Effectiveness of Three Best Management Practices for Highway-Runoff Quality along the Southeast Expressway, Boston, Massachusetts

By Kirk P. Smith

Abstract

Best management practices (BMPs) near highways are designed to reduce the amount of suspended sediment and associated constituents, including debris and litter, discharged from the roadway surface. The effectiveness of a deep-sumped hooded catch basin, three 2-chambered 1,500-gallon oil-grit separators, and mechanized street sweeping in reducing sediment and associated constituents was examined along the Southeast Expressway (Interstate Route 93) in Boston, Massachusetts. Repeated observations of the volume and distribution of bottom material in the oil-grit separators, including data on particle-size distributions, were compared to data from bottom material deposited during the initial 3 years of operation. The performance of catch-basin hoods and the oil-grit separators in reducing floating debris was assessed by examining the quantity of material retained by each structural BMP compared to the quantity of material retained by and discharged from the oil-grit separators, which received flow from the catch basins. The ability of each structural BMP to reduce suspended-sediment loads was assessed by examining (a) the difference in the concentrations of suspended sediment in samples collected simultaneously from the inlet and outlet of each BMP, and (b) the difference between inlet loads and outlet loads during a 14-month monitoring period for the catch basin and one separator, and a 10-month monitoring period for the second separator. The third separator was not monitored continuously; instead, samples were collected from it during three visits separated in time by several months. Suspended-sediment loads for the entire study area were estimated on the basis of the long-term average annual precipitation and the estimated inlet and outlet loads of two of the separators. The effects of mechanized street sweeping were assessed by evaluating the differences between suspended-sediment loads before and after street sweeping, relative to storm precipitation totals, and by comparing the particle-size distributions of sediment samples collected from the sweepers to bottom-material samples collected from the structural BMPs. A mass-balance calculation was used to quantify the accuracy of the estimated sediment-removal efficiency for each structural BMP. The ability of each structural

BMP to reduce concentrations of inorganic and organic constituents was assessed by determining the differences in concentrations between the inlets and outlets of the BMPs for four storms. The inlet flows of the separators were sampled during five storms for analysis of fecal-indicator bacteria.

The particle-size distribution of bottom material found in the first and second chambers of the separators was similar for all three separators. Consistent collection of floatable debris at the outlet of one separator during 12 storms suggests that floatable debris were not indefinitely retained.

Concentrations of suspended sediment in discrete samples of runoff collected from the inlets of the two separators ranged from 8.5 to 7,110 mg/L. Concentrations of suspended sediment in discrete samples of runoff collected from the outlets of the separators ranged from 5 to 2,170 mg/L. The 14-month sediment-removal efficiency was 35 percent for one separator, and 28 percent for the second separator. In the combined-treatment system in this study, where catch basins provided primary suspended-sediment treatment, the separators reduced the mass of the suspended sediment from the pavement by about an additional 18 percent. The concentrations of suspended sediment in discrete samples of runoff collected from the inlet of the catch basin ranged from 32 to 13,600 mg/L. Concentrations of suspended sediment in discrete samples of runoff collected from the outlet of the catch basin ranged from 25.7 to 7,030 mg/L. The sediment-removal efficiency for individual storms during the 14-month monitoring period for the deep-sumped hooded catch basin was 39 percent.

The concentrations of 29 inorganic constituents in bottom sediments were typically higher for the size fraction less than 0.062 mm in diameter. Concentrations of total organic carbon (TOC) were similar for the size fraction less than 0.062 mm in diameter and the fraction greater than 2.00 mm in diameter. Concentrations of total polyaromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) were larger in the fraction greater than 2.00 mm in diameter than in the size fractions less than 2.00 mm in diameter. Since PAHs and PCBs are commonly associated with TOC (including organically coated sediment), it is believed that the PCB and PAH concentrations in the solid fraction less than 0.062 mm in diameter were similar to the concentrations in the solid fraction greater than 2.00 mm in diameter, if not greater because of the effects of the surface area.

The estimated annual suspended-sediment load for the entire study area was about 29,000 kg. Approximately 24,000 kg discharged directly to Malibu Beach and Tenean Beach embayments, and the remaining 5,000 kg discharged to the land surface. These loads do not include an estimated 2,000 kg of suspended sediment retained by the five oil-grit separators in the area.

Mechanized street sweepers were used on the pavement three times during the study. Samples of sweepings were collected each time for the analysis of particle size. The first mechanized street sweeping had no observable effect on subsequent storm loads of suspended sediment. Following the second sweeping, a net increase of the suspended-sediment load was observed at one station and a net decrease of the suspended-sediment load was observed at the second station. These effects, however, were only temporary. The third time the highway was swept was after continuous monitoring was terminated. The particle-size distribution in sweeper samples for the size fraction less than 4 mm in diameter was similar to the particle-size distribution in bottom sediment in the catch basin. The concentration of particles greater than 0.5 mm in diameter was higher in sweeper samples than in samples from the separators, so the sweepers were successful in removing the larger particles. Because the highway lacks curbing that would provide a physical boundary to trap debris and sediment, and the equipment was inefficient in trapping particles less than 0.062 mm in diameter, pavement sweeping provided few water-quality benefits for the Southeast Expressway.

The primary factor controlling the efficiency of each structural BMP in removing suspended sediment was retention time. Examination of constituent-sediment relations suggests that the retention time for many highway-related constituents was short; these constituents either were dissolved and not subject to treatment by simple gravity separation, or were associated with particles less than 0.062 mm in diameter, which commonly passed through the BMPs. Thus, the potential effectiveness of the separators and the catch basins to reduce loads of inorganic and organic constituents was much less than their ability to reduce loads of suspended sediment.

The average relative percent difference (RPD) between concentrations of trace metals in stormwater samples from the inlets and the outlets of the separators ranged from 15 to 30 percent. The average RPD for concentrations of organic constituents was commonly less than about 10 percent and negative in several cases. The separators did not affect the concentrations of dissolved solids as they passed through their chambers. The average RPD between the event mean concentrations for trace metals in samples collected from the inlet and outlet of the catch basin during storms was about 25 percent. The average RPD for concentrations of organic constituents was typically less than 20 percent and even negative in several cases, except for oil and grease, which was near 30 percent. The observed ranges of the RPDs for both types of BMPs were probably larger than the actual ranges because the particle-size and concentration of suspended sediment sampled in the BMP inflows during the four storms introduced a bias in favor of higher concentrations.

Concentrations of fecal and *Enterococci* bacteria were found throughout the storms at the inlets of the two continuously monitored separators; this result indicated that the pavement washoff process was inefficient or that there was a continuous source of bacteria in the drainage area. The efficiency of the structural BMPs tested in this study in reducing fecal-indicator bacteria concentrations was not quantified; each BMP chamber is likely to retain a quantity of fecal-indicator bacteria proportional to its storage volume after a storm. Removal of bacteria from the BMP is dependent on how well the bacteria survive until the next storm and the potential for bacterial export during the next storm.

INTRODUCTION

Suspended particulate matter transported from roadway surfaces represents one of the most substantial sources of non-point source pollution in highway runoff (Young and others, 1996). In addition to increasing turbidity and depositional loading, suspended sediment can retain and transport other pollutants to receiving water bodies. Roadway suspended-solid loads may be reduced by diverting storm flows through various structural end-of-pipe devices or by removing particulate matter from roadway surfaces prior to runoff transport (for example, source control). The effectiveness of these best management practices (BMPs) is limited by the general lack of information about the site-specific size distribution and quantity of the source material.

The U.S. Geological Survey (USGS), in cooperation with the Federal Highway Administration and the Massachusetts Highway Department (MassHighway), began a study in November 1998 to determine the effectiveness of current BMPs in reducing suspended-solid loads and related constituents along the Southeast Expressway (Interstate Route 93) in Boston, Massachusetts. The Southeast Expressway is typical of heavily used highways within urban and industrialized areas, although it passes through the coastal zone watersheds of Dorchester Bay in Boston. In 1994, the Expressway was modified to provide a moveable "zipper barrier" to increase traffic flow in the peak direction. This zipper barrier consisted of cast-concrete barriers connected to one another and mechanically moved by a specialized machine to create an additional travel lane. During this time, in an effort to remove oils and grit (sand- and gravel-size particles) from highway runoff, five off-line oil-grit separators (commonly referred to as water-quality inlets) were integrated into the primary drainage system of the highway adjacent to Dorchester Bay.

The BMPs examined in this study include a deep-sumped hooded catch basin, three 1,500-gal off-line oil-grit separators, and mechanized sweeping. The effectiveness of each structural BMP was estimated by monitoring the quality and quantity of stormwater at the inlet and outlet of each device. At the end of the monitoring period, each device was drained and the captured material was measured and quantified. Street-sweeping effectiveness was evaluated by examining the differences in suspended-sediment loads in highway runoff before and after storms relative to precipitation amounts and antecedent periods, and by comparing the size distribution of sediment collected from the street sweeper to bottom sediments collected in the catch basin and the separators. These monitoring results will provide state and local highway planners with specific information regarding the current quality and quantity of highway runoff from major urban highways in the northeastern United States, and the scientific basis for future consideration and application of these BMPs. Monitoring methods developed during this study may be useful for assessing the effectiveness of new BMPs.

This report describes the effectiveness of each BMP along the Southeast Expressway in reducing suspended-sediment loads, debris loads, and chemical and biological loads in highway runoff. It also describes the physiochemical characteristics of structural BMP bottom materials, the estimated suspended-solid loads for the study area, and documents the monitoring methods by which the effectiveness of each BMP was estimated. These results are based on highway-runoff data collected from November 1998 through June 2000.

Description of Study Area and Highway-Drainage Systems

The study area comprised 2.2 mi of Interstate 93 from the Neponset River to Savin Hill in Boston (fig. 1). This section of highway, including ramps, covers about 35 acres. About 1.5 mi of this eight-lane highway crosses the Neponset drainage basin and 0.7 mi crosses the Boston Harbor Coastal subbasin. Within the study area, 209 catch basins provide primary treatment for highway stormwater runoff; also included is one 3-chamber 4,500-gal off-line oil-grit separator and four 2-chamber 1,500-gal off-line oil-grit separators. Highway runoff collected by the catch basins is either discharged to the local land surface or to a separator through a concrete or steel drainage pipe. Highway runoff from 26.4 acres discharges through the structural BMPs to the embankment along the Malibu Beach and Tenean Beach embayments. Runoff from the remaining 8.2 acres infiltrates into the ground.

Catch basins are circular concrete containers below the highway with steel grates at the pavement surface. The sumps (that is, storage area below the outlet pipe) of 184 catch basins are 4 ft deep, and the remaining 25 are 3 ft deep. Hinged cast-iron hoods, intended to retain floatable debris at the water surface, are loosely fitted over the sump outlet of most catch basins. The hoods encapsulate the entire outlet opening and extend about 0.5 ft below the bottom of the outlet.

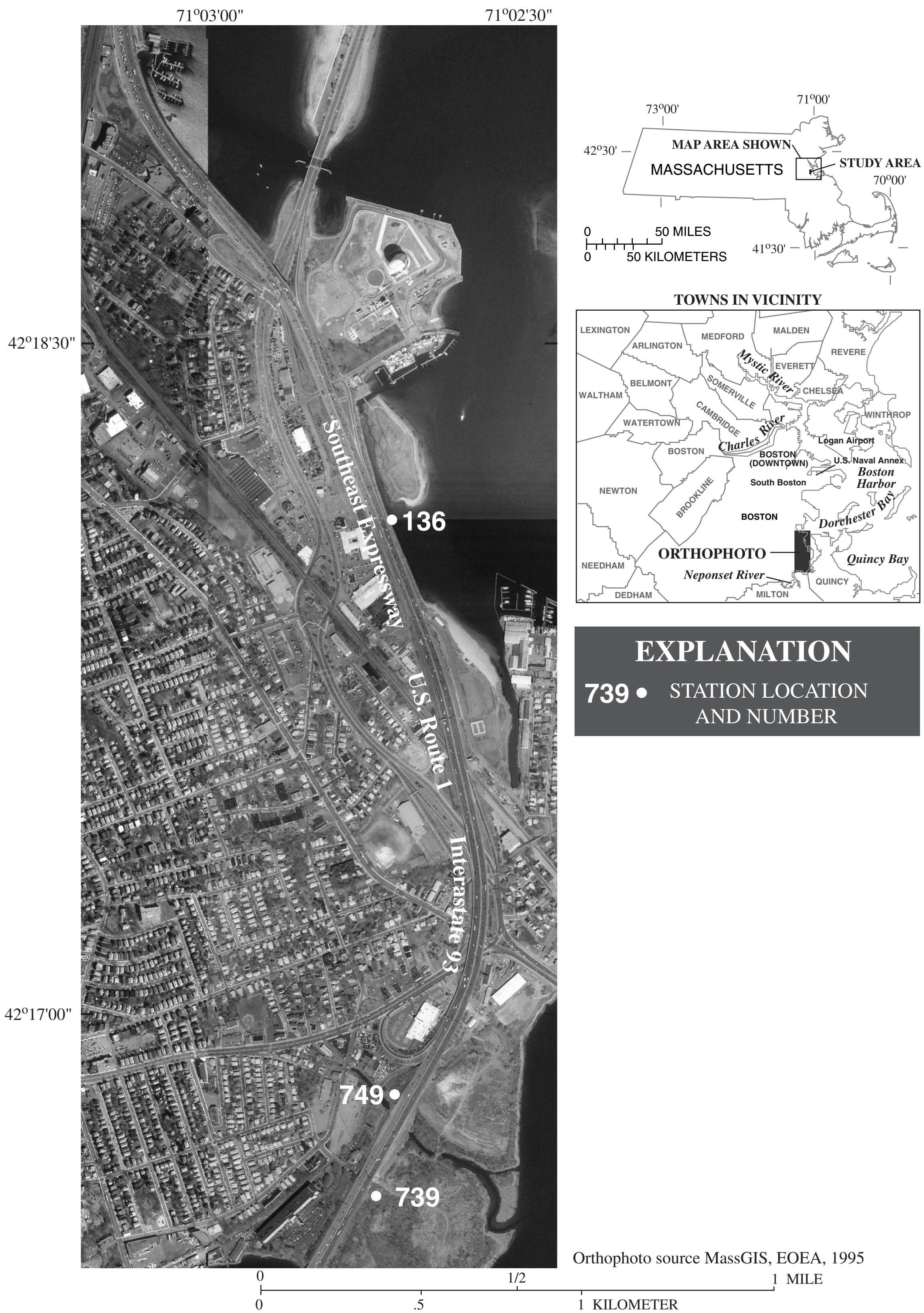

Figure 1. Study area where best management practices were tested, Southeast Expressway, Boston, Massachusetts.

Oil-grit separators, large cast-concrete containers subdivided by one or more baffles, are buried next to the highway. They provide additional treatment of stormwater runoff by capturing suspended particulate matter, oil and grease, and floatable debris (fig. 2). A hood or an inverted elbow was not installed over the outlet of the second chamber of the separators. A baffle separated the primary chamber from the secondary chamber, and contained three circular 12-in. outlets 1.5 ft from the chamber floor. Each separator included a bypass pipe that carried flow past the device during intense runoff by use of a diversion weir placed near the inlet of the separator. Although this design feature allows untreated stormwater to bypass the separator, it theoretically prevents extreme flows from flushing captured materials from the separator. Stormwater runoff from as many as 6 to 26 catch basins was diverted through the five separators. Highway runoff diverted through the 3-chamber 4,500-gal separator and two 2-chamber 1,500-gal separators is discharged to the embankments of Malibu Beach and Tenean Beach embayments, and runoff from the other two 2-chamber 1,500-gal separators is discharged to land near a small tributary of the Neponset River.

The highway does not have a breakdown lane; however, it does have three emergency pull-off areas. Beyond the edge of pavement, which begins beneath the guard rail, the ground consists of loosely packed sandy-loam with sparse vegetation cover. Granite curbstone lines the ramps; but in most cases, there is either no curb along the highway, or the curb is buried and the material at the edge of the pavement is able to erode onto the roadway during storms. Concrete barrier walls are installed on overpasses and separate the pavement from the areas with steep embankments and curves.

The three 1,500-gal separators evaluated during the study were designated sites 136-01, 739-01, and 749-01 (fig. 3). The first three digits refer to the surveyed highway reference points (stations). The outflow and inflow monitoring and sampling point designations of each separator consisted of the same prefix followed by –02 and –03, respectively. The deep-sumped hooded catch basin is within the drainage area of the separator 136-01 and was designated as site 136-06. The outflow and inflow monitoring and sampling point designations of the catch basin consisted of the same prefix followed by –04 and –05, respectively. All drainage pipes are 1 ft in diameter and accessible through manholes. The three separators are located about 5 ft from the right edge of pavement. Site-specific details for each structural BMP are listed in table 1. The greatest difference between the drainage areas of the five separators is the size and the number of catch basins. Only the separators at monitoring sites 136 and 739 were selected for continuous monitoring because the inlet manhole for the oil-grit separator at station 749 is in a travel lane, and the remaining two are periodically subjected to tidal action from Dorchester Bay. The catch basin at site 136 was selected for evaluation because the outlet pipe is isolated from the combined drainage infrastructure. Thus, the data from samples at this outlet could be compared to data from samples collected from the separator inlet.

Acknowledgments

Henry L. Barbaro of the Environmental Division and Thomas R. Lemisz of the Granite Avenue Maintenance Office provided planning and logistical support for MassHighway during this study, including periodic traffic control, structural BMP cleaning, and street sweeper sample collection. Paul D. Capel of the USGS developed a feasible and cost-effective sample-processing method for trace organic and inorganic constituents that was adapted for automatically collected highway runoff samples.

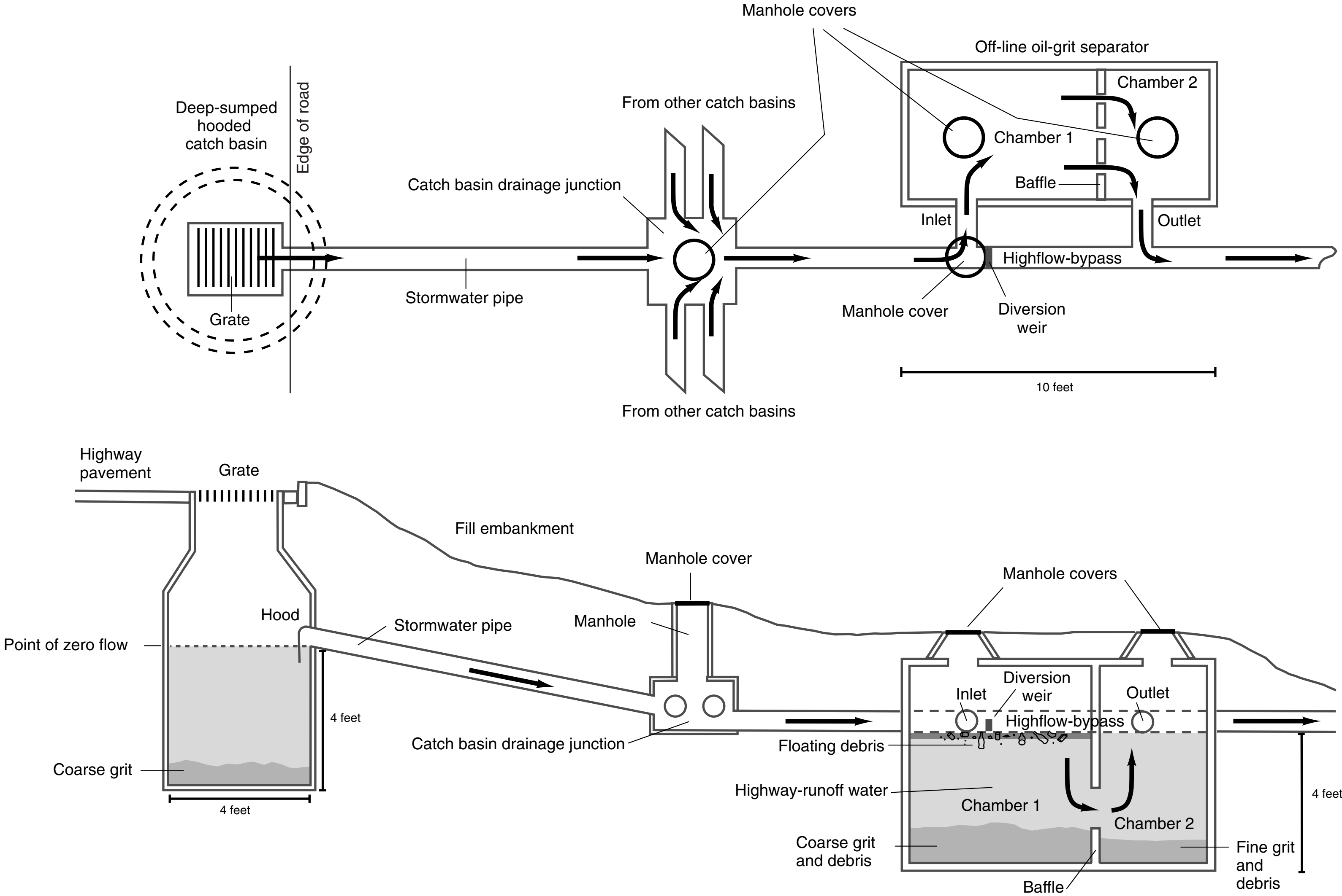

Figure 2. Schematic section of a deep-sumped hooded catch basin and a 1,500-gallon off-line oil-grit separator.

