	<165	<380	--	< 10
C5-128 isomers, C5-alkylated naphthalenes	<50	<55	<75	<130	<200	--	< 10
C5-178 isomers, C5-alkylated phenanthrene/ anthracenes	<130	<110	<150	<280	<660	--	< 10
C5-202 isomers, C5-alkylated fluoranthene/pyrenes	<50	<45	<55	<120	<330	--	< 10
C5-228 isomers, C5-alkylated benzo[<i>a</i>]anthracene/ chrysenes	<80	<60	<85	<190	<470	--	< 10
C5-252 isomers, C5-alkylated benzopyrene/ perylenes	<65	<60	<190	<380	<650	--	< 10
Chrysene	320	360	770	1,250	1,910	77	< 10
Dibenzo[<i>a,h</i>]anthracene	59	54	120	130	330	74	< 10
Fluoranthene	570	710	1,750	2,550	2,960	76	< 10
Indeno[1,2,3- <i>c,d</i>]pyrene	94	180	480	440	1,330	77	< 10
Naphthalene	<10	13	15	30	<85	64	< 10
<i>p</i> -cresol	e17	17	e17	e25	<85	e0	< 10
Perylene	<10	57	130	140	320	69	< 10
Phenanthrene	267	412	785	1,200	1,150	62	< 10
Phenol	23	39	51	79	380	57	e15.5
Pyrene	450	550	1,150	1,950	2,300	80	< 10
nitrobenzene-d5-surrogate (percent recovery)	115	96	96	109	87	66	74.13
2-fluorobiphenyl-surrogate (percent recovery)	66	115	64	74	67	60	58.64
terphenyl-d14-surrogate (percent recovery)	112	56	109	105	116	90	81.08
An/178	.16	.17	.13	.14	.21	--	--
FI/FI+Py	.56	.57	.60	.57	.56	--	--
BaA/228	.41	.39	.37	.36	.35	--	--
IP/IP +Bghi	.47	.58	.55	.38	.52	--	--
C0/C0+C1 (P/A)	.66	.71	.74	.73	.69	--	--
C0/C0+C1 (F/P)	.73	.79	.82	.82	.78	--	--

The ratios of certain PAH compounds provide information on the sources of PAHs. Ratios of PAH compounds examined in this study were similar to ratios of PAH compounds reported in other studies for street-dirt samples. For example, Yunker and others (2002) reported the ratio of anthracene to anthracene plus phenanthrene (An/178) is typically 0.18 in street dirt. The An/178 ratios calculated in this study ranged from 0.13 to 0.21 for the particle-size ranges tested, and averaged 0.16 (table 4). The ratios of fluoranthene to fluoranthene plus pyrene (Fl/Fl+Py); benzo[*a*]anthracene to benzo[*a*]anthracene plus triphenylene (not measured in this study) plus chrysene (BaA/228); and indeno[1,2,3-*cd*]pyrene to indeno[1,2,3-*cd*]pyrene plus benzo[*ghi*]perylene (IP/IP +Bghi) have also been used to characterize street dirt. The Fl/Fl+Py, BaA/228, and IP/IP +Bghi ratios measured in this study averaged about 0.57, 0.37, and 0.50, respectively, compared to 0.42 and 0.13 measured by Rogge and others (1993) and 0.51 measured by Wakeham (1996) for street dirt. An/178 (0.10), Fl/Fl+Py (0.57), BaA/228 (0.37), and IP/IP +Bghi (0.55) ratios measured in dirt swept from the Southeast Expressway, Boston, MA (K.P. Smith, U.S. Geological Survey, unpub. data., 1999), were also similar to those measured in this study.

In addition, the ratio of selective parent PAHs to the sum of parent PAHs plus C_1 alkyl homologs (C_0/C_0+C_1) of the phenanthrene/anthracene (P/A) and fluoranthene/pyrene (F/P) series have been used to characterize street dirt (Yunker and

others, 2002). C_0/C_0+C_1 P/A values and C_0/C_0+C_1 F/P ratios measured by this study averaged about 0.71 and 0.80, respectively (table 4). These ratios are similar to those measured by Rogge and others (1993) for street dirt (0.76 P/A and 0.89 F/P). Physical and chemical processes, however, may degrade certain PAHs, which would change the ratios (O'Malley and others, 1996).