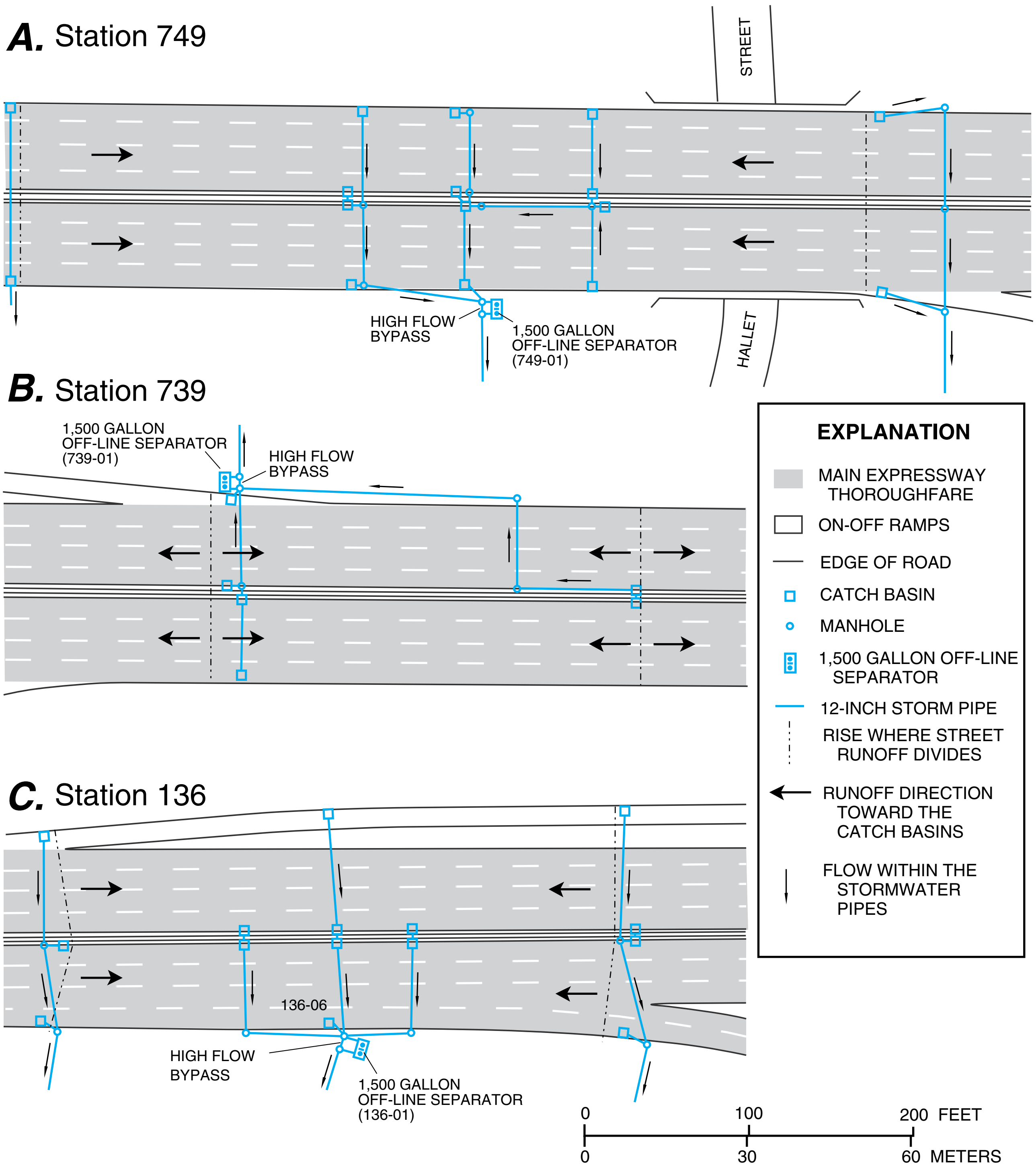

Figure 3. Actual drainage area of stations (*A*) 749, (*B*) 739, and (*C*) 136, along the Southeast Expressway, Boston, Massachusetts.

Table 1. Location and construction properties of selected structural best management practices, Southeast Expressway, Boston, Massachusetts

[**Latitude and longitude**: In degrees, minutes, and seconds. BMP, best management practice; ft, foot; na, not applicable; --,no data]

Station identifier	Latitude ° ′ ″	Longitude ° ′ ″	Total drainage area (acres)	Isolated shoulder perimeter (percent)	Number of catch basins	Median catch basin drainage area (acres)	Diversion weir height (ft)	Type of BMP
739-01	42 16 47	71 02 47	1.48	22	12	0.12	0.7	oil-grit separator
749-01	42 16 56	71 02 42	.73	6	6	.12	--	oil-grit separator
136-01	42 17 45	71 02 45	1.11	10	8	.10	.5	oil-grit separator
136-06	42 17 45	71 02 45	.23	6	1	na	na	deep-sumped hooded catch basin

METHODS FOR CONTINUOUS MONITORING OF HIGHWAY DRAINAGE

Automatic-monitoring techniques were used to characterize the temporal and spatial variability in water quality through two 1,500-gal separators and one deep-sumped hooded catch basin. Monitoring sites 136 and 739 were continuously monitored from April 1999 through June 2000, and August 1999 through June 2000, respectively. At each site, instruments automatically collected water samples and measured precipitation, air temperature, water level, flow velocity, turbidity, specific conductance, and water temperature in the structural BMP. Flow-proportional samples, which represent equal volumes of runoff, were collected for the analysis of suspended-sediment concentrations from the inlet and the outlet of each structural BMP at stations 136 and 739 during their respective monitoring periods. Flow-proportional composites were collected from the inlet and the outlet of each structural BMP during four storms and were analyzed for the event mean concentration (EMC) of chemical constituents. Discrete and EMC samples analyzed for concentrations of suspended sediment were used to estimate suspended-sediment loads and determine the effectiveness of each BMP in reducing suspended sediment and chemical concentrations. The frequency and spatial occurrence of fecal-indicator bacteria in highway runoff was determined by analyzing flow-proportional samples collected at the inlets of the two separators. Particles greater than 6 mm in diameter were collected at the outlet of station 739 during 12 storms to determine how effectively the separators were retaining large particles, particularly floatable debris. Precipitation was measured to estimate the total runoff of the drainage area for each station. Air temperature was measured to determine whether the precipitation was rain or snow. Water-level and flow-velocity data were used to estimate discharge to and from the structural BMPs. Turbidity was investigated as a surrogate for the concentration of suspended sediment. Water temperature was measured to correct conductivity values to 25˚C. Small saline flows containing high concentrations of dissolved solids associated with deicing compounds commonly used during the winter maintenance period caused large changes in the specific conductance of the water in each separator. The increase in the concentration of dissolved solids increased the density of the water and introduced errors to the measured water levels. A linear correction, estimated from measurements of specific conductance, was used to correct the water-level measurements.

Just prior to the monitoring period, each structural BMP was drained and cleaned with a vacuum truck, and visually inspected to ensure that the chambers were clean enough for an accurate mass balance calculation at the end of the study. The quantity of bottom material retained in separators 136-01 and 749-01 was assessed three times, and the quantity of bottom material retained in separator 739-01 was assessed four times during the project. Because the catch basin 136-06 was in a highway travel lane, it was not practical to routinely measure the quantity of bottom material. This BMP was assessed just once, at the end of the monitoring period. Samples for particle size and visual analysis were collected twice from each of the three separators and once from the catch basin to compare with water-quality samples and street-sweeper samples. Samples of bottom material were collected and analyzed for concentrations of chemical constituents twice at each of the three separators to determine chemical-sediment relations. Street-sweeper samples were collected and analyzed for particle size three times during the project. The quantity and type of samples collected are summarized in table 2.

Table 2. Quantity and type of samples collected, and location of water level, water-velocity, water-quality, meteorology, and physical measurements made at each structural best management practice, Southeast Expressway, Boston, Massachusetts

[Sample quantities do not include quality-assurance samples; C, continously monitored; (x), number of months]

Measurement or sample location	Water level	Velocity	Water temper-ature	Air temper-ature	Specific conductance	Turbidity	Precip-itation
Station 136	--	--	--	C(14)	--	--	C(14)
Oil-grit separator 136-01 (storage)	C(14)	--	C(14)	--	C(14)	--	--
Oil-grit separator 136-02 (outlet)	C(14)	C(14)	C(14)	--	C(14)	C(14)	--
Oil-grit separator 136-03 (inlet)	--	--	C(14)	--	C(14)	C(14)	--
Oil-grit separator 739 (bypass)	C(14)	C(14)	--	--	--	--	--
Catch basin 136-04 (outlet)	--	--	--	--	--	--	--
Catch basin 136-05 (inlet)	--	--	--	--	--	--	--
Catch basin 136-06 (sump)	C(14)	--	--	--	--	--	--
Station 739	--	--	--	--	--	--	C(10)
Oil-grit separator 739-01 (storage)	C(10)	--	C(10)	--	C(10)	--	--
Oil-grit separator 739-02 (outlet)	--	--	C(10)	--	C(10)	C(10)	--
Oil-grit separator 739-03 (inlet)	C(10)	C(10)	C(10)	--	C(10)	C(10)	--
Oil-grit separator 739 (bypass)	C(10)	C(10)	--	--	--	--	--
Oil-grit separator 749-01 (storage)	--	--	--	--	--	--	--

Measurement or sample location	Suspended sediment	Water quality	Bacteria	Bottom-material quantity	Bottom-material particle size	Bottom-material quality	Debris collection
Station 136	--	--	--	--	--	--	--
Oil-grit separator 136-01 (storage)	--	--	--	3	2	[1]2	--
Oil-grit separator 136-02 (outlet)	379	4	--	--	--	--	--
Oil-grit separator 136-03 (inlet)	379	4	4	--	--	--	--
Oil-grit separator 739 (bypass)	--	--	--	--	--	--	--
Catch basin 136-04 (outlet)	314	4	--	--	--	--	--
Catch basin 136-05 (inlet)	243	4	--	--	--	--	--
Catch basin 136-06 (sump)	--	--	--	1	1	--	--
Station 739	--	--	--	--	--	--	--
Oil-grit separator 739-01 (storage)	--	--	--	4	2	[1]2	--
Oil-grit separator 739-02 (outlet)	369	4	--	--	--	--	12
Oil-grit separator 739-03 (inlet)	465	4	5	--	--	--	--
Oil-grit separator 739 (bypass)	--	--	--	--	--	--	--
Oil-grit separator 749-01 (storage)	--	--	--	3	2	[1]2	--

[1]Two or more particle size ranges analyzed.

Design of Highway-Drainage Monitoring Stations

Instrumentation shelters with trap doors were installed over the distribution manhole next to each separator. Trap doors provided protective entry to the drainage-distribution system for probe and sample-line maintenance. Sites 136-01 and 136-06 were monitored from the same location and instrument bank. The instrumentation consisted of a Campbell Scientific Inc. (CSI) 23X datalogger as the measurement, control, and data-storage module. Because electric and phone lines were not readily available, two 60-amp hour batteries recharged by 30-watt solar panels were used to power the controller and other instruments. A CSI VS1 voice-data telephone modem and a cellular phone were used for telecommunications. The datalogger measured precipitation from an 8-in. Texas Electronics, Inc. tipping bucket rain gage and air temperature from a CSI 107 probe mounted at a height of 9 ft above ground surface. A CSI precipitation adapter was installed on each rain gage during the winter months to measure snow and ice quantities, as well as rainfall. Water level was measured by a KPSI series 173 submersible pressure transducer mounted within each structural BMP near the outlet and 2 ft below the point of zero flow (PZF). The PZF water level was controlled by the height of the outlet pipes (fig. 2). Two Marsh McBirney, Inc., submersible electromagnetic pressure sensors measured water velocity and level within each separator bypass pipe and the inlet of station 739 and the outlet pipe of station 136.

Water level, air temperature, and precipitation were measured at 1-minute intervals. Water-level measurements were used to determine whether to activate sensors for flow and water quality. During periods of little or no flow, when water level in the separator or catch basin was less than 0.02 ft above the PZF and there was no precipitation, all sensors were activated, measured, and recorded on a two-hour basis; during storms, however, the frequency of data recording and instrument activation for all sensors increased to 1-minute intervals. The dataloggers were programmed with these intervals to maximize the information about changes in stage, velocity, precipitation intensity, and water quality, and for the collection of water samples, while preventing collection of excess data at times of little or no flow. Data were usually retrieved via modem every two days.

Measurement of Discharge

Discharge measurements did not alter the capacity of the structural BMPs, or create artificial backwater conditions that could prevent suspended solids or bed-load materials from either entering or discharging from the structural BMPs. Continuous measurements of water level in each structural BMP indicated that the water level generally remained at or near the PZF; thus, it was assumed that any amount of inflow (not including bypass flow) displaced an equal amount of outflow.

Instantaneous discharge to and from the associated separators was calculated by one of two methods. During higher flows, an integrated electromagnetic velocity and level sensor measured pipe-flow velocity and water level. Using the velocity and level measurements and the physical dimensions of the measurement location, a flowmeter calculated discharge on the basis of the cross-sectional area of runoff at a given section of pipe and the associated mean velocity. Flowmeter measurements and flow calculations were transmitted to, and recorded by, the datalogger. An integrated electromagnetic velocity and level sensor was installed in the bypass pipe of each separator and in the inlet of station 739 and in the outlet pipe of station 136. Sensor placement differed between the two sites because of differences in the drainage-system construction. After installation, each flowmeter was calibrated to site-specific conditions on the basis of a known quantity of flow. Calibrated flow, created by pumping water with a 9,600-gal/hr centrifugal pump, was discharged upstream of the sensor location. Pump flow was measured by a Data Industrial flow sensor (series 200) inserted into an 8-ft long, 4-in.-diameter polyvinylchloride (PVC) pipe connected to the pump discharge. In addition to this calibration method and prior to the monitoring period, instantaneous stormwater flowmeter measurements were compared to flow measurements made simultaneously from a 12-in. Thelmar volumetric weir in conjunction with a WaterLog (H350-Lite) pressure transducer and a pneumatic bubble regulator upstream of the integrated sensor. The maximum difference between the two methods in the flow range of 0.1 to 0.45 ft^3/s was 0.04 ft^3/s. When the water depth at the flow sensor was less than 0.1 ft, flow values calculated by the flowmeter were not considered reliable because the velocity sensor was not fully submersed.

A second method to measure flow was needed during low flows because the flowmeter was not capable of calculating discharge when the integrated sensor lost contact with the water surface. Therefore, a stage/discharge relation based on the water level within the second chamber of the separator was used to compute flows. Each stage/discharge relation was developed during the pre-monitoring period by monitoring water levels in each separator while simultaneously monitoring flow with the volumetric weir and associated equipment. Volumetric measurements made from the separator outlet pipe were also used to develop and test the low-end stage/discharge rating.

Inflow to the catch basin was calculated by applying a stage/discharge relation to continuous water-level measurements made in the sump of the catch basin. This relation was developed by simultaneously measuring pump flow from the two 9,600-gal/hr centrifugal pumps, measuring flow from a 12-in. weir located downstream of the catch basin, and measuring catch-basin-sump level. Paired stage and discharge values were produced from a series of water-level measurements made after pump flow, weir flow, and catch-basin-sump level stabilized at multiple pumping rates over the range of the pumps. This process was repeated until both pumps were at the maximum setting. After stabilization occurred at the maximum setting, the process was repeated to the start point. The stage/discharge relation was based on 21 discrete discharge measurements and mathematically extended above the greatest flow rate (about 0.25 ft^3/s). The resultant stage/discharge relation sufficiently covered 83 percent of the peak discharges during the monitoring period.

Measurements of Turbidity, Specific Conductance, and Water Temperature

To reduce systematic error (error associated with sensor drift and fouling) and increase the ability to make measurements at water levels less than the physical submersion limit of the probes, a single Global (model WQ 700) turbidity sensor, and a single CSI (model 247) integrated specific conductance and water-temperature probe were used to measure alternating pump-activated streams of water from the inflow and outflow of each structural BMP. The respective sensors were installed in a self-draining-flow cell equipped with a debubbler pipe. A pipe tee combined the peristaltic-pump discharge tubes; mechanical closure of the silicon tubing in the pump head prevented back flow through the quiescent pump. A Data Industrial flow sensor (series 4000) was used to measure intermittent flow from the two peristaltic pumps (ISCO model 110). Pump intakes were mounted next to the automatic sampler intakes for sample uniformity. Pump-transport velocities were similar to those in the automatic samplers; therefore, in situ turbidity measurements in pumped water were technically similar to those in water samples collected by the automatic samplers.

During the first 2 hours of a runoff event, if flow was greater than or equal to 0.02 ft^3/s, the datalogger was programmed to start a 2-minute cycle: the inflow peristaltic pump was activated for a period of one and a half minutes, pump flow was measured and recorded by the inline flow meter, and specific conductance, water temperature, and turbidity were measured and recorded at the end of the pumping interval. The pumping interval provided enough time to exchange the volume of water within the flow cell several times. The flow cell was allowed to drain during the final 30 seconds of the 2-minute cycle. The cycle was then repeated by the use of the outlet peristaltic pump. Alternating 2-minute cycles of measurements of specific conductance, water temperature, and turbidity were made for a period of 2 hours; thereafter, cycles of measurement were made less frequently and proportional to flow to reduce battery-power consumption during extended operations. An example of water quality and stage data collected from this system for a separator at station 739 is shown in figure 4.

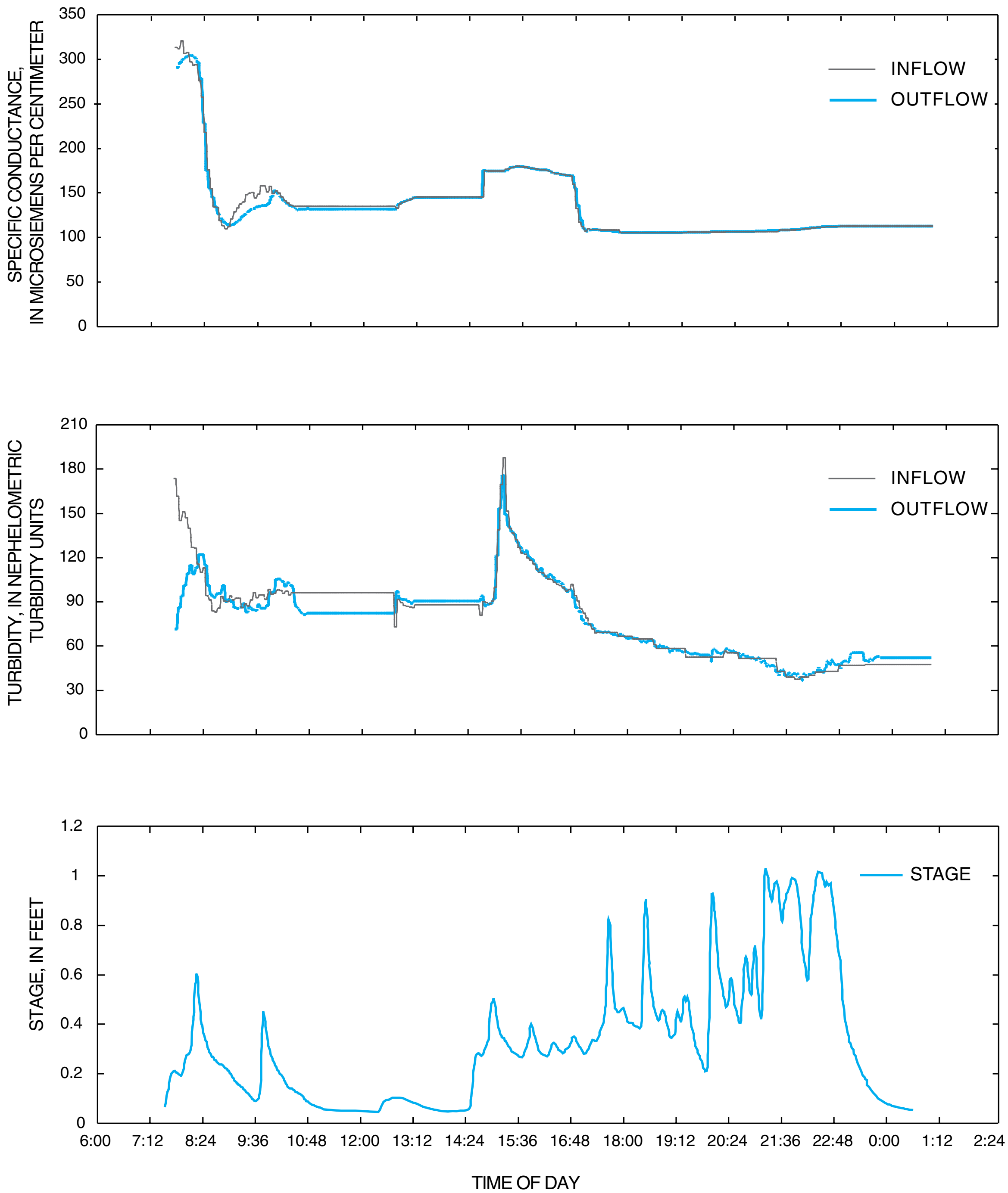

Figure 4. Specific conductance, turbidity, and stage measured at highway runoff monitoring station 739, September 10–11, 1999, Southeast Expressway, Boston, Massachusetts.

COLLECTION AND ANALYSIS OF SAMPLES

Highway-runoff samples for the analysis of suspended-sediment concentration, water chemistry, and bacteria were collected automatically with flow-proportional methods at each structural BMP. Sampling-equipment setup, however, varied with respect to the constituent sampled. Large debris entrained in highway runoff was composited in a collection structure at the outlet of a separator. Bottom material retained in the structural BMPs was volumetrically assessed and sampled several times during the study. Samples of bottom material were analyzed for particle size, density, and chemical concentrations. Samples of sediment collected from street sweepers in the vicinity of the highway test sites were analyzed for particle size. The contents of the bottom material, street sweeper, and debris samples were quantified in identifiable categories.

Automatic Sample Collection

Highway-runoff samples for the analysis of suspended-sediment concentration and water chemistry were collected at the inlet and outlet of each structural BMP by an automatic sampler (ISCO model 6700) controlled by a datalogger. The first sample was collected when flow exceeded 0.02 ft^3/s and subsequent samples were collected at flow-proportional intervals. Maximum vertical-sampling distance from the sampler-pump head to any fixed sampling point was about 10 ft. All sampler lines were mounted in a sloping manner when possible to allow for the complete purging and draining of sample water between samples. The lengths of the sampler lines ranged from 12 to 30 ft for the separators, and were 24 and 59 ft long for the inlet and the outlet of the catch basin, respectively.

Sampler intakes were fixed to static mixers at each sampling point for all sampling locations, except for the catch-basin inflow (fig. 5). The purpose of the static mixer was to provide a secure and consistent mount for the sampler intake, reduce transport velocity, and to provide agitation to produce a sample that represented the average concentration of suspended sediment. Sampler intakes were oriented in a horizontal and downstream direction. This configuration minimizes debris accumulation by forming a small eddy that captures sand particles at the intake, and thus, allows the sampler to collect a more representative sample of the coarse load (Edwards and Glysson, 1999). The static mixers were constructed from a 0.5-in. marine-grade homogenous polymer sheet and consisted of two semicircular plates 1.2 in. high at the center. Two polyvinylidenefluoride (PVDF) 0.5-in. bulkhead-compression fittings were attached to each side of the first plate 1.2 in. from the center and 0.6 in. from the bottom. The second plate had two semi-circular 0.7-in. holes in parallel with the bulkhead fitting to prevent sediment accumulation between the two plates and was mounted about 4 in. behind the primary plate.