Street dirt, although likely a major source of PAHs in water, sediments, and biota collected from urban rivers and streams, is ultimately not the original PAH source. PAHs in street dirt originate from many sources including asphalt, motor oil, gasoline, tire particles, wood soot, and natural materials such as grass. It may be possible to identify the original PAH sources by means of characteristic PAH ratios. For example, a comparison of PAH ratios previously calculated for samples of asphalt, used motor oil, and tire particles (K.P. Smith, U.S. Geological Survey, unpub. data, 1999) to the corresponding ratios calculated for street dirt (table 5) shows that some of the ratios of PAHs in street dirt closely resemble those measured in asphalt and used motor oil. More research would be needed to definitively identify the sources of PAHs in street dirt.

Table 5. Element and polyaromatic hydrocarbon concentrations and ratios of selective parent and alkyl polyaromatic hydrocarbons in five constituents of swept street dirt.

[**Street dirt:** Data collected from Southeast Expressway, Boston, MA (K.P. Smith, U.S. Geological Survey, unpub. data, 1999). An/178, ratio of anthracene to anthracene plus phenanthrene; FI/FL+Py ratio of fluoranthene to fluoranthene plus pyrene; BaA/228, ratio of benzo[*a*]anthracene to benzo[*a*]anthracene plus triphenylene (not measured in this study) plus chrysene; IP/IP+Bghi, ratio of indeno[1,2,3-*cd*]pyrene to indeno[1,2,3-*cd*]pyrene plus benzo[*ghi*]perylene; C0/C0+C1 (P/A), ratio of phenanthrene plus anthracene to phenanthrene plus anthracene plus C1-178 isomers; C0/C0+C1 (F/P), ratio of fluoranthene plus pyrene to fluoranthene plus pyrene plus C1-202 isomers. ppb, parts per billion; ppm, parts per million; <, actual value is less than value shown; --, not done]

Constituent	Sand	Used motor oil	Transmission fluid	Asphalt	Tire particles	Street dirt
Inorganic elements						
Aluminum, in percent	1.8	1.3	4.9	2.3	<0.1	3.5
Cadmium, in ppm	<3.5	19	<2.4	<3.4	<3.4	5.2
Chromium, in ppm	26	26	<17	33	<31	190
Copper, in ppm	22	180	<15	160	59	700
Iron, in percent	2.7	.14	6.3	4.5	.05	7.5
Lead, in ppm	51	180	22	200	26	670
Manganese, in ppm	760	1,200	600	1,950	<87	1,140
Nickel, in ppm	<57	<40	<39	<56	<56	100
Zinc, in ppm	<1,000	26,500	1,270	1,040	7,190	2,220
Polyaromatic hydrocarbons						
Acenaphthene, in ppb	<3,800	<8,800	<7,600	<3,800	140	73
Acenaphthylene, in ppb	<3,800	<8,800	<7,600	<3,800	1,230	42
Anthracene, in ppb	<3,900	650,000	<7,800	98	530	180
Benzo[<i>a</i>]anthracene, in ppb	<4,700	241,000	<9,500	248	<4,800	626
Benzo[<i>a</i>]pyrene, in ppb	<5,500	<12,700	<11,000	<5,500	26,000	740
Benzo[<i>b</i>]fluoranthene, in ppb	<6,000	<13,700	<11,900	780	<6,000	1,060
Benzo[<i>g,h,i</i>]perylene, in ppb	49	48,600	<12,000	400	1,300	290
Benzo[<i>k</i>]fluoranthene, in ppb	<6,400	829,000	<12,800	<6,400	<6,400	740
Chrysene, in ppb	<5,200	260,000	<10,400	1,350	<5,300	1,080
Dibenzo[<i>a,h</i>]anthracene, in ppb	<6,600	<15,000	<13,000	<6,600	<6,600	<6,600
Fluoranthene, in ppb	<4,600	340,000	<9,200	370	11,530	2,090
Fluorene, in ppb	<4,000	<9,000	<8,000	<4,000	720	150
Indeno[1,2,3- <i>c,d</i>]pyrene, in ppb	<5,900	24,400	<11,800	<5,900	13,800	360
Naphthalene, in ppb	<4,000	1,236,000	<8,000	<4,000	1,200	<4,000
Perylene, in ppb	<4,400	320,000	<8,800	760	94,000	1,550
Phenanthrene, in ppb	<4,500	697,000	<8,000	1,140	12,800	1,500
An/178	--	.48	--	.08	.04	.10
FI/FL+Py	--	.51	--	.32	.11	.57
BaA/228	--	.48	--	.16	--	.37
IP/IP+Bghi	--	.33	--	--	.91	.55