The structure for stormwater sample collection was mounted below the grate in the catch basin and was designed to concentrate stormwater through a common point from which the sample was collected. The structure was constructed from a 0.5-in. marine-grade homogenous polymer sheet and was designed similar to the collection box described by Spangberg and Niemczynowicz (1992). A 1.25-in. PVDF tee was located at a common drainage point on the bottom of the structure. A free-swinging flapper valve was attached to one end of the tee. The sampler line was inserted through a compression fitting at the opposite end of the tee and parallel to the direction of flow. The end of the sampler tube was positioned approximately midway between the tee and the flapper valve. The flapper valve created a small amount of backpressure enabling sample collection at flows as low as 0.02 ft^3/s.

Suspended Sediment

Automatic samplers to collect suspended sediment held 24 1-L plastic bottles attached to sample lines made of 0.5-in. polyethylene tubing. Discrete samples were generally collected on one of three flow-proportional thresholds based on the volume of the structural BMP. Once the accumulated flow was equal to or greater than the threshold, the automatic sampler collected a water sample, and the accumulated flow was zeroed. In general, the threshold for the second, third, and fourth sample collected from the inlet and outlet of the separator was 100 ft^3 (1/2 the volume of the device), the threshold for the next 16 samples was 200 ft^3, and the threshold for the last four samples was 400 ft^3. The dataloggers were programmed in this way to maximize the information obtained about the initial

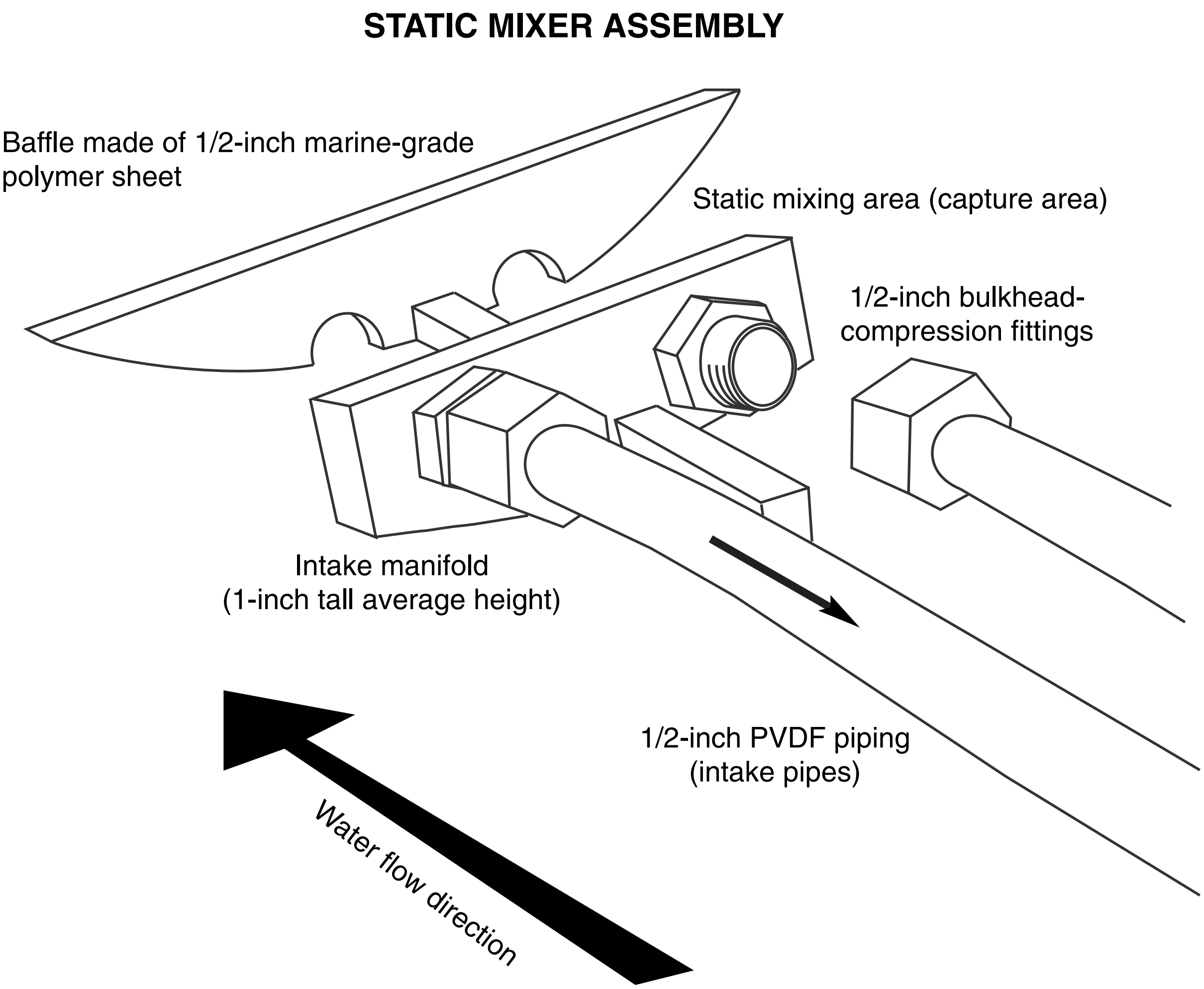

Figure 5. Schematic diagram of a static mixer used in conjunction with the automatic samplers.

runoff period and to ensure that samples for the analysis of suspended-sediment concentration were collected throughout the entire storm. During large storms, sample bottles were retrieved and replaced as needed to characterize the entire storm. The date, time, water level, sample number, and sampler response was recorded by the datalogger each time a sample was triggered.

Solid-phase concentration values may be determined by the suspended-sediment concentration (SSC) or the total suspended solids (TSS) method. Although SSC and TSS are often cited interchangeably in the literature to describe the total concentration of suspended solid-phase material, the analytical methods differ and can produce substantially different results (Bent and others, 2000). The SSC method (ASTM, 2000) uses standardized procedures and equipment to measure all of the sediment and the net weight of the water-sediment mixture to calculate concentration. The TSS method (American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1995) requires analysis of a subsample extracted from the original sample. Contrary to the literal description, SSC includes clays, silts, sands, gravels, asphalt particles and other road-surface debris, and organic and synthetic materials. Although analytical uncertainties for the two methods are similar, larger errors can occur during processing of TSS samples because agitation of a sample containing sand-size materials can produce aliquots which under-represent the true sediment concentration (Gray and others, 2000). Therefore, the SSC method was chosen to measure the solid-phase concentrations to provide the most accurate assessment of BMP efficiencies. Samples were analyzed for SSC and particle size at the USGS Kentucky District Sediment Lab (Guy, 1970; Sholar and Shreve, 1998).

Water Chemistry

Several changes were made in the sampling equipment and programming for the automatic collection of water samples for analysis of inorganic and organic constituents. Each automatic sampler was configured to hold one 20-L Teflon-lined plastic bottle. The Teflon lining consisted of a double wall Teflon pouch manufactured by NOW Technologies and constructed in a clean room without the use of glue or adhesives. Automatic sample lines were replaced with pre-cleaned 0.5-in. Teflon tubing. The pump-head tubing was also exchanged with a pre-cleaned replacement and a Teflon discharge tube. Samples were collected on a single flow-proportional threshold on the basis of the expected volume of runoff, volume of individual samples, and maximum number of sample volumes relative to bottle size. The empty space around the sample bottle was packed with ice prior to each storm to preserve sample integrity.

A multi-step process was used to clean all wetted parts associated with the automatic sampler and the processing equipment before collecting trace inorganic and organic constituents. The initial cleaning consisted of washing the interior and exterior with a phosphate-free laboratory grade soap and tap water, scrubbing surfaces with a plastic brush, rinsing with tap water, and a final rinse with deionized water. Circulating the solution through the tubing with a peristaltic pump cleaned the interior of the sampler tubing. Cotton balls were forced hydraulically through the tubing to remove internal deposits or films that were difficult to remove by circulating solution alone. All components were dried in a laboratory-circulating oven for a minimum of 12 hours at 105˚C. After the water evaporated and the components cooled, they were placed in a large stainless steel pan in a fume hood and immersed in a 1-to-1 hexane-to-acetone solution. A Teflon diaphragm pump was used to circulate the solution through the sampler tubing. The components were allowed to soak, with occasional agitation, for a period of six hours. After appropriately dispensing the waste solution, all components except the tubing were rinsed with a 1-to-1 hexane-to-acetone solution from a Teflon squeeze bottle, air-dried in a fume hood over night, and dried in a laboratory circulating oven for a minimum of 12 hours at 60˚C. Because the rate of cleaning-solution volatilization was limited within the sampler tubing, the tubing was purged with purified nitrogen gas for approximately 20 minutes and then thoroughly rinsed with copious amounts of deionized water. The final steps involved immersing the components in a 5-percent solution of hydrochloric acid for a period of 6 hours. The same solution was slowly circulated through each sampler tube for 6 hours. All components were thoroughly rinsed with deionized water until the specific conductance of the waste rinse water was less that 1 μS/cm. Sample bottles, Teflon lines, pump-head tubes, discharge tubes and processing components were double-bagged to maintain clean techniques. Bags were left on the bottles during installation for subsequent transport.

Samples were collected and processed according to “clean hands-dirty hands” techniques (Wilde and Radtke, 1999). Samples were processed in the USGS Massachusetts District laboratory clean room, usually within 24 hours of the time that collection of the first sample was triggered by the automatic sampler. Subsamples for the analysis of suspended sediment, and inorganic and organic constituents were split directly from the Teflon-lined bottle. This method eliminated sample contact with additional processing equipment and reduced the potential for contamination. Subsamples were dispensed under low pressure directly from the sample bottle with a specialized cap, which included a 3.1-mm (inner diameter) Teflon dispensing tube, a pressure port, and a relief valve. Compressed nitrogen gas applied to the pressure port filled the interior area between the bottle wall and the pouch, compressing the pouch and dispensing the sample. Homogenization of the sample was accomplished by fastening the bottle to a cradle assembly capable of rotating 210 degrees. The sample bottle was rocked the full 210 degrees at least 20 times at a frequency of one cycle per second prior to dispensing. The rocking motion was continued throughout dispensing for all samples except for samples analyzed for dissolved constituents. Dissolved inorganic constituents were filtered through a 600-cm Gelman capsule filter with a 0.45-mm pore size. Dissolved organic carbon was filtered through an inline Teflon filter holder with a 47-mm silver membrane filter with a 0.45-mm pore size. All samples were double bagged and stored on ice for overnight delivery to the USGS National Water Quality Laboratory in Lakewood, Colorado, for chemical analysis (Wershaw and others, 1987; Fishman and Friedman, 1989; Fishman, 1993; Fishman and others, 1994).

Bacteria

Flow-proportional, discrete water samples for the analysis of bacteria were collected from a second dedicated automatic sampler at the inlet of each separator. Each automatic sampler was configured to hold twenty-four 350-mL glass bottles. Sample lines consisted of sterile 0.5-in. silicon tubing. The pump head and discharge tubing were pre-cleaned and sterilized. Sample bottles were autoclaved and treated with a 15-percent solution of ethylenediaminetetraacetic acid (EDTA) to chelate sample trace-metal concentrations that would be potentially toxic to bacteria (American Public Health Association and others, 1992). The sampler base was packed with bagged ice prior to each storm. Samples for analysis of bacteria were collected automatically along with the samples collected for analysis of inorganic and organic constituents.

Sequential discrete samples for analysis of fecal and *Enterococci* bacteria were periodically composited because the amount of equipment and personnel limited the number of analyses that could be completed within the method holding time. The entire aliquot of two or more sequential discrete samples was composited into a sterile 2-L bottle. The samples for bacteria analysis were processed on the basis of the methods described by Myers and Sylvester (1997) and the U.S. Environmental Protection Agency (USEPA) method 1600 (1997) on-site and placed in portable incubators in a mobile field laboratory. Figure 6 illustrates an example of flow-proportional automated collection of samples for analysis of chemical and bacterial constituents. EMCs for analysis of fecal-indicator bacteria were mathematically determined by calculating the average value for flow-weighted concentrations of sub-composites.

Miscellaneous Debris Samples

The automatic samplers used at the inlet and outlet of each structural BMP limited the particle sizes of suspended sediment collected to less than 9.5 mm in diameter; this limitation excluded large organic particles and debris such as litter and leaves. Thus, large buoyant and neutral buoyant (particles that neither settle or float) particles were sampled by attaching a debris-collection device (fig. 7) to the outlet headwall of station 739. Sampling the inflow for debris was not practicable during this study because the sampling process could adversely affect the flow to the oil-grit separator. The device consisted of a 1.5- by 1.5- by 2-ft wood frame covered on 5 sides with a 6- by 6-mm galvanized-steel screen. The captured material was retrieved, through an access door on the top of the device at the end of each storm or series of storms. The quantity of captured material was determined by drying the contents at 105˚C to a constant weight, and the debris was identified by visual inspection of each dried sample. Identifiable materials were placed in general categories, such as gravel, cigarette butts, plastics (wrappers, Styrofoam, and other plastics), and vegetative matter. The net weight of each category for each sample was measured and recorded to the nearest milligram.

Measurement of Volume and Mass of Bottom Material in the Oil-Grit Separators and the Catch Basin

Bottom material is a mixture of sediment, natural organic material (leaves and sticks), roadway materials, and litter remaining on the bottom of structural BMPs between storms (Bent and others, 2000). For the purpose of this report, bottom sediment is bottom material that does not contain litter or other identifiable materials, such as metal objects. Two methods were used to measure the volume of bottom material in each BMP. During site assessments in November 1998 and during active monitoring in December 1999 and January 2000, measurements of depth (from the water surface to the top of the accumulated bottom material) were made with a calibrated staff at a minimum areal density of 1 measurement per square foot. During the site assessment of separator 739-01 in August 1999, prior to the monitoring period, and also in June 2000 during subsequent assessments of all three separators and the catch basin at the end of the monitoring period, at least four depth measurements were made with an engineer's rule per square foot after each BMP was drained.

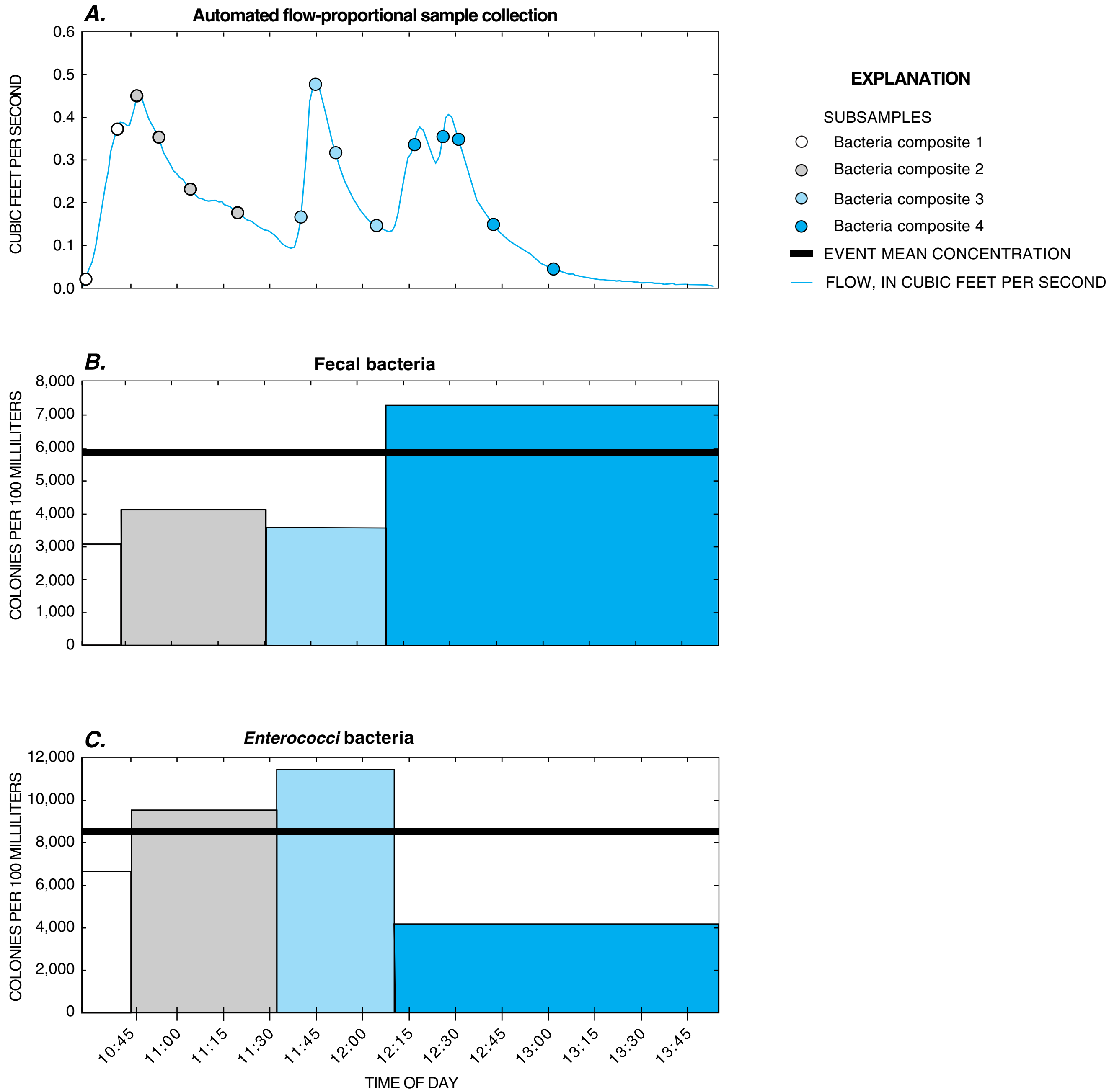

Figure 6. Example of automated flow-proportional collection of stormwater samples at station 739, along the Southeast Expressway, Boston, Massachusetts.

Figure 7. Debris-collection structure at the outlet of an oil-grit separator during a rainstorm on May 25, 2000, station 739, Southeast Expressway, Boston, Massachusetts.

A centrifugal pump with a transparent discharge line was used to drain each device. The pump intake was fitted with a strainer that had a 1-ft^2 plate mounted on the bottom to reduce direct vertical drafting near the sediment interface. The pump intake was placed just below the water surface in the first chamber of the separators to avoid drawing floating debris into the second chamber, and was lowered as the water level decreased until the BMP was nearly empty. The discharge hose was continually monitored for visual changes in turbidity as the intake lowered. The volume of bottom material was estimated by iterative averaging between volumetric measurement points at an areal density of 16 points per square foot.

Bottom-material cores were collected in the catch basin and the first chamber of the separators with a 2-in.-diameter acrylic tube. A thin flexible spatula was used to seal the core in the tube prior to removal. The length of the core was recorded and the contents stored in a resealable bag. Cores were not collected in the second chamber of the separators because the core tube could not penetrate the large amount of decaying vegetation and other debris in the bottom material. Instead, grab samples were collected at several locations and composited into a resealable bag. The volume of the grab samples was estimated by measuring the depth of bottom material after allowing it to settle over several days in a vessel of known size. Several cores and samples were collected in each structural BMP (and chamber, where possible) for particle-size and density analysis. Particle-size analysis was performed at the USGS Iowa Sediment Laboratory (Guy, 1969). Density was determined in the USGS Massachusetts District laboratory by drying known volumes of sediment to a constant weight. The bottom-material mass in each structural BMP was estimated by multiplying the total volume of bottom material contained in each chamber by the associated density.

The contents of the bottom material were identified by visual inspection of each dried sample. Identifiable materials were placed in general categories, such as glass, metal (tin foil, bottle caps, and other metal objects), cigarette butts, plastics (wrappers, Styrofoam, and other plastics), and vegetation. The net weight of each category for each sample was measured and recorded to the nearest milligram.

Collection of Bottom-Material Samples from the Oil-Grit Separators

Samples of bottom material were collected from three 1,500-gal oil-grit separators in November 1998 and from December 1999 through January 2000 with the use of a stainless steel Eckman dredge (Wildco). The Eckman dredge can be used to collect clay, silt, and sand-sized particles (Mudroch and MacKnight, 1994). The dredge was deployed several times at different locations from each manhole to provide adequate sample volume and a representative sample. Samples of bottom material from each chamber were removed from the dredge and placed in a pre-cleaned, stainless steel bowl and homogenized with a stainless steel spatula. Samples were collected and placed in pre-cleaned containers and preserved on ice for subsequent processing of bottom sediment in the USGS Massachusetts District laboratory and for particle-size analysis at USGS Iowa Sediment Laboratory. Grab samples of native water were also collected and placed in pre-cleaned, Teflon-lined bottles. The Eckman dredge, stainless steel bowl, and stainless steel spatula were cleaned in the field between sites by washing the interior and exterior with a phosphate-free laboratory-grade soap and tap water, scrubbing the surfaces with a plastic brush, and rinsing with deionized water.

Samples of bottom material collected from three separators in November 1998 were composited in proportion to the estimated volume of retained material in each separator. Composites of bottom material collected from each separator from December 1999 through January 2000 were processed individually for chemical analysis relative to three particle sizes, in part, by using the methods described by Shelton and Capel (1994). The contents of the bottom material were visually inspected and nonhomologous materials (for example, plastic and foil wrappers) that could bias chemical analysis were removed. With a Teflon squeeze bottle and native water, the original sample was wet-sieved through a pre-cleaned 2.00-mm sieve. A subsample of the sieved material was wet-sieved a second time with a pre-cleaned 0.062-mm nylon-mesh sieve and plastic-sieve frame. Native water and sediment particles less than 0.062 mm in diameter were collected in a pre-cleaned bottle and allowed to settle for several days. The supernatant was decanted and the sediment retained for chemical analysis. Particles (consisting of gravel, asphalt, leaves, and woody debris greater than 2.00 mm in diameter) were reduced to less than 2.00 mm in diameter and homogenized in a laboratory blender made of stainless steel and borosilicate glass to ensure a representative sample.