Street-Sweeper Efficiencies

The overall average street-sweeper efficiency, determined as a particle-size-weighted average, ranged from 20 to 31 percent for the mechanical sweeper and from 60 to 92 percent for the vacuum sweeper (table 6). These ranges are somewhat larger when each particle-size range is considered—9 to 40 percent for the mechanical sweeper and 31 to 94 percent for the vacuum sweeper (table 6, fig. 8). Sixty-percent sweeper efficiency obtained for the vacuum sweeper was likely low because of the windy conditions during the experiment (wind likely blew away some portion of available dirt). Despite this potential source of error, the vacuum-sweeper efficiency was consistently greater than that of the mechanical sweeper, and their efficiency ranges did not overlap for any particle-size range (fig. 8). The vacuum sweeper was at least 1.6 and as much as 10 times more efficient than the mechanical sweeper for all particle-size ranges. Sweeper efficiencies are probably a function of street-dirt availability (total mass and location with respect to the curb) and the particle-size distribution and variations in sweeper operation and maintenance. Measured sweeper efficiencies, therefore, may reflect the controlled conditions used in this experiment rather than the true range of efficiencies that may occur as a function of these factors.

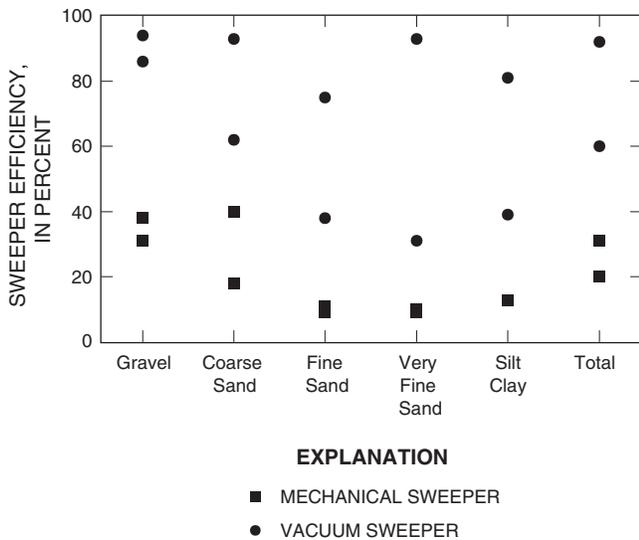


Figure 8. Street-sweeper efficiencies measured for the Pelican Series P mechanical sweeper and the Johnston 605 Series vacuum sweeper, New Bedford, Massachusetts.

Table 6. Results of street-sweeper efficiency experiments with a Pelican Series P mechanical sweeper and a Johnston 605 Series vacuum sweeper, by particle size.