Samples of bottom sediment consisting of particles less than 0.062 mm in diameter, between 0.062 mm and 2.00 mm in diameter, and particles originally greater than 2.00 mm in diameter were submitted to XRAL Laboratory for analysis of 32 inorganic elements and total organic carbon (TOC). Concentrations of inorganic constituents were determined with the use of ICP emission spectroscopy and two different digestion methods for size fractions less than 0.062 mm in diameter and between 0.062 mm and 2.00 mm in diameter (site 136 did not include both digestion methods for particles less than 0.062 mm because of a lack of available sample volume). Two analytical methods were used to compare the differences in digestion procedures that can affect measured trace-element concentrations and to provide greater transferability to other studies. The primary method, USEPA method 3050B (U.S. Environmental Protection Agency, 2000), digested samples with repeated additions of nitric acid and hydrogen peroxide. The secondary method, XRAL method ICP70 (Société Générale de Surveillance, 2001), digested samples with aqua regia acid. Digestion procedures for total recoverable trace elements, such as the two methods discussed, have been previously considered by the USEPA as a method that could provide an indication of the bioavailability of trace elements (U.S. Environmental Protection Agency, 1986); however, concentrations of total recoverable trace elements do not necessarily relate to ecosystem effects and should be considered as one of many explanatory variables to be measured in addition to more direct measurements of the ecological effects on aquatic biota (Breault and Granato, 2000; Buckler and Granato, 1999). TOC was determined by infrared spectroscopy. Samples of bottom sediment consisting of particles less than 2.00 mm in diameter and particles originally greater than 2.00 mm in diameter were submitted to the USGS National Water Quality Laboratory in Lakewood, Colorado, for analysis of polyaromatic hydrocarbons (PAHs) and total polychlorinated biphenyls (PCBs) (Foreman and others, 1995). Particle-size analysis excluded all identifiable debris, such as leaves, sticks, cigarette butts, wrappers, and other plastic items.

Sediment Samples from Mechanical Street Sweepers

Mechanical street sweepers were used on the pavement three times during the study period (November 1998 through June 2000). Mechanical sweepers use revolving brushes to move particulates into the path of a horizontal cylindrical brush that pushes material onto a conveyer belt leading to a storage hopper. The street was swept during the late evening hours to reduce traffic disruptions. MassHighway personnel collected grab samples from the center of the hopper when the street sweeper was in the vicinity of the highway test sites. Samples were processed for particle-size analysis at USGS Iowa Sediment Laboratory as described previously.

QUALITY ASSURANCE/ QUALITY CONTROL

The reliability of the real-time measurements and suspended sediment, chemical, and biological data was ensured by the preparation and analysis of many types of quality-control samples. These data were summarized to assess the potential for sample contamination and the accuracy and precision of various types of sample analysis and sampling methods. These analyses provided the basis for the interpretation of the efficiency of each BMP.

Quality-Control Samples

The reliability of the data collected as part of this study was ensured by the preparation and analysis of concurrent field replicates, replicate splits, sequential replicates, equipment blanks, field blanks, source-solution blanks, material blanks, and ambient-atmospheric blank samples. In addition to the collection of quality-control samples, numerous other tests were done to ensure the reliability and representativeness of the data. Replicate samples provide a measure of any variability introduced during sample collection, processing, and analysis. In this study, concurrent field replicates were samples collected at the same time by comparable methods; split replicates were subsamples from a single sample; and sequential replicates were two or more samples collected at the same location, but at slightly different times. Replicate samples were analyzed by comparing the relative percent differences (RPD) of the results. Equipment blank samples were used to test for positive bias that could have resulted from contamination from any stage of the collection or analytical process. A processing blank was similar to an equipment blank, but sample water was exposed only to sample-processing equipment, not sampling equipment. Source-solution blanks were prepared from deionized water produced by a Millipore purification system that uses reverse osmosis and electrodeionization. Deionized water was also used to clean equipment. The material blank consisted of source solution in which a material fragment was soaked. Ambient-atmospheric blanks consisted of source solution exposed to ambient and atmospheric conditions that prevailed when the sampling equipment was cleaned and when environmental samples and equipment blanks were processed. Quality-control samples are summarized in table 3.

Table 3. Summary of quality-control samples collected in the structural best management practices along the Southeast Expressway, in the U.S. Geological Survey, Massachusetts District laboratory, and by the U.S. Geological Survey, Office of Water Quality, Branch of Quality Systems

[--, no data]

Sample type	Number of quality-control samples collected			
	Suspended-sediment concentrations	Bottom-sediment quality	Water quality	Fecal-indicator bacteria
Field blank	--	--	--	4
Equipment blank	16	--	[1]1	2
Replicate split	4	3	5	2
Lab duplicate	--	2	--	--
Sequential replicate	27	--	--	--
Concurrent replicate	30	--	--	--
Single blind	3	--	--	--
Double blind	6	--	--	--
Particle size	--	3	--	--
Source-solution blank	--	--	2	1
Ambient-atmospheric blank	--	--	2	--
Material blank	--	--	1	--
Data location (this report)	Appendix 1, Table 1B, 1C, 1D, 1H	Appendix 1, Table 1G	Appendix 1, Table 1H	Appendix 1, Table 1I

[1]Two equipment blanks collected for dissolved organic carbon.

All continuous-monitoring equipment was tested under controlled conditions prior to installation and met or exceeded the manufacturer's specifications. Site visits were generally conducted at a minimum frequency of once per week. During each site visit, an independent measurement of the water level of the oil-grit separator was compared to the current datalogger measurement, and debris accumulation was noted and removed from the inlet, outlet, and bypass pipe of each oil-grit separator and from the stormwater-collection structure installed in the deep-sumped hooded catch basin. Probes were inspected, cleaned, and calibrated as necessary, and the sample and pumping system tubes were inspected for wear and debris accumulation. On a less frequent schedule, the precipitation gage was inspected and tested. In general, continuous water-level measurements were within 0.02 ft, temperatures were within 0.5°C, and specific conductance was within 10 percent of check measurements. Error associated with turbidity sensor fouling was minor, but sensors exhibited a large amount of drift and became inoperative when temperatures were near freezing. The water-quality pumping system that operated semicontinuously performed satisfactorily; however, coarse debris and glass particles periodically deteriorated the pump-head tubing, which caused the pump to malfunction.

About 3 percent of all samples for the analysis of suspended-sediment concentration from the structural BMPs were quality-control samples. These included equipment blanks, field replicate and sequential replicate samples, composite split replicates, and double-blind samples. These data are tabulated in appendix 1, tables 1*B*, 1*C*, and 1*D*. Equipment blanks were collected with the use of deionized water. Blank water was processed through the automatic-sample collection system, collected, and analyzed by the sediment laboratory, in a manner similar to the processing of environmental samples. Equipment blank samples were compared to the most recently collected environmental samples to determine the amount and extent of any cross-contamination between samples. Concurrent field replicates were collected by several different methods to assess sampling variability. Grab replicate samples were collected simultaneously with environmental samples collected automatically. Grab samples were limited to intake locations where highway runoff discharged from elevated pipes. Automatic replicate samples were collected simultaneously with a second automatic sampler with the intake mounted on the static mixer adjacent to the primary sampler intake. Concurrent replicate automatic samples were collected over the duration of the entire storm for four runoff events. In order to determine the average particle-size distribution, concurrent and sequential replicate samples of suspended sediment were collected with three automatic samplers that had intake tubes vertically distributed throughout the water column. The lowest tube was fixed to the static mixer. Samples of suspended sediment were collected at three different depths simultaneously at flows of 0.13, 0.22, and 0.45 ft^3/s. Composite-split replicates were prepared from the samples in the Teflon-lined 20-L bottles with the processing methods described earlier.

In addition to other quality-control samples, single-blind and double-blind samples were submitted to the sediment laboratory during 1999 and 2000. Single-blind samples were samples of known concentrations and particle-size distribution values that were submitted to the sediment lab for analysis and identified as quality-control samples. Laboratory results were compared to the known values to measure the bias and variance of suspended-sediment data. In addition, double-blind samples were identified as environmental samples and submitted to the laboratory to measure the bias and variance of suspended-sediment data. Quality-assurance procedures for the USGS Kentucky District Sediment Laboratory are described in Sholar and Shreve (1998).

Replicate samples for chemical analysis were random subsamples of processed homogenized bottom sediment from the separators. Quality-control samples for particle size consisted of subsamples of processed homogenized bottom sediment in the size range of 0.062 mm to 2.00 mm in diameter from each separator. These samples were mixed with deionized water and analyzed for particle size at the 0.062-mm break to determine the composition of the size fraction. Examination of the 0.062-mm sieves subsequent to processing indicated that there was no observable distortion to the screen.

About 20 percent of all water-quality samples collected from the structural BMPs were replicate composite splits. In addition, one equipment blank, one material blank, two ambient-atmospheric blanks, and two source-solution blanks, which were used for sample-equipment cleaning and equipment blanks, were collected. The material blank was collected on a small piece (about 54 cm^2) of the polymer that was used to construct the static mixers and the stormwater-collection structure. Preparation of the polymer piece was consistent with the procedures for cleaning the water-quality-sampling equipment outlined earlier. Sample preparation for metal analysis included soaking the polymer piece in inorganic blank water acidified to a pH less than 2 with hydrochloric acid for 48 hours. Sample preparation for PCB and PAH analysis included soaking the polymer piece in organic blank water for a period of 48 hours.

Replicate split samples for analysis of fecal-indicator bacteria were collected from composites of two or more discrete samples. Processing blanks were collected for analysis of fecal and *Enterococci* bacteria during each sampled storm. Equipment blanks and source-solution blanks also were analyzed.

Quality-Control Data

Quality-control data were summarized to assess the potential for contamination, and to assess the accuracy and precision of the data. The quality-control data indicated that continuous records of water level, flow, and precipitation were within the measurement uncertainties of the individual sensors. About 90 percent of the estimated precipitation, determined on the basis of the drainage area of each monitoring site, was accounted for in stormwater flows at each site. These relations of total flows to total precipitation for each storm compared favorably with runoff coefficients developed in other highway studies (Driscoll and others, 1990). The mean RPD between the concentration of suspended sediment in samples collected by the automatic sampler and in replicate grab samples collected concurrently was 4 percent over a range of flows from about 0.03 to 0.41 ft^3/s. The mean RPD between the concentrations of suspended sediment in pairs of replicate suspended-sediment samples collected concurrently by automatic samplers was about 8 percent over a range of flows from about 0.01 to 0.10 ft^3/s. The aforementioned flow ranges span the average storm flows for the monitoring period at each BMP. The average cross-contamination among equipment blanks for samples of suspended sediment for the six sites is estimated to be about 5 percent. Replicate samples for the analysis of suspended-sediment concentration collected automatically across the water column within the inlet of a separator, collected concurrently and sequentially, indicated that particles less than 0.062 mm in diameter were evenly distributed throughout the water column. Concentrations of particles greater than 0.062 mm in diameter, however, tend to be higher near the bottom of the pipe despite the turbulence created by the static mixers. Flow-weighted vertical concentration trends relative to three flow rates are illustrated in figure 8. This concentration distribution compared favorably with patterns in data from natural fluvial systems (Guy, 1970) and described in other highway systems (Bent and others, 2000). Figure 9 illustrates the range of runoff flows at stations where samples for the analysis of suspended-sediment concentration were collected through the study period. The maximum rate of flow and the median of average rate of flows for the monitoring periods for the separators were 2.85 and 0.06 ft^3/s, respectively, at station 739; and 1.72 and 0.05 ft^3/s, respectively, at station 136. The maximum rate of flow and the median of average rate of flows for the monitoring period for the catch basin were 1.37 and 0.01 ft^3/s, respectively. The differences between the median and interquartile ranges of the separators were the result of how long and when each station was monitored. Station 136 was operated for four months longer than station 739, and the monitoring period included the entire spring and early summer of 1999. During the summer, storms were short and intense; thus, the flows were typically greater than storms later in the study.

The results of the USGS Kentucky District Sediment Laboratory participation in the USGS Branch of Quality Systems (BQS) single-blind reference project indicated that sample bias for concentrations of suspended sediment-size fractions less than 0.062 mm and greater than 0.062 mm in diameter during the study period was minimal, typically less than 5 percent (Shreve, E.A., U.S. Geological Survey, written commun., 2001). The median difference between concentrations of double-blind suspended sediment samples and known sample concentrations was less than 4 percent (appendix 1, table 1*C*).

Quality-control data indicated that the results of the analyses of most bottom-sediment samples for inorganic elements and organic compounds were accurate and reproducible (figs. 10 and 11, appendix 1,

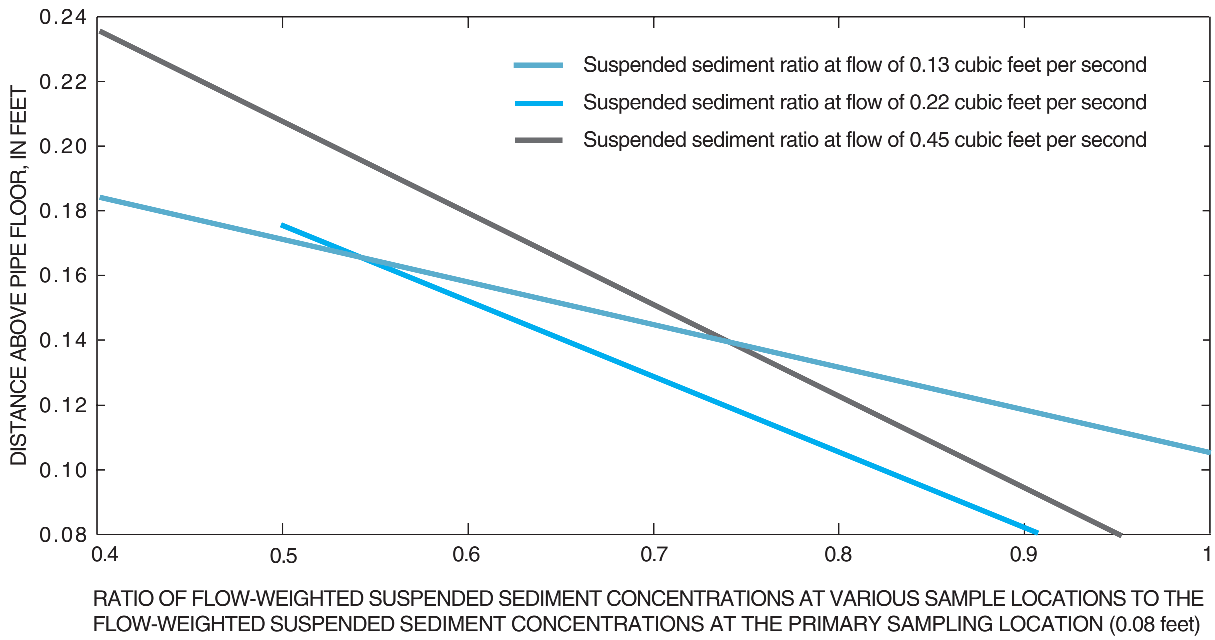

Figure 8. General trend for flow-weighted suspended-sediment concentrations relative to the sample location in the water column of a 12-inch pipe at the inlet of the oil-grit separator at station 136, along the Southeast Expressway, Boston, Massachusetts.

table 1*G*). Field and laboratory replicate samples were analyzed by comparing the RPDs of the results. The RPD was typically less than 25 percent for most pairs of samples; an RPD of less than 50 percent between measurements from replicate bottom-sediment samples is considered to be acceptable (Breault and others, 2000). RPDs exceeded 50 percent for only two replicate samples for TOC, two samples for barium (Ba), one sample for cadmium (Cd), and one sample for lead (Pb). The large RPD for the Cd sample was a result of one concentration near the detection limit and the other concentration below the detection limit. Particles less than 0.062 mm in diameter (about 0.5 percent) were virtually absent in samples of bottom sediment in the size range of 0.062 to 2.00 mm indicating that the particle-size composition of these samples was relatively pure. This is important because particles less than 0.062 mm in diameter contained higher concentrations of selected constituents compared to other size ranges; thus, the presence of even small quantities (as low as 5 percent) of particles less than 0.062 mm in diameter could have increased the concentrations of selected constituents in the size range of 0.062 to 2.00 mm in diameter.

Quality-control data indicated that most of the results of analysis for water samples were accurate and reproducible (appendix 1, table 1*H*). The median RPD between replicate composite splits for dissolved major ions, dissolved organic carbon (DOC), oil and grease (O&G), and nutrients—except for total phosphorus (P), orthophosphorus (PO_4), and total organic ammonia (NH_3), were less than 4 percent. The median RPDs between replicate composite splits for total P, PO_4, and total organic NH_3 were about 16, 9, and 9 percent, respectively. The median RPDs between replicate splits for suspended organic carbon (SOC) and total petroleum hydrocarbons (TPH) were 25 and 12 percent, respectively. The median RPDs between replicate splits for chemical oxygen demand (COD), total PAHs, and total PCBs were all less than about 8 percent. The median RPDs between replicate splits for total Cd, chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), Pb, and zinc (Zn) were all less than 5 percent.

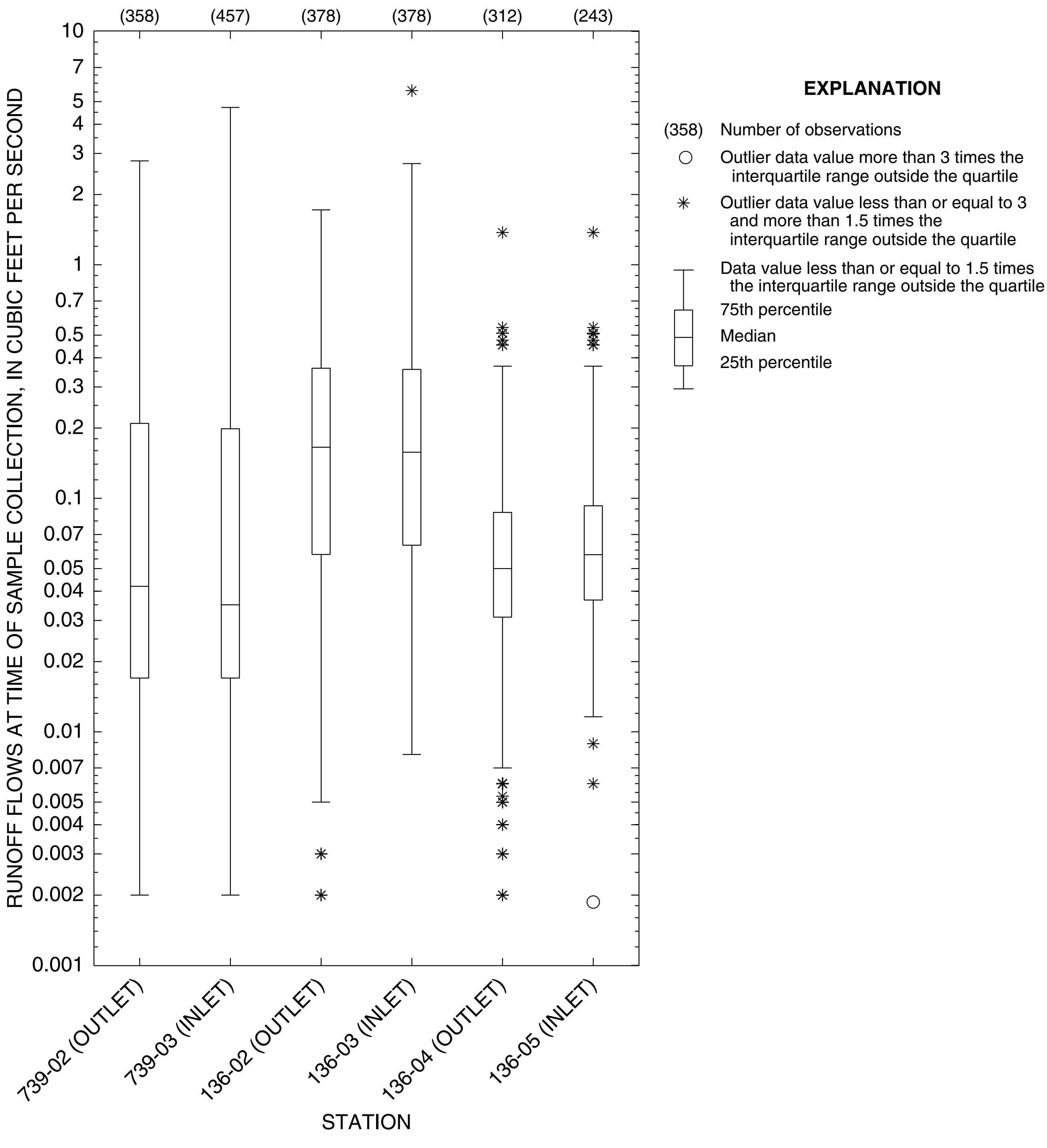

Figure 9. Distribution of runoff flows at time of sample collection for the inlet and outlet of each structural best management practice, along the Southeast Expressway, Boston, Massachusetts.