[Street-sweeper efficiencies are given in percent. Particle-size distribution is given as percent retained. **Experiment 1a:** Done on 8-3-04. **Experiment 1b:** Done on 8-6-04. **Experiment 2a:** Done on 8-5-04. **Experiment 2b:** Done on 8-6-04. Weighted average is determined from the efficiency in each particle-size fraction]

Particle size	Mechanical		Vacuum	
	Experiment 1a	Experiment 1b	Experiment 2a	Experiment 2b
Sweeper efficiencies (percent)				
Gravel ¹	38	31	86	94
Coarse sand ²	40	18	62	93
Fine sand ³	9	11	38	75
Very fine sand ⁴	9	10	31	93
Silt and clay ⁵	13	13	39	81
Weighted average	31	20	60	92
Particle-size distribution (percent)				
Gravel ¹	28	37	32	24
Coarse sand ²	63	46	50	49
Fine sand ³	5	9	10	13
Very fine sand ⁴	2	4	4	8
Silt and clay ⁵	3	4	4	6

¹Gravel: Larger than 2.0 millimeters.

²Coarse sand: Smaller than 2.0 millimeters, larger than or equal to 250 micrometers.

³Fine sand: Smaller than 250 micrometers, larger than or equal to 125 micrometers.

⁴Very fine sand: Smaller than 125 micrometers, larger than or equal to 63 micrometers.

⁵Silt and clay: Smaller than 63 micrometers.

New Bedford's Street-Sweeping and Contaminant-Load Reduction Program

The city of New Bedford Department of Public Works is responsible for maintaining city streets and operating the street-sweeper program. As part of its sweeping program, the Department of Public Works records the volume of street dirt swept. For example, in 2004 city street sweepers swept about 2,500 m³ of street dirt, of which 10 percent was swept by the Pelican Series P mechanical sweeper and 90 percent by the Johnston 605 Series vacuum sweeper (Vincent Furtado, city of New Bedford Department of Public Works, oral commun.,

2004). This volume is equal to about 3.8 million kg of street dirt (with an assumed average density of 2.0 g/cm³; Pitt and others, 2004). Based on this information, the masses of dirt swept by the city's Pelican Series P mechanical sweeper and Johnston 605 Series vacuum sweeper during 2004 are about 10 and 90 percent of the total mass of swept dirt, respectively. Based on the assumption that the particle-size distribution and chemistry of samples collected from both types of street sweepers (tables 7 and 8) are representative of the city's street dirt, and that contaminant concentrations measured in swept street-dirt samples are representative of what is swept by each sweeper type (table 8), then the mass of contaminants removed by the city's street sweepers can be estimated:

$$M_i = \frac{\sum_{r=1}^2 M_{swept} \times P_r \times C_{i,r}}{1,000,000}$$

where

- M_i is equal to the mass of constituent i , in kilograms;
- M_{swept} is equal to the mass of swept dirt, in kilograms;
- P_r is equal to the percent of the total mass swept by sweeper type r ; and
- $C_{i,r}$ is equal to the concentration of constituent i measured in street dirt swept by sweeper type r , in milligrams per kilogram.

Table 7. Particle-size distribution of solids swept by the city of New Bedford by a Pelican Series P mechanical sweeper and a Johnston 605 Series vacuum sweeper.

[Particle-size distribution is given as percent retained]

Particle size	Mechanical	Vacuum
Gravel ¹	61	56
Coarse sand ²	26	31
Fine sand ³	6	5
Very fine sand ⁴	4	4
Silt and clay ⁵	2	4

¹Gravel: Larger than 2.0 millimeters.

²Coarse sand: Smaller than 2.0 millimeters, larger than or equal to 250 micrometers.

³Fine sand: Smaller than 250 micrometers, larger than or equal to 125 micrometers.

⁴Very fine sand: Smaller than 125 micrometers, larger than or equal to 63 micrometers.

⁵Silt and clay: Smaller than 63 micrometers.

Although estimating contaminant-load reductions realized by the city of New Bedford street-sweeping program was not part of the scope of the original study, information was available to estimate the mass of potentially toxic contaminants swept from city streets (fig. 9). Without an active street-sweeping program, these contaminants would likely end up in the municipal sewer system or treatment facility, or be carried into urban rivers and streams by runoff.

Table 8. Element and polyaromatic hydrocarbon concentrations measured in solids swept in the city of New Bedford, Massachusetts, by a Pelican Series P mechanical sweeper and a Johnston 605 Series vacuum sweeper.