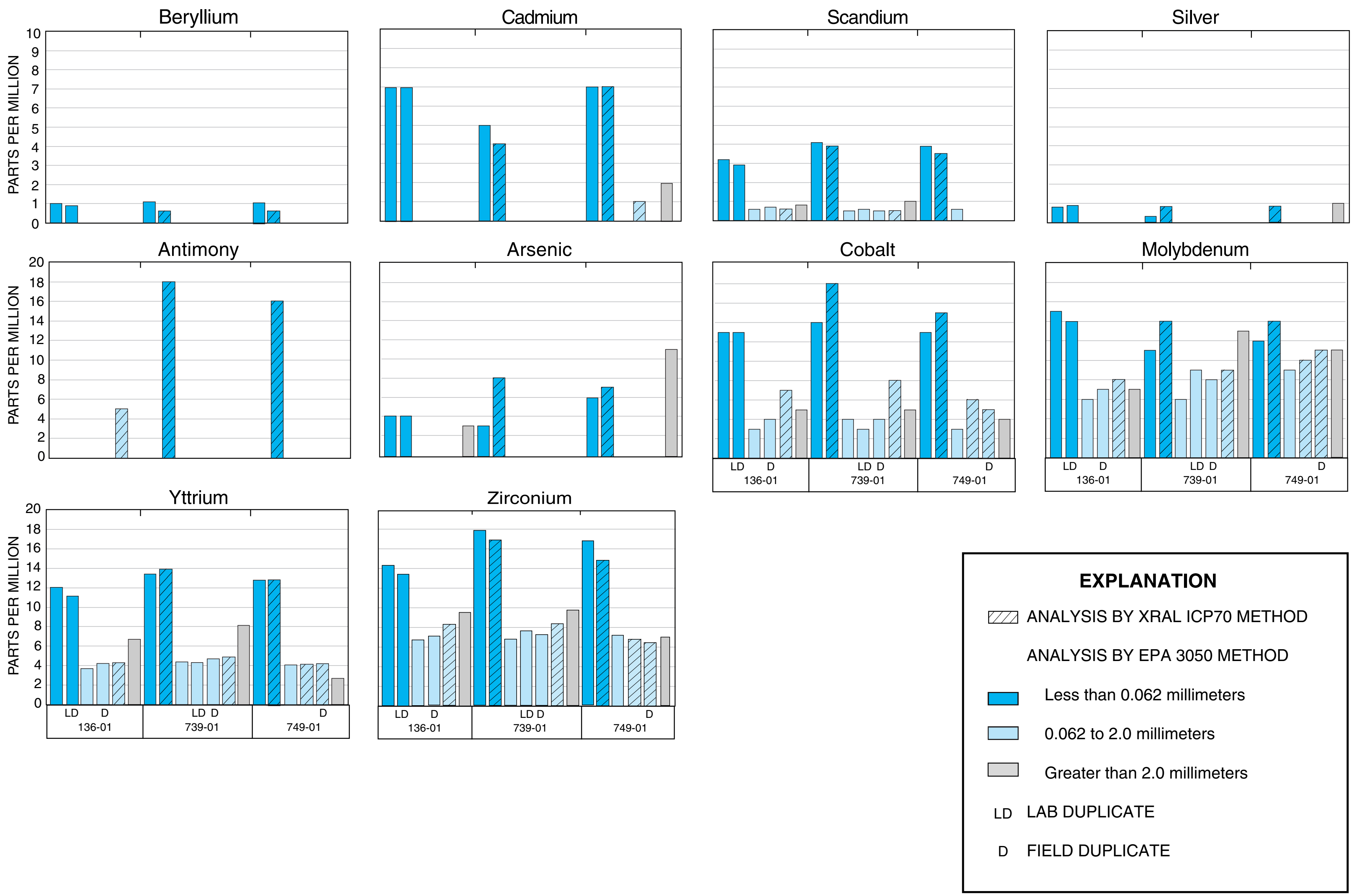

Figure 10. Distribution of inorganic elements by particle size in sediment samples collected from oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

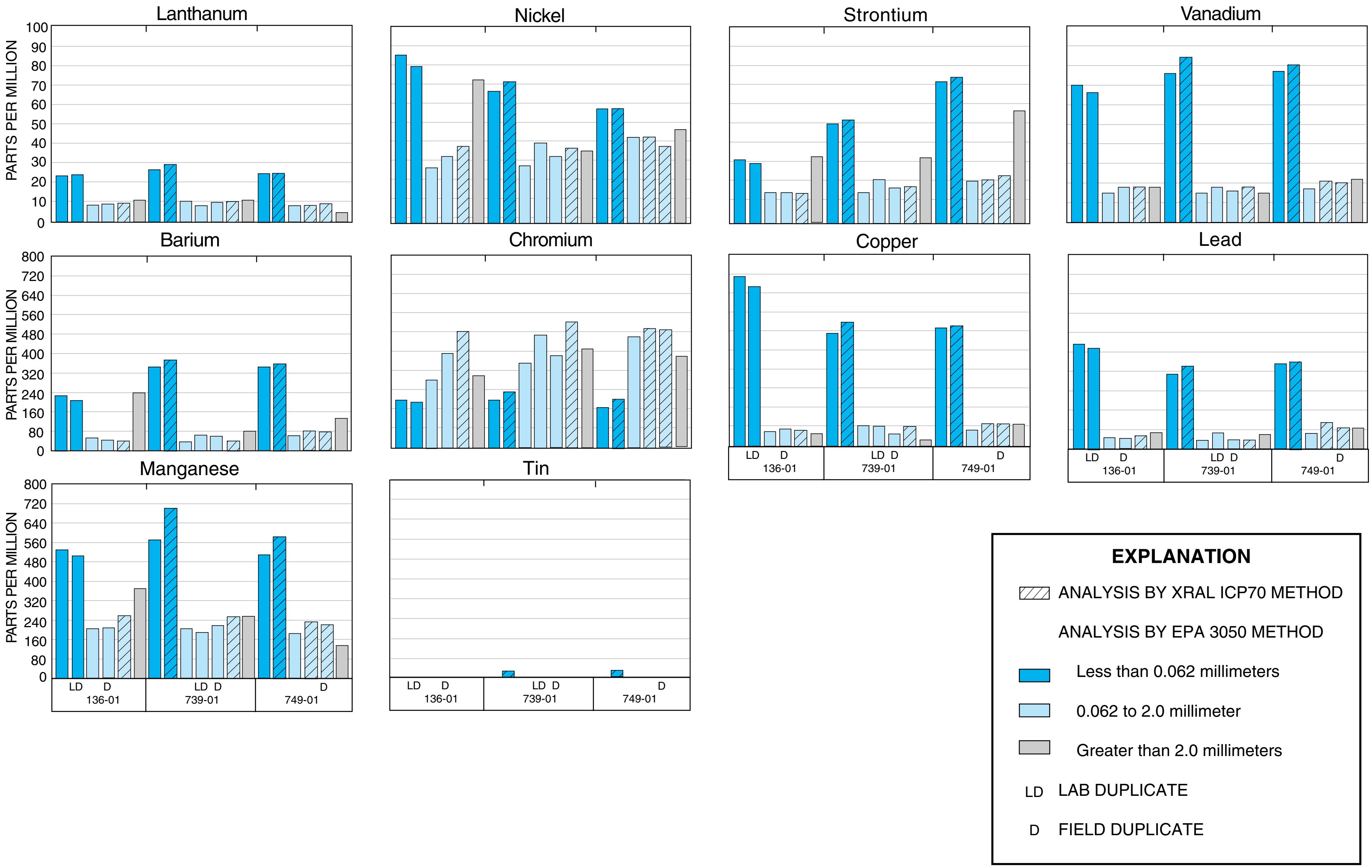

Figure 10. Distribution of inorganic elements by particle size in sediment samples collected from oil-grit separators located along the Southeast Expressway, Boston, Massachusetts—*Continued.*

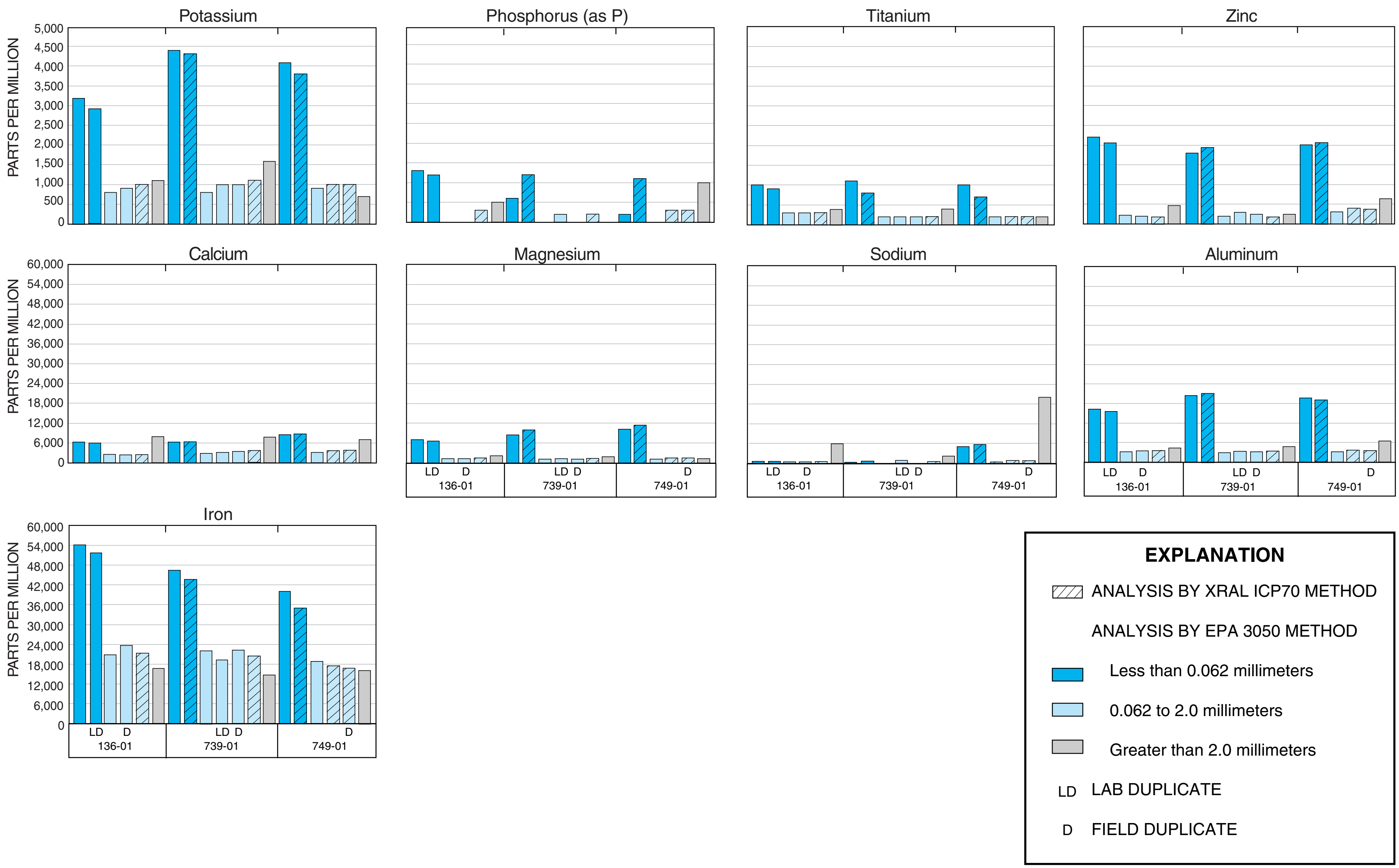

Figure 10. Distribution of inorganic elements by particle size in sediment samples collected from oil-grit separators located along the Southeast Expressway, Boston, Massachusetts—*Continued.*

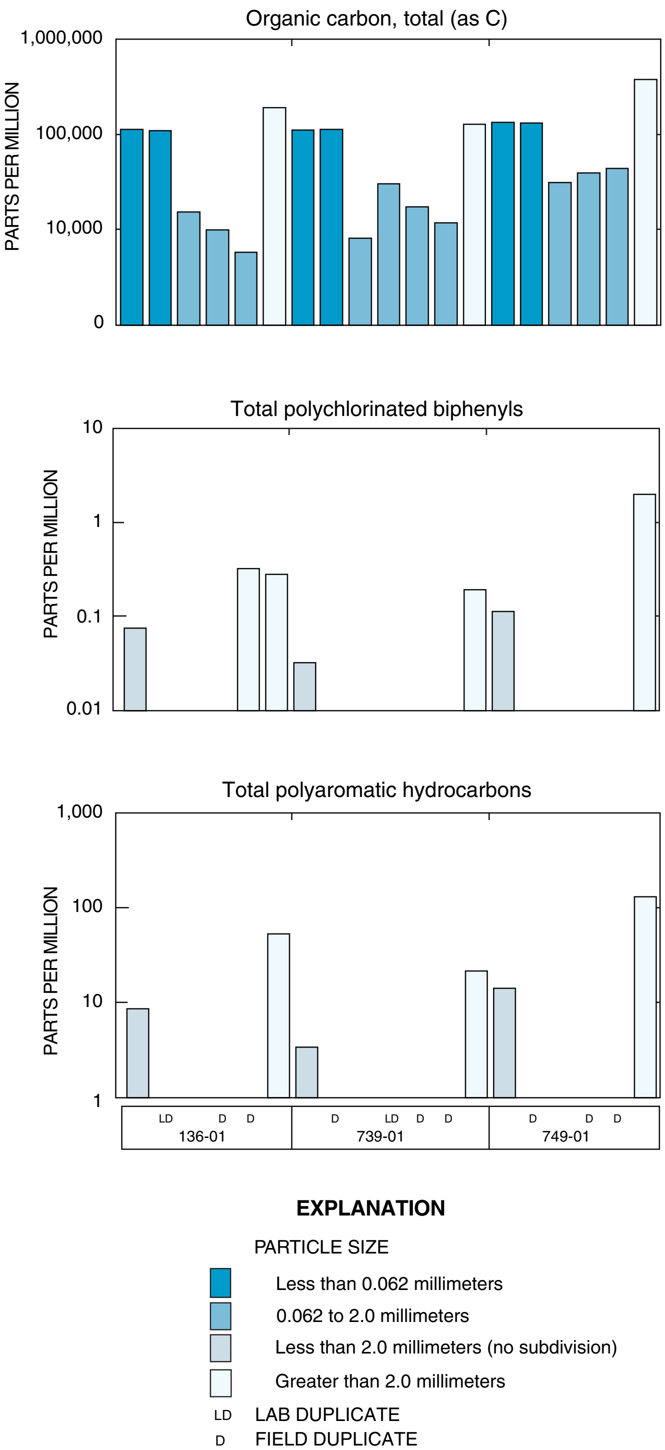

Figure 11. Distribution of organic constituents by particle size in sediment samples collected from oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

The median RPDs between replicate splits for total arsenic (As) and nickel (Ni) were 14 and 8 percent, respectively. In general, the largest RPDs were found in samples that contained high concentrations of coarse particles (in excess of 0.250 mm). The median RPD for concentrations of suspended sediment in replicate splits was about 13 percent. The RPD between samples with a majority of particles less than 0.062 mm in diameter, however, was about 4 percent. Particles found in composite samples were as large as 4 by 7 mm and weighed as much as 180 mg; thus, the low precision of the analysis of suspended-sediment samples containing coarse material was likely caused by one sample with only a few additional particles.

Source-solution blanks prepared from deionized water for the analyses of water and bacteria were free from contaminants with respect to the minimum reporting limit (MRL) used for sample analyses, with the exception of trace amounts of silica, and a single detection of ammonia (NH_4-N) and benzo-[GHI] perylene. Ambient-atmospheric blanks prepared from source water were free from contaminants. The material blank was free from contaminants, with the exception of trace amounts of Ni and aluminum (Al). The equipment blank contained trace amounts of NH_4-N and DOC, but analysis of this blank indicated no substantial contamination from the wetted parts of the equipment, the cleaning procedure, or any stage of the sample collection. A subsequent analysis of the equipment blank indicated that DOC was below the MRL.

Equipment and source-solution blanks analyzed for bacteria indicated that the cleaning and sterilization process was satisfactory. A single processing blank suggested that contamination occurred once in the field. The contamination, which may have been the result of an airborne particle in the mobile laboratory, occurred prior to any sample collection and was several orders of magnitude below sample concentrations. The RPDs between all pairs of replicate split samples for fecal-indicator bacteria were less than 21 percent.

ANALYSIS OF DATA

Concentrations of suspended sediment were combined with continuous records of flow and quality-control data to estimate suspended-sediment loads for each monitoring location. A mass-balance calculation was used to assess the effectiveness of each structural BMP in reducing suspended-sediment loads. An annual suspended-sediment load was estimated for the entire highway surface for the study area, on the basis of the long-term average annual precipitation and the suspended-sediment loads estimated during this study.

Suspended-Sediment Loads

Suspended-sediment loads for the inlet, outlet, and bypass (oil-grit separator only) of each structural BMP were estimated by multiplying the concentration of suspended sediment in discrete samples by the discharge represented by the samples. The discharge applied to a particular sample (the "sample discharge") was computed as the sum of half the flow that occurred since the collection of the preceding sample and half the flow that occurred before the collection of the subsequent sample. In the case of the first sample, the sample discharge was computed as the sum of the entire flow that preceded the collection of the sample and half the flow that occurred before the collection of the subsequent sample. In the case of the last sample, the sample discharge was computed as the sum of half the flow that occurred since the collection of the preceding sample and the entire volume of flow that occurred after the collection of the sample. In most cases, samples were collected in proportion to flow, so that in effect all sample discharges were equivalent. Storm loads were estimated from the summed sequential sample loads. During four storms, the automatic samplers were configured to collect composite samples; storm loads were estimated by multiplying the EMC of suspended sediment by the total storm discharge.

Bypass loads were estimated on the basis of the concentration of suspended sediment in the inflow samples because no bypass samples were collected. In other words, the suspended-sediment concentration in the separator bypass and inlet pipe was assumed to be the same. This assumption may not necessarily be correct because quality-control data indicated that particles greater than 0.062 mm were not evenly distributed vertically at comparable flows. Conversely, bypass flow was believed to have been thoroughly mixed because the inflow impacted the diversion weir at a 90-degree angle. In fact, small gravel (greater than 6 mm in diameter) was found in the debris-collection structure at station 739 after bypass flow occurred, which indicates a high degree of mixing.

An adjustment factor was applied to inlet loads of suspended-sediment because quality-control data indicated that suspended-sediment concentrations were not evenly distributed throughout the water column. Inlet loads would have been overestimated without this adjustment, because the sampler intake was at the bottom of the water column. No adjustment was necessary for the separator outlet loads because samples of suspended sediment from the outlet had few particles greater than 0.062 mm in diameter (fig. 12). No adjustment was made in the suspended-sediment loads of the inlet or outlet of the catch basin because stormwater flows and the resultant water-column depths were substantially smaller than those for the separator. A regression equation was developed to normalize the mean suspended-sediment concentration to the primary sample location for samples from the separator inlets. This equation was based on the analysis of experimental samples of suspended sediment categorized by a particle-size break at 0.062 mm and collected at flows characteristic of observed field conditions. The mass of sediment particles greater than 0.062 mm in diameter in experimental samples ranged from 63 to 96 percent of the mass of the total suspended sediment. This particle-size distribution was similar to observed particle-size distributions at the separator inlets at each station (fig. 12). The following adjustment equation was used to normalize the mean concentration of suspended sediment to the primary sample location for samples from the oil-grit separator inlets:

$$C_A = C \times 10\text{\^{}}\ ^{(-0.265\ \mathrm{Log}_{10}(Q)\ -0.369)},$$

where

C_A is the adjusted SSC,

C is the initial suspended-sediment concentration, and

Q is the instantaneous discharge in cubic feet per second.

No adjustment was made to the concentration of suspended sediment for samples collected at discharges less than 0.09 ft^3/s because the position of the sampler intake was centered approximately in the water column and the suspended sediment was generally dominated by particles less than 0.062 mm in diameter. The equation provided a correction to the experimental data to within 24 percent of the flow-weighted suspended-sediment concentration. The accuracy of the adjustment was dependent on the size and concentration of particles present; these quantities varied with storm intensity, duration, antecedent conditions, and season. Although adjustment of only that size fraction greater than 0.062 mm in diameter was ideal, particle-size information was not available for every storm. The average difference, however, between the adjustments for nine storms for which particle-size information was

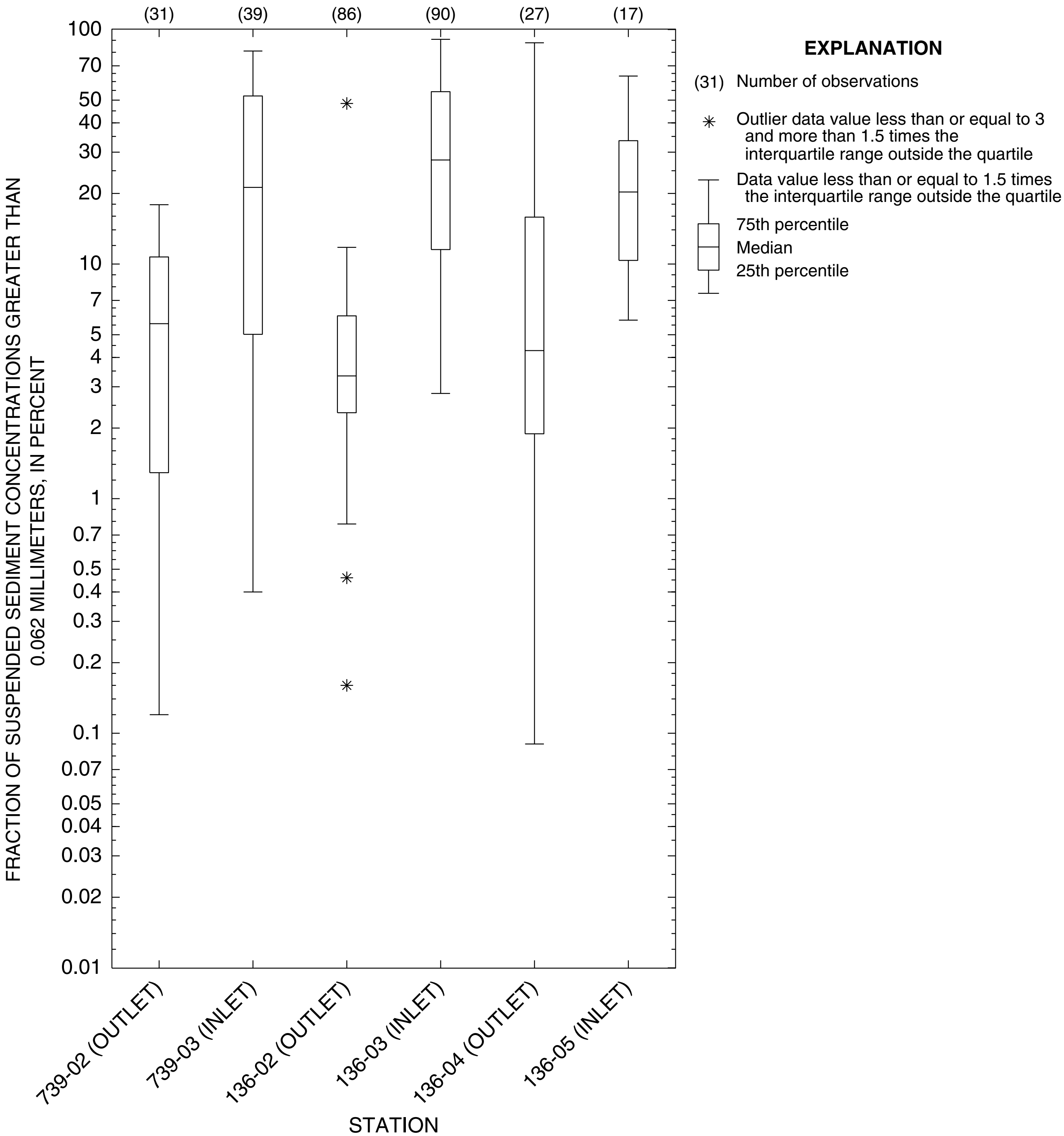

Figure 12. Particle-size distribution for samples of suspended sediment collected from the inlet and outlet of a deep-sumped hooded catch basin and two oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

available and for which total suspended-sediment loads and suspended-sediment loads greater than 0.062 mm in diameter were adjusted separately, was 16 percent. The small difference between the adjustment techniques suggested that the greatest correction was necessary during peak flows, which was generally when the largest suspended-sediment loads occurred and coarse materials were mobilized.