[An/178, ratio of anthracene to anthracene plus phenanthrene; Fl/Fl+Py ratio of fluoranthene to fluoranthene plus pyrene; BaA/228, ratio of benzo[a]anthracene to benzo[a]anthracene plus triphenylene (not measured in this study) plus chrysene; IP/IP+Bghi, ratio of indeno[1,2,3-*cd*]pyrene to indeno[1,2,3-*cd*]pyrene plus benzo[ghi]perylene. %, percent; <, actual value is less than value shown; --, not done]

Constituent	Mechanical sweeper	Vacuum sweeper	Laboratory control sample (%)	Blank
Elements				
Antimony, in ppm	<0.38	0.68	97	<0.33
Arsenic, in ppm	1.1	<.76	100	<.67
Beryllium, in ppm	<.38	<.38	96	<.33
Cadmium, in ppm	1.8	1.6	96	<.33
Chromium, in ppm	35	35	95	<.33
Copper, in ppm	43	56	95	<1.33
Lead, in ppm	69	51	91	<.33
Mercury, in ppm	<.073	<.071	95	<.067
Nickel, in ppm	12	14	95	<.33
Selenium, in ppm	<.76	<.76	94	<.67
Silver, in ppm	<.38	<.38	82	<.33
Thallium, in ppm	<.14	<.14	86	<.13
Zinc, in ppm	100	120	97	<1.33
Polyaromatic hydrocarbons				
2-Methylnaphthalene	<550	<560	67	<50
Acenaphthene, in ppb	<550	<560	86	<50
Acenaphthylene, in ppb	<550	<560	93	<50
Anthracene, in ppb	<550	<560	93	<50
Benzo[a]anthracene, in ppb	1,500	1,100	83	<50
Benzo[a]pyrene, in ppb	1,400	<560	93	<50
Benzo[b]fluoranthene, in ppb	1,400	1,000	89	<50
Benzo[<i>g,h,i</i>]perylene, in ppb	<550	<560	131	<50
Benzo[<i>k</i>]fluoranthene, in ppb	1,500	1,400	79	<50
Chrysene, in ppb	1,600	1,400	80	<50
Dibenzo[<i>a,h</i>]anthracene, in ppb	<550	<560	67	<50
Fluoranthene, in ppb	3,100	2,700	93	<50
Fluorene, in ppb	<550	<560	102	<50
Indeno[1,2,3- <i>c,d</i>]pyrene, in ppb	<550	<560	110	<50
Naphthalene, in ppb	<550	<560	75	<50
Phenanthrene, in ppb	1,400	1,300	83	<50
Pyrene	4,700	3,900	73	<50
nitrobenzene-d5-surrogate (percent recovery)	--	--	72	90
2-fluorobiphenyl-surrogate (percent recovery)	--	--	80	92
terphenyl-d14-surrogate (percent recovery)	--	--	80	86
An/178	--	--	--	--
Fl/FL+Py	.40	.41	--	--
BaA/228	.48	.44	--	--
IP/IP+Bghi	--	--	--	--

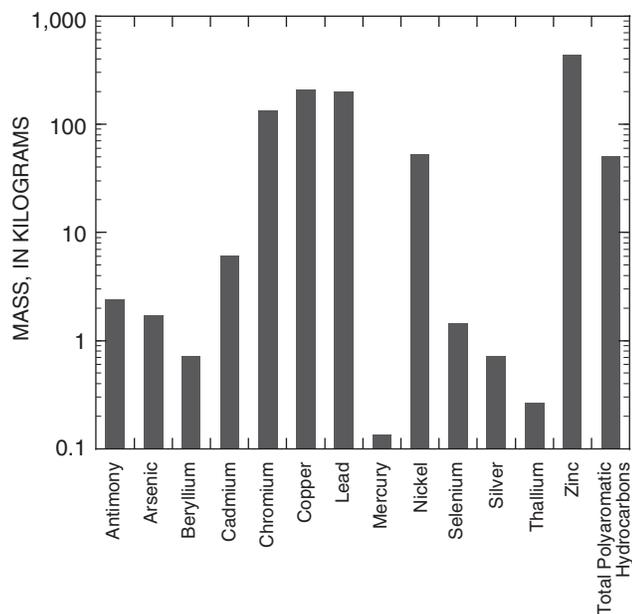


Figure 9. Estimated mass of selected metals and total polyaromatic hydrocarbons (sum of parent polyaromatic hydrocarbons) removed by street sweeping during 2004 by the city of New Bedford, Massachusetts.

Summary and Conclusions

Street-dirt-accumulation rates, street-dirt chemistry data, and street-sweeper efficiencies can be used to estimate the potential benefits gained by implementing a sweeping program. Existing information about sweeper efficiencies comes either from studies done in the late 1970s and early 1980s that focus mainly on older brush-type street sweepers or from manufacturers' reports on newer types of sweepers. Similarly, data on street-dirt-accumulation rates and chemistry also come primarily from these earlier studies, which include few done in the northeastern United States. Additional information on newer sweeping technologies and street-dirt-accumulation rates and chemistry for cities in Massachusetts may aid managers in the northeastern United States in determining the effectiveness of street sweeping as a water-quality-management tool.

To this end, the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), Massachusetts Department of Environmental Protection (MDEP), and the city of New Bedford Department of Public Works, undertook a study to evaluate street-dirt-accumulation rates, its chemical composition, and street-sweeping efficiencies in 2003 and 2004. Specifically, this study entailed three distinct field efforts: (1) measurement of street-dirt accumulation from two residential areas in the city

of New Bedford, Massachusetts, after specific time intervals; (2) collection of street dirt for analysis of chemical composition from these same two areas and from two street sweeper-types; and (3) controlled measurement of street-dirt removal efficiency for a Pelican Series P mechanical sweeper and a Johnston 605 series vacuum sweeper.

Although the study results are based on a limited number of samples, they provide useful information for city managers and water-resource managers tasked with improving urban waterways. Street-dirt accumulation experiments were repeated twice at two different street locations. Street-dirt chemical composition was determined in a sample collected from the same streets used in the street-dirt accumulation experiment and in the samples of street dirt collected by each of the two sweepers. Two controlled experiments of sweeper efficiency for each type of sweeper were also done. Other factors to consider in a more detailed study would include seasonality, temporal and spatial variability, and land use.

It is important to note that the most important result of this preliminary study is the similarity observed between this study's data and those collected by others from across the Nation. For example, average street-dirt-accumulation rates measured in this study (14 g/curb-m/d) are similar to those measured by others (9 to 15 g/curb-m/d); estimated total recoverable concentrations of arsenic (4 ppm), cadmium (0.9 ppm), chromium (261 ppm), copper (404 ppm), lead (335 ppm), nickel (31 ppm), and zinc (260 ppm) in street dirt collected in this study are for the most part similar to average concentrations of these contaminants measured by others; the average anthracene/anthracene plus phenanthrene PAH ratio of 0.16 calculated for street dirt collected from New Bedford is similar to the ratio of 0.18 calculated for street dirt collected by others; C_0/C_0+C_1 (phenanthrene/anthracene) and C_0/C_0+C_1 (fluoranthene/pyrene) ratios measured in this study (0.71 and 0.80) are similar to those measured by others (0.76 and 0.89); and the mechanical (20 to 31 percent) and vacuum (60 to 92 percent) sweeper efficiencies measured here are similar to the mechanical (10 to 30 percent) and vacuum (90 percent) sweeper efficiencies measured by others.

In addition, concentrations of trace elements and organic compounds measured in street dirt swept by the city of New Bedford may represent overall street-dirt chemistry for all land use areas within the city. The limited data collected indicate that, generally, trace element concentrations were lower than those measured in samples collected in the predominately multifamily land-use areas, whereas PAH concentrations were generally higher in the swept dirt. Data collected in this study indicate that New Bedford's street-sweeping program has removed about 3.8 million kilograms of street dirt, which contains potentially toxic chemicals such as trace metals and PAHs that may have otherwise ended up in the city's catch basins, treatment plants, and rivers and streams that receive urban runoff.

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