During the monitoring period of this study, 74 storms produced measurable runoff at station 136, and 59 storms produced measurable runoff at station 739. Samples for analysis of suspended sediment were not collected for 17 percent of the storms for the separator at station 739, for 28 percent of the storms for the separator at station 136, and for 43 percent of the storms at the catch basin at station 136. No bypass flows occurred during any of the unsampled storms. Typically, samples were not collected because of equipment malfunctions. Water levels in the outlet pipe and in the collection structure of the catch basin were lower than the sampler intakes during low-intensity storms, so more storms were not sampled for the catch basins than for the separators. Runoff events were sampled at a higher frequency for the oil-grit separators because they received the combined flows from several catch basins. To complete a mass-balance analysis, suspended-sediment loads were estimated for unsampled storms by multiplying the median EMC for suspended sediment at the inlet and outlet of each respective structural BMP by the total recorded flow.

Efficiencies of Structural BMPs

A mass-balance approach was used to assess the effectiveness of each structural BMP in reducing suspended-sediment loads. For each sampled storm, the efficiency of each device was estimated by subtracting the outlet load from the inlet load and dividing that difference by the inlet load ((IN-OUT)/IN). Similarly, the efficiency of each device for the entire monitoring period was estimated by subtracting the sum of all of the outlet loads from the sum of all of the inlet loads and dividing that difference by the sum of all of the inlet loads (($\sum$IN-$\sum$OUT)/$\sum$IN). In this case, the load sums included loads estimated from unsampled storms. The overall difference between the inlet and outlet loads was compared to the estimate of bottom material retained at the conclusion of the monitoring period in each structural BMP ($\sum$IN-$\sum$OUT=$\sum$RETAINED).

Annual Suspended-Sediment Loads

An annual suspended-sediment load was estimated for the study area by multiplying the annual highway discharge by normalized suspended-sediment loads measured during this study. The annual highway discharge was estimated by multiplying the estimated pavement runoff—relative to the long-term average annual precipitation measured by the National Oceanic and Atmospheric Administration (NOAA) in Boston, Massachusetts—by the total highway area. The sum of the monthly precipitation values at station 136 was about 2 in. less than the sum of the average monthly precipitation values measured by NOAA for 127 years. The inlet and outlet suspended-sediment loads estimated for similar time periods for the separators at stations 136 and 739 were respectively summed and normalized to the sum of the respective contributing areas. The pavement area of the two separator drainage basins represented about 9 percent of the total study area. Normalized inlet loads represented catch-basin discharge and normalized outlet loads represented separator discharges. The average effectiveness of each structural BMP and load was assumed to be similar throughout the study area. An annual mass of sediment retained by the five separators was estimated by normalizing the retained mass of bottom material for the separators at stations 136, 739, and 749 to the respective periods of operation during the study.

Predictors for Unsampled Suspended-Sediment Loads

Continuous measurements of turbidity were examined as a possible predictor for suspended-sediment concentrations. Turbidity is a measure of the light scatter caused by interference from suspended materials (such as silt, clay, and fine organic particles) and dissolved materials that produce color. Turbidity has been used in other studies to estimate suspended-sediment concentrations in fluvial systems (Brown and Ritter, 1971; Brown, 1973; Reed, 1978; Beschta, 1980; Smith, 1986; Gippel, 1995; and Lewis, 1996) and in many urban- and highway-runoff studies, including Irwin and Losey (1978), Cramer and Hopkins (1981), McKenzie and Irwin (1983); Dupuis and others (1985), Schiffer (1989); Spangberg and Niemczynowicz (1992); and Barrett and others (1996). Laboratory analysis of turbidity and suspended-sediment concentrations for 1,135 runoff samples collected from the inlet of each oil-grit separator and the outlet of the deep-sumped hooded catch basin indicates that the relation between measured values was qualitative (that is, it represents a range of values rather than an exact number) over the full range of measured sediment concentrations. For example, at a measured turbidity of 100 nephelometric turbidity units (NTU), the suspended-sediment concentrations ranged from about 70 to 2,000 mg/L and at a turbidity of 1,000 NTU, the suspended-sediment concentrations ranged from about 700 to 3,000 mg/L (fig. 13). The variability in the measurements was caused by larger particles that disproportionally influenced the turbidity in the small field of view of the instrument. Thus, the variability in turbidity measurements relative to suspended-sediment concentrations became smaller for samples with fewer particles greater than 0.062 mm in diameter. Therefore, the measurement of turbidity is an unreliable surrogate for suspended-sediment concentrations when the water sample contains particles greater than 0.062 mm in diameter, such as in highway runoff.

The relation of the EMCs for suspended sediment and load estimated from samples at each structural BMP inlet and outlet to measured storm precipitation and duration were investigated as a potential predictors for unsampled storm loads. Other potential predictors were 5-minute and 60-minute precipitation intensities, antecedent dry period, runoff duration, and average, peak, and total storm flow. Simple and multiple regression models with EMCs for suspended sediment and suspended-sediment loads from individual storms, however, indicated that no measured predictor could explain the variability in the EMCs for suspended sediment; the significant relations that were found between some of the potential predictors and the suspended-sediment loads resulted from the relations with rainfall or runoff characteristics that quantified flow per storm and the flow component (total discharge) of the suspended-sediment loads value. Therefore, because the EMCs for suspended sediment were characterized as log-normal, the median EMC value for suspended sediment for the monitoring period for each structural BMP was used with the measured flows to estimate unsampled storms. Consequently, the percentage of the suspended-sediment load estimated for the inlet and outlet of each structural BMP during the entire monitoring period was: about 11 percent and 18 percent, respectively, at the separator at station 739; and 17 percent and 20 percent, respectively, at the separator at station 136; and 23 percent and 17 percent for the catch basin at station 136. Suspended-sediment loads (including estimated loads) at the inlets and outlets of the BMPs, relative to storm precipitation measured at station 136, are shown for each structural BMP in figure 14.

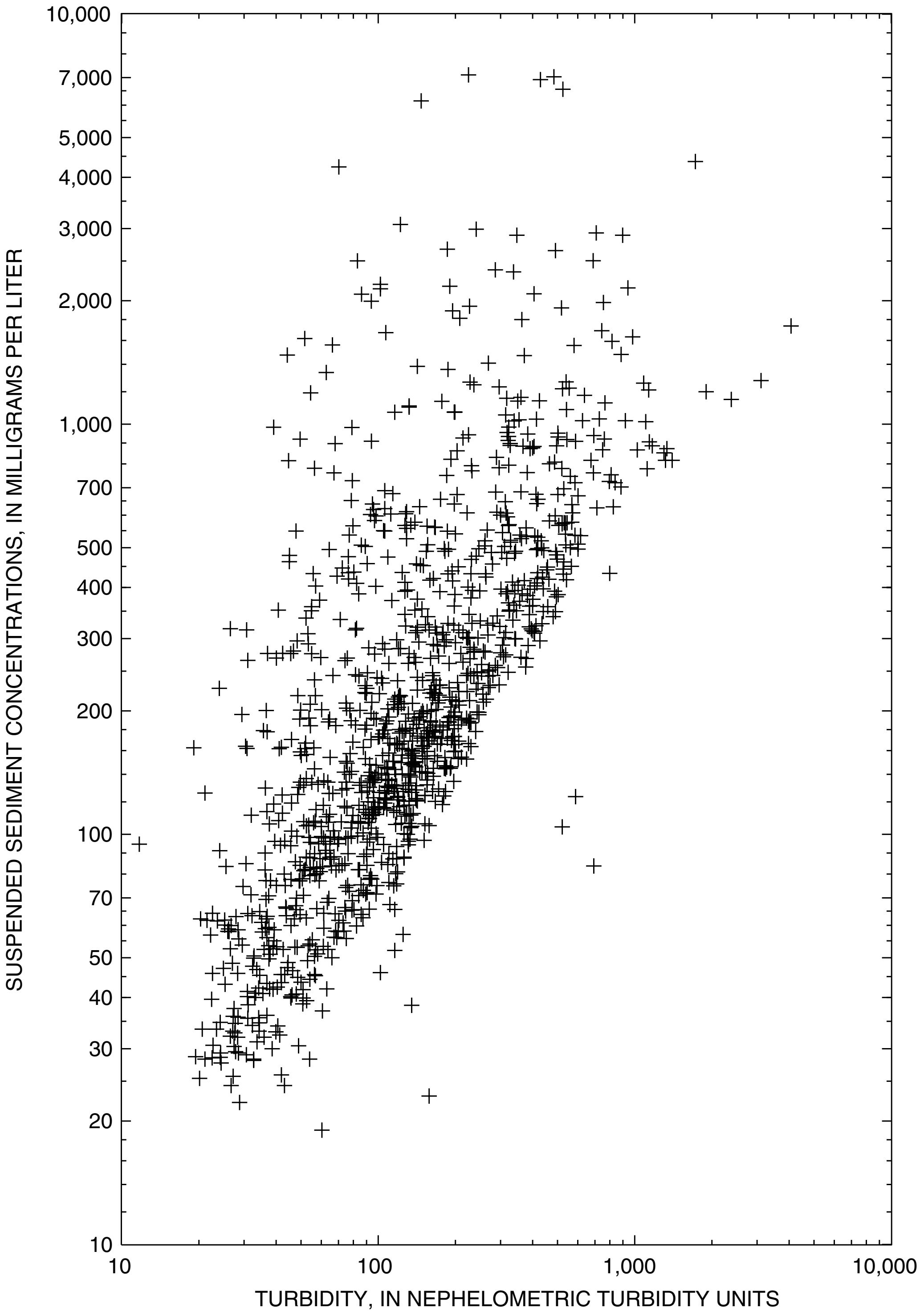

Figure 13. Relation of suspended-sediment concentrations to laboratory measurements of turbidity in samples collected from the outlet of a deep-sumped hooded catch basin and the inlet of two oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

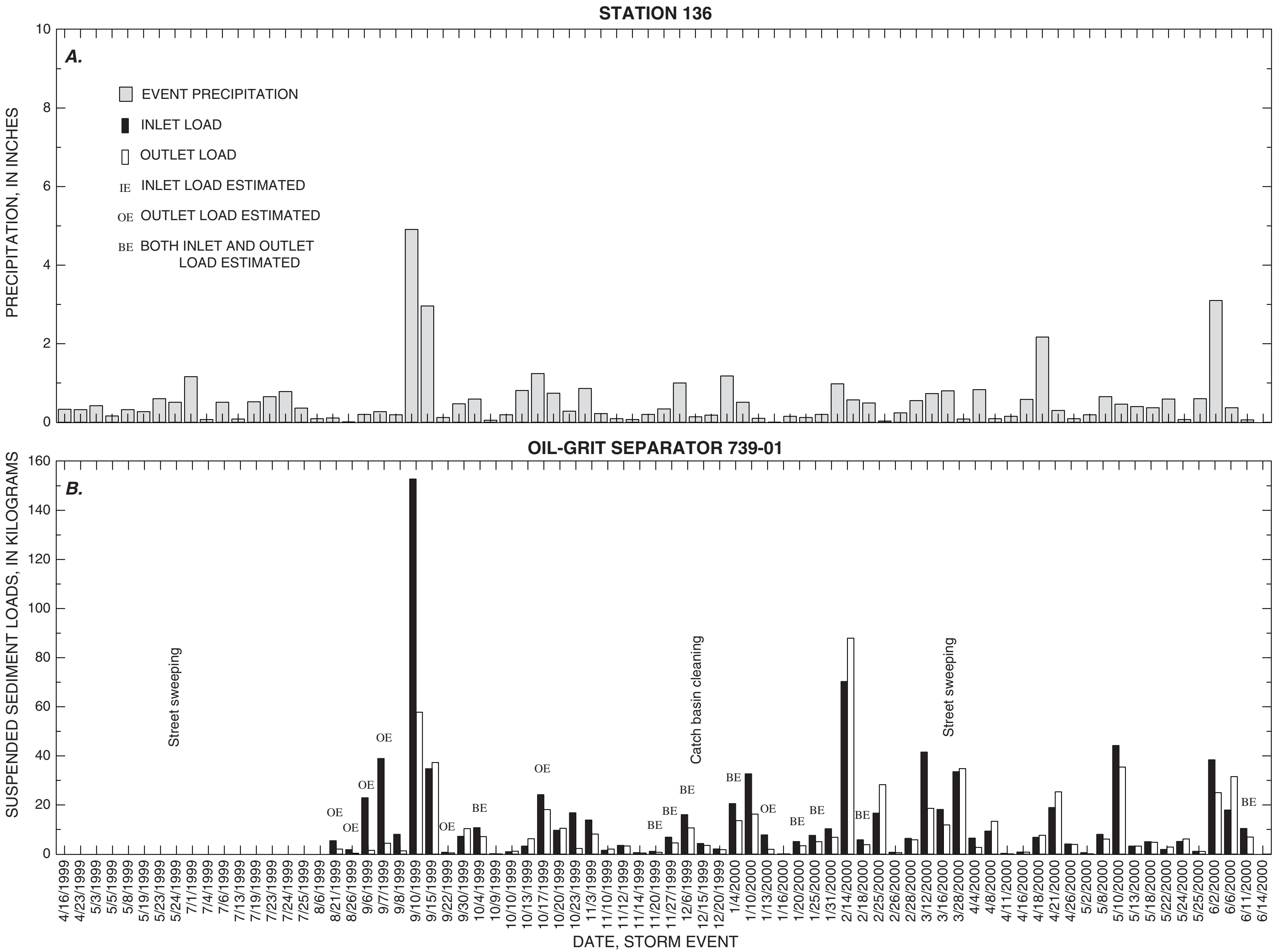

Figure 14. Total precipitation measured at station 136 for each runoff event and suspended-sediment loads for the inlet and the outlet of a deep-sumped hooded catch basin and the inlet and outlet of two oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

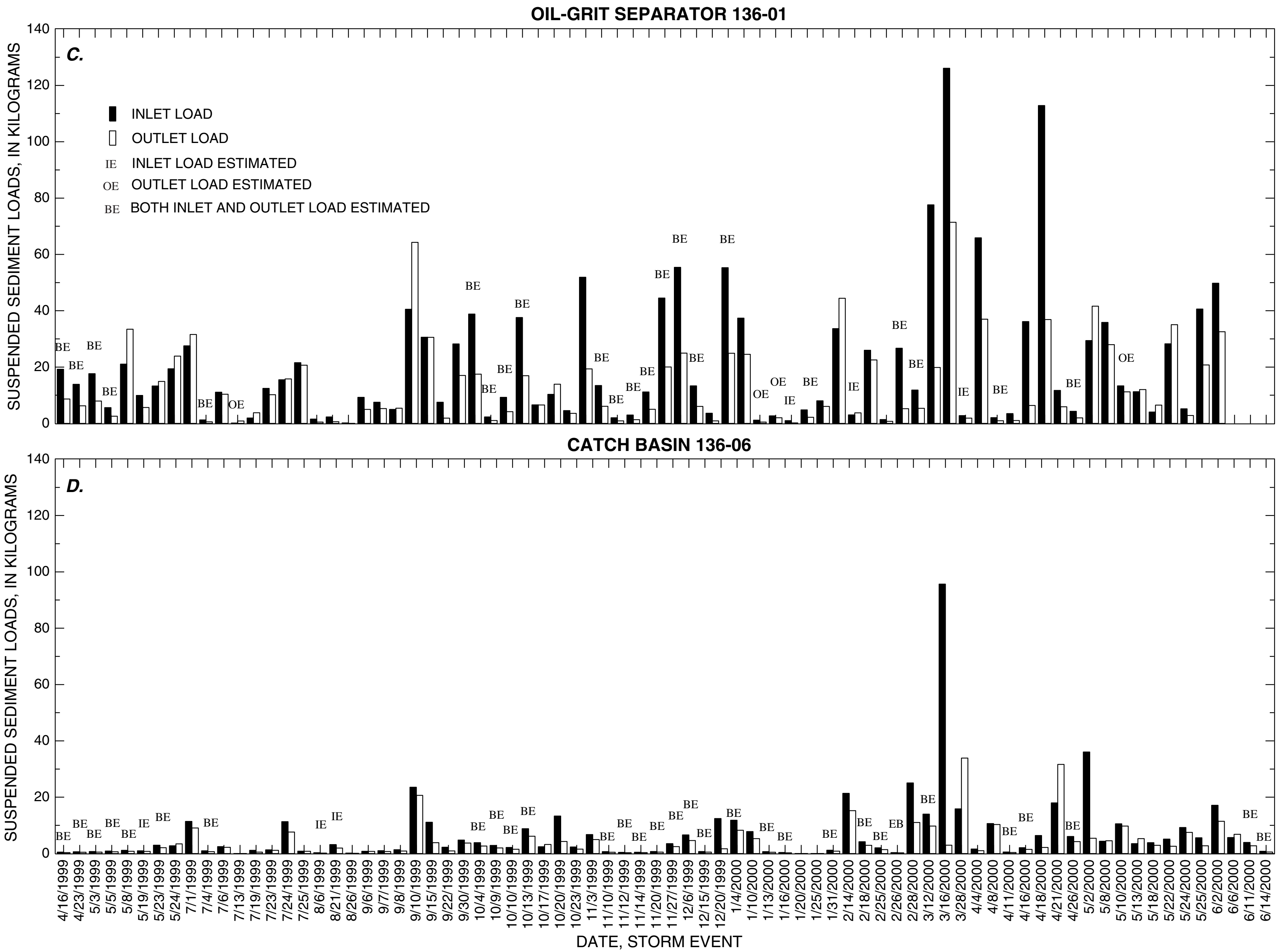

Figure 14. Total precipitation measured at station 136 for each runoff event and suspended-sediment loads for the inlet and the outlet of a deep-sumped hooded catch basin and the inlet and outlet of two oil-grit separators located along the Southeast Expressway, Boston, Massachusetts—*Continued*.

ASSESSMENT OF BEST MANAGEMENT PRACTICES

The principal purpose of most highway BMPS is to reduce the amount of sediment and sediment-associated constituents discharged from the roadway surfaces. The advertised effectiveness of many BMPs, in many cases, was determined theoretically, or the effectiveness was estimated on the basis of a few artificial storms where flow rate and particle size was controlled. In this study, structural BMPs were tested under real highway operating conditions for as long as 18 months. Automatic-monitoring and -sampling techniques were used to characterize the temporal and spatial variability in suspended-sediment loads and selected chemical concentrations transported through each structural BMP. A mass-balance calculation was used to quantify the accuracy of the estimated sediment removal-efficiency for each structural BMP. Thorough estimates of BMP efficiencies, such as these, are necessary to guide, substantiate, and defend highway BMP selection and planning decisions.

Temporal Variability of Retained Bottom Material

The volume of bottom material in the separators was estimated three times at stations 136 and 749, four times at station 739, and once in the catch basin at the conclusion of the monitoring period. Additional assessments of the bottom material in the catch basin were not practicable because the device was located beneath the travel lane of the highway. The volume of retained bottom material estimated during the initial assessment of each separator in November 1998 represented sediment accumulation from about three years of operation. Subsequent assessments were done in December 1999, January 2000, and in June 2000, when data collection was completed. Prior to cleaning the separator at station 739, one additional assessment was made in August 1999.

The physical distributions of bottom material in the separators were similar. In general, coarse material was deposited near the inlet of the primary chamber (fig. 2). A lateral deposit of less coarse material extended to each of the three baffle openings, with the greatest amount of material deposited near the baffle in the primary chamber. The corner opposite to the inlet and to the baffle of the primary chamber was generally free of deposition. The depth of bottom material in the second chamber of each separator was greatest near the baffle outlets and decreased near the chamber outlet. As the volume of material in the second chamber increased over time, the distribution of the bottom material became more uniform. The estimated total volume of retained bottom material in the separators at the conclusion of the study, in contrast to the estimated volume of retained bottom material in the separators after three-years of operation without any maintenance, was about 25 percent less at station 136 after a 14-month period, about 46 percent less at station 739 after a 10-month period, and about 108 percent greater at station 749 after a 18-month period (fig. 15). The depth of the bottom material in each chamber of the separators at stations 136 and 739 was not more than

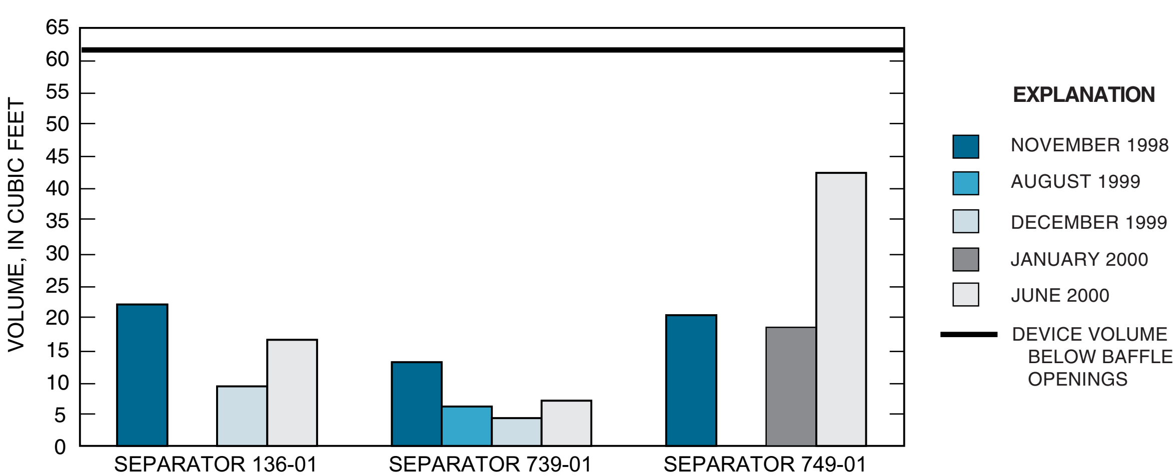

Figure 15. Temporal variability of the volume of bottom material in three oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

about 5 in.; the surface of the bottom material was located at about 72 percent of the distance to the bottom of the baffle outlets. The depth of the bottom material in each chamber of the separator at station 749, however, was about 14 in.; the surface of the bottom material was located at about 22 percent of the distance to the bottom of the baffle outlets. The difference between the volume of bottom material measured in each separator after three years of operation without any maintenance and at the end of the study periods indicate that the estimated rate of bottom-material accumulation was about two times greater during the study period at stations 136 and 739, and about seven times greater at station 749. The increase in the estimated rate of bottom-material accumulation is uncertain because the density of the bottom material for the first three years of operation was unknown and suspended-sediment data was not available prior to this study. One possible explanation for the increase in the rate of bottom-material accumulation during the study, or perhaps more specifically, the lack of accumulation during the first three years of operation, is that a single (or multiple) storm(s) resuspended a portion of the bottom material retained in the separators during the first three years of operation and flushed the suspended materials from the device. Thus, the rate of accumulation would have been distorted by the loss of retained bottom material. The lack of bottom-material accumulations in separators due to resuspension was noted by Schueler and Shepp (1993), who monitored 17 separators on a monthly basis. They found that sediment depths changed frequently, but that the mass of accumulated bottom material did not increase from year to year. In this study, the small increase of retained materials in the second chamber of the separator at station 749 between January 2000 and June 2000 indicated that small particles were easily resuspended as the level of sediment approached the bottom of the baffle openings.

Particle-Size Distribution and Contents of Retained Bottom Material

Samples of bottom material collected from each structural BMP and analyzed for particle size when data monitoring was completed represented a temporal composite of sediment and debris deposition for each structural BMP. Particle-size data for samples of bottom material are listed in appendix 1, table 1*F*. Most sediment in the catch basin (about 83 percent) and in the primary chamber of the three separators (a weighted average of 85 percent) was coarse-grained (greater than 0.25 mm in diameter), whereas a greater amount of sediment in the secondary chamber of the three separators was fine-grained (a weighted average of about 50 percent was less than 0.25 mm in diameter) (fig. 16). The percentage of particles found in each size class, for classes less than 0.062 mm in diameter and greater than 0.5 mm in diameter, was substantially

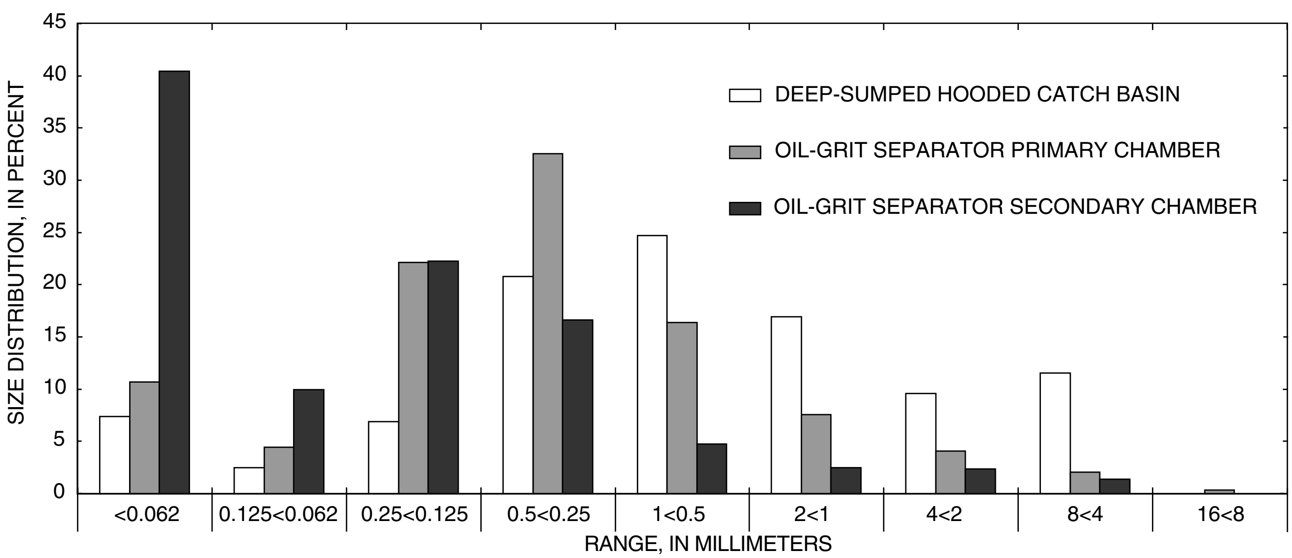

Figure 16. Particle-size distribution of a sample of bottom sediment collected from a deep-sumped hooded catch basin and the weighted-average particle-size distribution of samples of bottom sediment collected from three oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

different for the two chambers of the separators. Otherwise, the percentage of bottom material particles in each size class was similar, with respect to sample location, for each separator.

About 17 percent of the material in each separator and about 7 percent of the material in the catch basin was less than 0.062 mm in diameter. These percentages were larger than expected because the retention times of the structural BMPs were short. For example, the estimated time to exchange one complete volume of water in the catch basin, based on the median of the maximum storm flows, was approximately 7 minutes; the exchange rate for the separators was about 11 minutes. Maximum instantaneous flows measured during the monitoring period for the catch basin and the separator would have exchanged the volume of water in a minute or less for each device. It was unlikely that particles less than 0.062 mm in diameter were deposited during flow through the BMPs, because it can take a time interval from an hour to several days for particles in this size class to settle, even under static conditions. Thus, the occurrence of bottom-material particles in this size range was likely a result of static settling subsequent to each storm. Furthermore, the proportion of particles less than 0.062 mm in diameter was larger in the second chamber; this result indicates that particles in this size range in the first chamber were more often resuspended during runoff events.

Each chamber of the three separators was periodically inspected throughout the monitoring period for floating debris. Within 6 months of the separator cleaning, about 70 percent of the surface area of each primary chamber was covered with nondescript floating debris. The secondary chamber of each separator very rarely contained floating debris. Despite the visual appearance of the surface of the primary chamber, samples of bottom material collected in the secondary chamber contained nearly an order of magnitude more debris than samples collected in the primary chamber. Over time, some floatable debris could become neutrally buoyant and pass through the baffle during flow. Such materials were commonly retained in the second chamber below the baffle, where they were out of the path of direct flow. The floatable and nondescript debris found in samples of bottom material for each structural BMP is listed in table 4. Most of the floatable debris found in the samples consisted of natural organic material (leaves and sticks), followed by cigarette butts and plastic materials. Even with the use of hoods, which are intended to prevent floatable debris from leaving the catch basin, no debris was found floating in the catch basin at the conclusion of the monitoring period, and less than 1 percent by mass of samples of bottom material collected from the catch basin was identified as debris. This is likely the result of floatable debris circumventing the hoods during peak flows. It is important to note that the catch basin (136-06) had twice the average drainage area of other catch basins within the study area, thus, the peak flows at the catch basin (136-06) were probably greater than flows from typical catch basins in the area. The presence of floating debris noted at the water surface of the primary

Table 4. Composition of bottom material collected from a deep-sumped hooded catch basin and each chamber of three oil-grit separtors located along the Southeast Expressway, Boston, Massachusetts

[Values, except as noted, are in percent, by weight. kg, kilogram]

Material	Catch basin 136-06	Oil-grit separator							
		136-01		739-01		749-01		Average	
		Chamber		Chamber		Chamber		Chamber	
		One	Two	One	Two	One	Two	One	Two
Cigarette butts	0.0	0.1	1.4	0.1	2.6	0.6	2.5	0.2	2.2
Glass	.1	.1	.0	.1	.0	.0	.0	.1	.0
Plastic	.5	2.0	2.1	.8	.1	.3	1.4	1.1	1.2
Natural organics	.1	.5	8.4	1.2	7.1	1.0	1.8	.9	5.2
Metal	.0	.1	.0	.0	.0	.0	.0	.0	.0
Paper	.0	.0	.0	.0	.7	.0	.0	.0	.2
Sediment	99.2	97.2	88.2	97.8	89.5	98.0	90.4	97.6	89.5
Total amount of debris (kg)	234	343	134	159	31	397	385	300	183

chamber of all of the separators, however, suggests that the hoods do not effectively prevent floatable debris from leaving the catch basins.

Reduction of Debris and Litter

To document the relative ability of an oil-grit separator to retain large floatable particles, a debris-collection device was attached to the headwall outlet of the drainage system at station 739. Composites from 12 runoff events were collected from April through June 2000, when the monitoring period ended (fig. 17). A total of about 1.8 kg of material was retrieved from the collection structure for the twelve storms. The quantity of material collected for each storm increased with an increase in peak discharge. Gravel was removed from the collection structure twice, and both times bypass flow was recorded. About 71 percent (by mass) of total debris collected was associated with these two high runoff events. The bypass flow represented 7 percent and 1 percent of the total flow, respectively, for the two storms during this period. The quantity of material contained in the bypass flow, as opposed to the quantity of material passing through the separator, was not determined. The quantity of floatable debris retrieved from the collection structure from April through June 2000 represented about 23 percent of the total estimate of floatable debris retained in the separator after 10 months of operation. The percent of the total estimate of floatable debris was reduced to about 8 percent, assuming the entire loads associated with the two storms were carried in bypass flow and did not pass through the separator or originate as a result of resuspension of previously retained debris in the separator. Thus, even under typical operating conditions, the separators were not effective at retaining floatable debris.

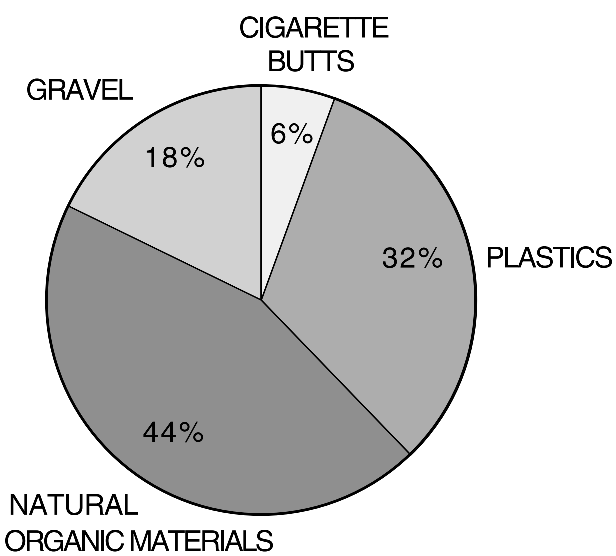

Figure 17. Relative quantity and type of debris retained from April 2000 through June 2000 in a collection structure mounted on a outlet of an oil-grit separator located along the Southeast Expressway, Boston, Massachusetts.

Variability in Suspended-Sediment Concentration Samples

The concentrations of suspended sediment in discrete samples of runoff collected from the inlets of the separators ranged from 8.5 to 7,110 mg/L, and concentrations of suspended sediment in discrete samples of runoff collected from the inlet of the catch basin ranged from 32 to 13,600 mg/L. The concentrations of suspended sediment in discrete samples of runoff collected from the outlets of the separators ranged from 5 to 2,170 mg/L, and concentrations of suspended sediment in discrete samples of runoff collected from the outlet of the catch basin ranged from 25.7 to 7,030 mg/L. Results of analysis of the inlet and outlet samples for each structural BMP are presented in appendix 1, table 1*A*. The median EMCs for suspended sediment at the inlet and the outlet for the separator at station 136 were estimated to be 333 and 150 mg/L, and 145 and 96 mg/L at station 739. The interquartile range (25th percentile minus 75th percentile) of the EMCs for suspended sediment for the inlet and the outlet of the separator at station 136 was estimated to be 362 and 180 mg/L, and 314 and 125 mg/L at station 739. The lower EMCs for suspended sediment at station 739 are likely due to the fact that a smaller portion of the drainage-area perimeter (outer edge of the highway) included an earth shoulder, which therefore produced less eroded soil on the pavement. The median EMCs for suspended sediment at the inlet and outlet for the catch basin were estimated to be 280 and 195 mg/L, respectively. The interquartile range for EMCs for suspended sediment at the inlet and the outlet of the catch basin was estimated to be 340 and 196 mg/L, respectively.

The results of the particle-size analysis of samples collected from the inlet of each structural BMP indicated that, generally, 50 percent or more of the suspended sediment in highway runoff consisted of material less than 0.062 mm in diameter (fig. 12), which is consistent with the findings in other studies. Yousef and others (1991) reported that 70 to 80 percent of the particles in highway runoff were less than 0.088 mm in diameter. Prych and Ebbert (1986) noted that most of the suspended material was less than 0.062 mm in diameter for many urban-runoff conditions. In the Southeast Expressway BMP study, more than 90 percent (by mass) of the particles in typical oil-grit separator outlet samples were less than 0.062 mm in diameter. The variability in the fraction of suspended sediment greater than 0.062 mm in diameter for samples collected from the outlet of the catch basin was substantial compared to samples from the catch basin inlet. This variability was an indication of device performance under different flow regimes. For example, the concentration of particles greater than 0.062 mm in diameter tended to increase during higher catch-basin outlet flows.

Effectiveness of Oil-Grit Separators in Reducing Suspended-Sediment Concentrations

The efficiency of the two 1,500-gal oil-grit separators in reducing suspended-sediment concentrations varied considerably. For example, the range of suspended-sediment removal efficiencies for individual storms was between -98 percent to +95 percent at station 136, and between -94 percent to +90 percent at station 739. Shepp (1995) reported a mean individual storm efficiency of -21.2 percent and a mean group storm efficiency of -7.5 percent from an oil-grit separator installed on a 1-acre parking lot. Other than Shepp's experiments, this author is not aware of any extensive testing of separators.

The principal factor affecting the efficiency of each device was retention time. Intense flows also affected the efficiency, but to a lesser extent. The ability of the separators to reduce suspended sediments characteristic of those along the Southeast Expressway was limited because the average particle size was less than 0.062 mm in diameter, and the average retention time in the separators ranged from about one hour to less than a minute. Although the separator volume was greater than that of a single catch basin, combined flows from multiple catch basins fed each separator, thereby increasing flow, reducing settling time, and inhibiting capture of fine material (fig. 18*C-D*). Settling velocities for urban and highway sediments can range from 0.03 to 65 ft/h (Dorman and others, 1996); thus, fine-grain sediment requires several days under static conditions to completely settle out. This effect becomes clear when examining the data from this study. For example, the average removal efficiency associated with storms less than 0.2 in. was 43 percent. Individual removal efficiencies greater than 43 percent for suspended sediment were observed in less than 37 percent of the storms at station 136 and less than 22 percent of the storms at station 739. This increase in device efficiency is a function of retention time and not a function of active treatment of the stormwater. Flows from small storms displaced previously retained stormwater in which the suspended sediments were reduced by settling during the static antecedent period. Consequently, the average efficiency ranged from about 32 to 81 percent when the same storms were sorted according to the antecedent period that ranged from less than a day to nearly six days (fig. 19). During this study, the median antecedent dry period was about 4.5 days.

In a few cases, outflow loads of suspended sediment from the separators exceeded inflow loads. This was likely the result of fine-grained bottom sediments that were previously captured becoming resuspended and discharged from the separators. These cases were marked by periods of high-intensity rainfall and high storm flows. The detection and quantity of resuspended sediment was difficult to determine because the amount of resuspended sediment may be small in comparison to the overall load. The relative retention time of the separators also affects the ability to detect and quantify resuspended sediment because a change in the inflow suspended-sediment concentrations is not immediately reflected in the outflow suspended-sediment concentrations. In fact, following high inflow suspended-sediment concentrations, it is not uncommon for discrete outflow suspended-sediment concentrations to be slightly higher than inflow suspended-sediment concentrations because a large concentration of the smaller size fraction of sediment remains in suspension and disperses throughout the device. The quantity of resuspended sediment may differ from storm to storm, due to the differences in prior storm characteristics. For example, a high-intensity storm may mobilize the fine-grained sediment retained in the separator over several small low-intensity storms, but subsequent high-intensity storms may cause no resuspension because little fine-grained sediment was available. Therefore, the absolute detection of resuspended sediment was limited to storms in which the suspended-sediment load discharged from the separator exceeded the suspended-sediment load entering the separator.

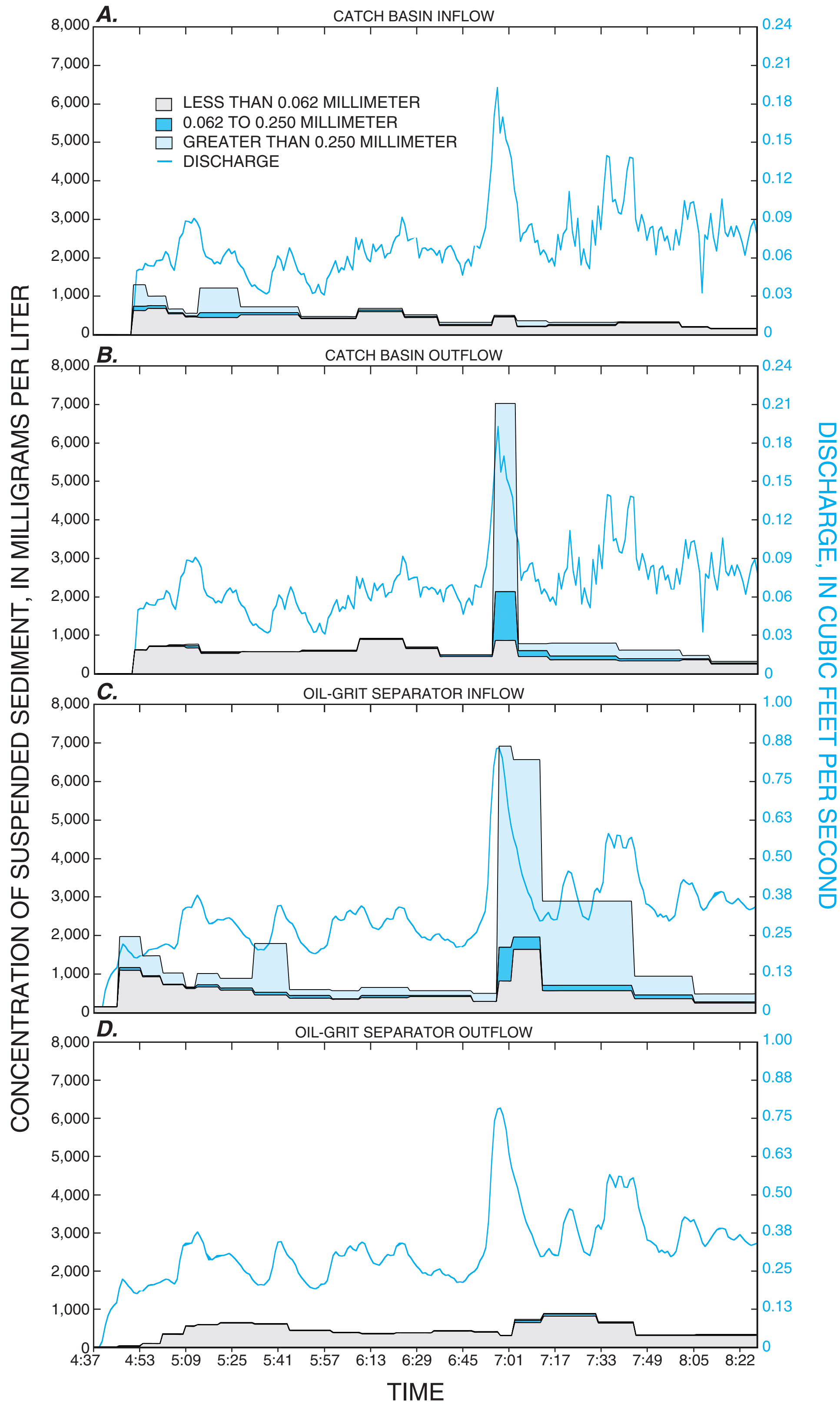

Figure 18. Suspended-sediment concentration and associated particle-size distribution in water moving through a deep-sumped hooded catch basin and a 1,500-gallon oil-grit separator located along the Southeast Expressway, Boston, Massachusetts.

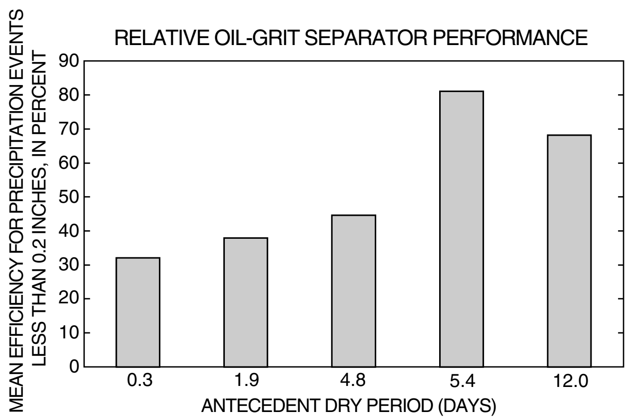

Figure 19. The relation of antecedent dry period to mean efficiency of oil-grit separators for precipitation events less than 0.2 inches, along the Southeast Expressway, Boston, Massachusetts.

The suspended-sediment load for the separator outlet exceeded the suspended-sediment load for the separator inlet, calculated directly from samples of suspended sediment without any water-column normalization, three times at each separator. The suspended-sediment load for the separator outlet, however, exceeded the normalized inlet load 14 and 13 times for separators 136 and 739, respectively. Because the normalization technique may be in error by as much as 24 percent, the suspended-sediment load for the separator outlet exceeded the normalized suspended-sediment load for the separator inlet (with respect to the potential error) nine and seven times for separators 136 and 739, respectively. The suspended-sediment load for the outlet of separator 136 exceeded the normalized inlet load six times during the operating period for station 739. The range of 5-minute rainfall intensities and separator flows during these storms was 0.04 to 0.23 in. and 0.46 to 0.97 ft^3/s, respectively, at station 136; and 0.04 to 0.18 in. and 0.48 to 2.81 ft^3/s, respectively, at station 739. During the monitoring period, storm flows in the separator at station 136 exceeded 0.46 ft^3/s 33 times, and storm flows in the separator at station 739 exceeded 0.48 ft^3/s 22 times. The flows from separator 136 exceeded 0.46 ft^3/s 24 times during the operating period for station 739. The greater maximum flows through separator 739 were the result of a higher diversion-weir elevation and a larger drainage area. The amount of resuspended sediment estimated for separators 136 and 739 represented about 8 percent of the final retained loads of suspended sediment. The frequency of instances in which outflow loads of suspended sediment exceeded inflow loads did not increase with the increase in captured sediment in either separator. The level of captured sediment in the second chamber of each separator, however, was several inches below the baffle, which would be out of the flow path.

Previous studies found resuspension of sediment to be a common problem in separators that were not located off-line (Schueler and Shepp, 1993). Untreated stormwater can bypass the separator during high flows, and the potential for flushing captured materials is reduced if the separator is off-line. In this study, bypass loads accounted for about 3 percent of the total load of suspended sediment for each separator. Bypass flow began when flows neared 0.4 and 1.9 ft^3/s at stations 136 and 739, respectively. The difference between the points at which bypass flow began to occur at each station was attributed to the differences in the diversion-weir height. Although the weir diverted a portion of stormwater to the bypass pipe, the flow through the separator was not limited and the flow through the device continued to increase with total flow. A decrease in weir height would increase the volume of bypass flow and reduce the frequency of resuspension of sediments; however, a reduction in weir height does not necessarily eliminate the potential for resuspension of sediments. Sediments (less than 0.062 mm in diameter), which settle under static conditions between each storm, will accumulate in the separators as long as flows are reduced to the point where no resuspension occurs. During most storms, a reduction in diversion-weir height may satisfy this condition. However, since the diversion weir does not limit flow through the separators, previously retained sediments (less than 0.062 mm in diameter) could become resuspended during the peak flow of a subsequent high intensity storm. Thus, the long-term operating efficiency of the separator would be reduced to a level similar to a separator with a greater weir height. Furthermore, an increase in bypass frequency will reduce overall device performance because a portion of the coarse-grained suspended sediment, typically mobilized during peak flows and easily retained by the separator, will bypass the structure completely. In this study, coarse-grained suspended sediment was not observed in samples from separator outflow during any hydrologic condition.

The estimated quantity of retained suspended sediment less than 0.062 mm in diameter relative to the total outlet load of suspended sediment for the separators at station 136 and 739, presumably consisting of suspended sediment less than 0.062 mm in diameter and larger low-density particles, was 9 and 6 percent, respectively. Because the particle-size distribution of suspended sediment was similar for the two stations, the smaller retained percentage of bottom sediment less than 0.062 mm in diameter measured at station 739 indicated that a greater amount of resuspension occurred at this station. This resuspension was likely attributed to greater flows caused by the higher diversion weir. The estimated quantity of suspended sediment that bypassed the separators compared to the amount of sediment resuspended at each station was about 20 percent higher at station 136 and about 16 percent lower at station 739. Bypass flow occurred more frequently at the separator at station 136. If the separators were not located off-line, and if all sediments less than 0.062 mm in diameter were resuspended and discharged between storms, the efficiency of each device would have been reduced additionally by about 5 percent. Conversely, decreasing the diversion weir height to a point at which no resuspension occurred would cause an exponential increase in untreated bypass load and would have reduced the overall efficiency for each separator substantially more than 5 percent. Thus, without the ability to limit flow to less than 0.46 ft^3/s through the device, changes in weir height will not cause a substantial benefit. Resuspension could be drastically eliminated by reducing the drainage area of the device by a factor of about five or by maintaining (cleaning) the device between storms. Neither option is cost effective or practical.

The absolute difference between all of the inlet and outlet loads of suspended sediment for the separators was 35 percent for station 136 and 28 percent for station 739. The separators retained 477 kg of solids (after 14 months) at station 136 and 190 kg (after 10 months) of solids at station 739, on the basis of volumetric assessments. The relative mass balance error (($\sum$SUSPENDED SEDIMENT IN-$\sum$SUSPENDED SEDIMENT OUT)=$\sum$RETAINED BOTTOM MATERIAL) for the separators was about 12 percent at station 136, and 25 percent at station 739. The efficiency computed from the estimated mass of material retained in each separator at the conclusion of the monitoring period and from the total outflow load was 32 percent at station 136 and 24 percent at station 739. The small difference between these results from the two methods used to estimate the efficiency of the separators indicates that the normalization of the inflow loads was reasonable. The estimated difference between the mass-balance approaches was within the cumulative uncertainties of the various measurement processes. In the combined-treatment system evaluated in this study, if catch basins that provided primary suspended-sediment treatment are assumed to have an average efficiency of about 41 percent, the separators reduced the suspended-sediment load by an additional 18 percent with respect to the initial load on the pavement.

Effectiveness of Deep-Sumped Hooded Catch Basins in Reducing Suspended-Sediment Concentrations

The efficiency of the deep-sumped hooded catch basin in removing suspended sediment for individual storms ranged from -114 to +97 percent. In simulated tests, where particle size, density, and concentrations were controlled, Lager and others (1977) found suspended-sediment removal efficiencies of 35 to 90 percent over a flow range of 0.25 to 6.3 ft^3/s for catch basins with 4-ft sumps. Catch basins with sumps ranging from 0.5 to 5 ft in an urban area were found to have suspended-sediment removal efficiencies ranging from -10 to +97 percent (Aronson and others, 1983).

Storm characteristics affected the hydraulic retention time, catch-basin turbulence, and the mobilization of sediment on the roadway. The average catch-basin retention time was about 1 hour; however, retention times were as low as 37 seconds during brief periods of peak flow. The catch basin lacked sufficient retention time, even during flows as low as 0.03 ft^3/s, to retain suspended sediment less than 0.062 mm in diameter. Particles less than 0.062 mm in diameter in the catch basin have been retained as the result of static settling. In general, the catch basin retained high-density, medium- and coarse-grained particles. Thus, the performance of the catch basin improved when these respective particle sizes were mobilized in storm flows. Catch-basin performance declined as flow increased, catch-basin turbulence increased, and retention time decreased. Lager and others (1977) found a 93-percent reduction in catch-basin performance with respect to small particles (0.250 to 0.100 mm in diameter) over a flow range of 0.25 to 6.3 ft^3/s in a clean catch basin, but only a 60-percent reduction in performance with respect to heavy solids (greater than 0.250 mm in diameter).

Resuspension of bottom sediments was caused by excessive turbulence within the catch basin during peak flows. The literature suggests that when the level of retained material approaches or exceeds 50 percent of the catch-basin sump depth, sediments are resuspended. In simulated tests, sediment that accumulated in catch basins did not affect removal efficiencies of suspended sediment until 40 to 50 percent of the storage depth was filled (Lager and others, 1977). In the Southeast Expressway BMP study, resuspension was detected during several storms, although the volume of sediment retained in the catch basin was less than 25 percent of the sump depth at the conclusion of the monitoring period. Sequential suspended-sediment concentrations of discrete outflow samples were frequently found to be substantially greater than respective inflow concentrations during flows greater than 0.14 ft^3/s. At this flow rate, the retention time of the catch basin was less than 6 minutes. Further increases in discharge during peak flow often diminished the retention time and caused sediments larger than 0.250 mm in diameter to become resuspended as illustrated in figure 18*A-B*. During seven storms, outflow loads of suspended sediment exceeded inflow loads because previously retained sediments were resuspended, mixed with suspended sediment from the inflow, and discharged from the catch basin. The range of 5-minute rainfall intensities and storm flows was 0.04 to 0.17 in., and 0.14 to 0.69 ft^3/s, respectively. Storm flows exceeded 0.14 ft^3/s 30 times during the monitoring period. The estimated amount of resuspended sediment represented 18 percent of the final retained load of suspended sediment. The frequency of cases where outflow loads of suspended sediment exceeded inflow loads did not increase with an increase in captured sediment volume in the catch-basin sump.

The total difference between the inlet and outlet loads for the catch basin was 39 percent. An estimated 234 kg of solids was retained by the catch basin. The relative mass-balance error for the catch basin was -14 percent. The efficiency computed from the estimated quantity of material retained at the conclusion of the monitoring period and from the total outflow load was 43 percent. The primary factor controlling the suspended-sediment removal efficiency of the catch basin was retention time. The efficiency for catch basins along roadways can vary depending on the drainage area, the particle-size distribution for suspended sediment, and device maintenance.

The particle-size distribution of suspended sediment measured in samples collected from the outlet of the catch basin was different from the particle sizes of suspended sediment measured in samples from the separator inflow at station 136 (fig. 18*B-C*), which collected outflows from eight catch basins. Higher sustained concentrations of particles greater than 0.062 mm in diameter in the combined catch-basin outlet flows indicated a reduction in suspended sediment removal efficiency in one or more of the catch basins within the separator drainage area. The performances of the catch basins could have been different from one another because the individual contributing areas affected the quantity and rate of flow for each catch basin. The contributing areas of the other catch basins were 50 percent less than the area of the monitored catch basin, except for one area, which was about 50 percent larger and represented about 31 percent of the separator drainage area. The catch basin in this larger area was located on a southbound emergency pull-off lane. The entire right-side shoulder did not have a curb and was subject to soil erosion during runoff events. In this location, the quantity of suspended sediment and the particle-size distribution could have been substantially different. The higher flow, increased turbulence, and reduced retention time would have negatively affected the performance of the single catch basin in removing suspended sediment in runoff from the larger contributing area. Therefore, the suspended sediment discharged from this single catch basin may have affected the particle-size distribution in the combined flows. Conversely, the performance of most catch basins within the separator drainage area in removing suspended sediment should have been equal to or higher than that of the monitored catch basin, because most of their contributing areas were smaller.

Annual catch-basin cleaning was accomplished with a mechanical bucket truck in the late fall of 1999. This crane-mounted cleaning mechanism, also known as an orange-peel excavator, consisted of four movable opposing jaws to remove retained bottom materials without sump water. This method did not remove all of the bottom material. In fact, fine material was lost from the bucket when it was raised from the sump. The combined suspended-sediment load from the catch-basin outlet, as estimated from the separator inflow, was not substantially different before and after annual catch-basin cleaning. This finding indicated that the differences in the amount of retained bottom material in the catch basins located within the drainage areas of stations 136 and 739 did not substantially affect catch-basin performance. Late winter or spring catch-basin maintenance may provide a greater benefit than fall maintenance because high-intensity rainfall, during summer thunderstorms can cause resuspension of bottom sediments in the catch basins, even when the volume of bottom material represents less than 25 percent of the catch-basin sump.

Estimated Loads of Suspended Sediment in the Study Area

The estimated annual load of suspended sediment for the entire study area of highway pavement is about 29,000 kg. About 24,000 kg is discharged near the Malibu Beach and Tenean Beach embayments and the remaining 5,000 kg is discharged to the land surface where it infiltrates into the ground. These loads do not include an estimated 2,000 kg of sediment and other materials, retained annually by the five separators, which are assumed to be cleaned annually.

Mechanized Street Sweeping

Mechanized street sweeping is an effective alternative to structural BMPs for reducing sediment and debris in commercial and urban areas (Young and others, 1996). Many variables can affect sweeping performance, such as, the number of passes made, road surface and curb condition, particle-size distribution, quantity of material on the road surface, interval between treatments, and the type of equipment used. Shoemaker and others (2000) noted that the total solid-removal efficiency for mechanical sweepers was 55 percent between storms and as high as 93 percent for vacuum-assisted sweepers. However, sweeping between storms and multiple passes were necessary to attain efficiencies this high. Despite poorer overall performance, mechanical sweepers are more effective at picking up larger debris (greater than 0.40 mm in diameter) than vacuum-assisted sweepers. In addition, vacuum-assisted sweepers have the disadvantage of low operation speeds which make them impractical for highway applications (Young and others, 1996).

The effectiveness of sweeping was assessed by evaluating the differences between suspended-sediment loads for each BMP inlet for storms before and after sweeping relative to storm precipitation totals. The highway was swept three times during the study period. The first sweeping occurred in June 1999 prior to the activation of station 739 and during a 6-week dry period. The second sweeping was done on March 16, 2000, and all stations were operating. Data collection at each station was discontinued before the final scheduled sweeping. The particle-size distribution of sweeping samples is presented in appendix 1, table 1*E*. Figure 14*B-D* illustrates the effects of each sweeping on suspended-sediment loads for each structural BMP. No substantial differences were observed between the pre-sweeping and post-sweeping inlet loads of the catch basin and the inlet loads of the separator at station 136 for the initial June 1999 sweeping. Substantial increases in inlet loads for both BMPs at station 136 were observed after the March 16, 2000, sweeping. Visual observations of the northbound highway shoulder in the vicinity of this station prior to the subsequent storm indicated that the sweeper's rotary brushes contacted and destabilized the soil near the edge of the pavement, from which large amounts of sediment were released and mobilized during the subsequent storms. Conversely, the suspended-sediment load measured in samples from the separator inlet at station 749 was reduced relative to previous storms of similar size. Furthermore, inlet and outlet suspended-sediment loads for station 749 were similar for the next two storms, which indicated that coarse material was absent. Sweeping-equipment limitations precluded the reduction of fine-grained sediment loads, which typically dominated the suspended-sediment load.

The effectiveness of street sweeping was qualitatively assessed by evaluating the differences among the particle-size distribution of sweeper samples, bottom-sediment samples collected in the catch basin and the weighted average of bottom-sediment samples collected from the three separators (fig. 20). The particle-size distribution of pavement sweepings closely resembled the particle-size distribution of the catch-basin sediments in all size classes less than 4 mm in diameter. Pavement sweepings had a lower concentration of particles greater than 0.5 mm in diameter than that of bottom sediment collected from the separators.

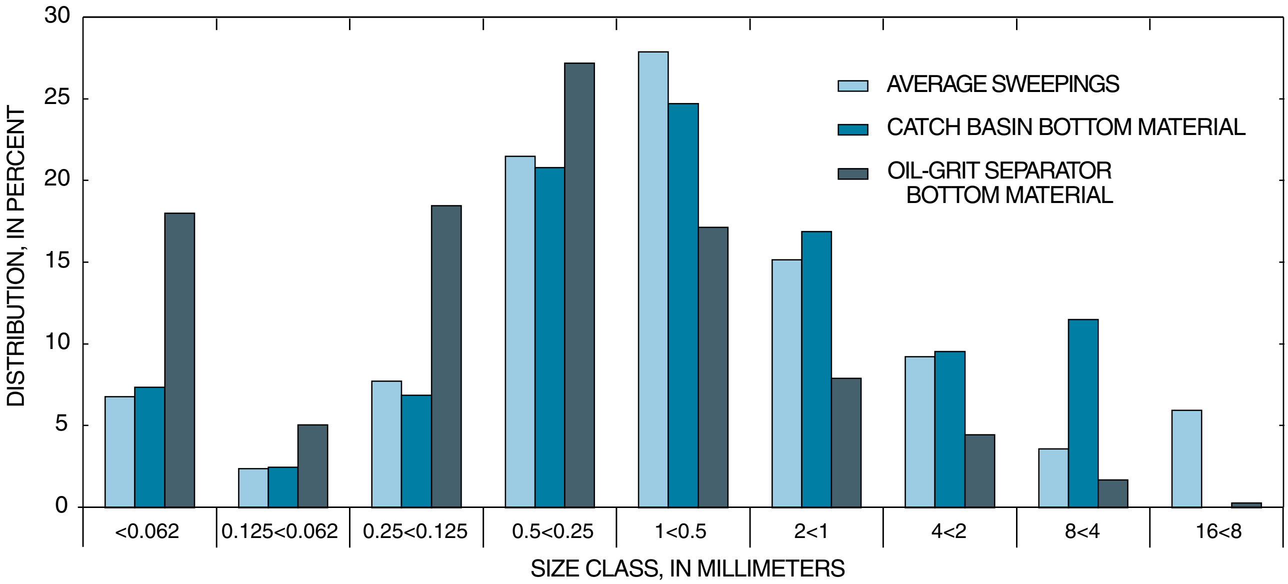

Figure 20. Average size distribution of pavement sweepings collected from a mechanical sweeper in contrast to the size distribution of a bottom-sediment sample collected from a deep-sumped hooded catch basin and the weighted-average particle-size distribution of samples collected from three 1,500-gallon oil-grit separators along the Southeast Expressway, Boston, Massachusetts.

On the basis on these data, the greatest benefit of annual street sweeping was the removal of particles greater than 8 mm in diameter that were not routinely mobilized during storm flows. Except for reducing the clean-out frequency for the catch basins and separators, frequent sweeping (several times a month) would provide little water-quality benefit beyond that offered by the existing structural BMPs along the Southeast Expressway. Sweeping provided little water-quality benefit for the Southeast Expressway because the highway lacks curbing that would provide a physical boundary to trap debris and sediment, and because the equipment did not remove the dominant particles (that is, particles less than 0.062 mm in diameter), efficiently.

Variability of Concentrations of Chemical Constituents in Sediment

Sieved bottom sediments from the three 1,500-gal oil-grit separators were analyzed for highway-related inorganic and organic constituents. Concentrations of inorganic constituents were determined by the EPA 3050 analytical method; a second method, XRAL analytical method ICP70, was used for analysis of selected samples. Constituent-concentration data are listed in appendix 1, table 1*G*. Bismuth (Bi) and Tungsten (W) were the only constituents not found in any of the samples at a detection limit of less than 10 ppm by either analytical method. Mercury (Hg) was not found in any of the samples at a detection limit of 1 ppm by the EPA 3050 analytical method; the XRAL method did not analyze for Hg. Antimony (Sb) was the only constituent not detected by the EPA 3050 analytical method, but it was detected by the XRAL method. In some cases, tin (Sn), and silver (Ag), and phosphorus (P) were not detected by the EPA 3050 analytical method, although they were detected by the XRAL method.

In general, concentrations of inorganic constituents generated by each method were similar. With the use of these digestive techniques, the constituents that are weakly sorbed with the solid phase and are not part of the mineral matrix are measured. Many environmental factors, such as low pH, low redox, low dissolved oxygen, or high ionic strength may consequently cause these weakly bound elements to repartition into the dissolved phase (Breault and others, 2000). Measurements of low dissolved oxygen in the water column of the separators during the summer and measurements of high specific conductance (an indicator of ionic strength) during winter maintenance periods were common. Therefore, high concentrations of trace elements measured in samples of bottom sediments indicate that, under favorable conditions (that is, in some state of equilibrium with the bottom sediments), the overlying water column may have become enriched with trace elements. These constituents would then be easily transported from the separators once they were redistributed to the dissolved phase.

Concentrations for all inorganic constituents were typically higher for the sediment fraction less than 0.062 mm in diameter, except for Cr and Na in all samples, and As and Sn in one sample. Beryllium (Be) was the only constituent not detected in sediment fractions greater than 0.062 mm in diameter. With a few exceptions, concentrations of Sb, As, Cd, and Ag were only found in the sediment fraction of less than 0.062 mm in diameter. Results of chemical analysis for inorganic elements in bottom sediment relative to particle size are illustrated in figure 10. The disproportional differences between concentrations of inorganic constituents relative to grain size are well documented (Forstner and Wittmann, 1981; Salomons and Forstner, 1984; Horowitz and Elrick, 1987, 1988; Horowitz, 1991). In general, sediment surface area and trace-element concentrations tend to increase with a decrease in sediment-grain size. Furthermore, the silt- and clay-sized particle group contains more clay minerals, which typically have higher sorptive capacities. The potential effectiveness of the separators in reducing loads of inorganic constituents was several times less (as much as an order of magnitude depending on the constituent relation to grain size) than its effectiveness in reducing suspended sediment (consisting of fine- and coarse-grained material); most of the suspended sediment entering the separators was less than 0.062 mm in diameter, and the concentrations of inorganic constituents in the sediments less than 0.062 mm in diameter were about 2 to 10 times higher than the concentrations of inorganic constituents in sediments greater than 0.062 mm in diameter.

Concentrations of TOC, PCBs, and PAHs were detected in all sediment samples and size fractions. Concentrations of organic constituents did not follow the same pattern as the inorganic constituents. Results of chemical analysis of organic compounds in bottom sediments relative to particle size are presented in figure 11. Concentrations of TOC were similar for the solid fraction less than 0.062 mm in diameter and greater than 2.00 mm in diameter. However, estimated concentrations of TOC for the entire solid fraction less than 2.00 mm in diameter were as much as one order of magnitude lower than for the fraction greater than 2.00 mm in diameter. The greater amount of TOC in the solid fraction greater than 2.00 mm in diameter was mainly attributed to natural organic particles (leaves) and asphalt particles. Total PAH and PCB compounds were found in larger concentrations in the solid fraction greater than 2.00 mm in diameter than in the solid fraction less than 2.00 mm in diameter. The greatest factor affecting concentrations of semivolatile organic compound (SVOCs) in the solid phase is the content of organic carbon (Lopes and Dionne, 1998). The grain size of mineral particles, unless they have an organic coating, is not a significant factor affecting SVOC concentrations (Witkowski and others, 1987). Thus, substantial differences in the TOC content of the size fractions less than 2.00 mm and greater than 2.00 mm in diameter may explain the PCB and PAH distribution. Furthermore, this would indicate that the PCB and PAH concentrations in the solid fraction less than 0.062 mm in diameter would be similar to the concentrations in the solid fraction greater than 2.00 mm in diameter; they might be greater in the smaller size fraction because of the effects of the increased surface area. Therefore, the potential effectiveness of the separators to reduce loads of organic constituents was several times less (as much as an order of magnitude) than its ability to reduce suspended sediment because (a) most of the suspended sediment entering the separators was less than 0.062 mm in diameter, (b) only about 6 percent of the bottom material retained in the separators was greater than 2 mm in diameter, and (c) the separators did not indefinitely retain floatable debris, which may contain concentrated levels of organic compounds.

Local soils can generate as much as 30 percent of suspended sediment entrained in highway runoff (Gupta, 1981). Local soils are deposited on the highway between storms by wind erosion or hydraulic erosion of the roadway shoulder and adjacent areas subject to similar forces, or directly deposited on the road from automobiles. Average constituent concentrations for bottom sediments in the three separators and weighted on the basis of the distribution for the three particle-size fractions were estimated from constituent concentrations of sieved samples. These data are contrasted to background soil samples representing coastal Massachusetts (Shacklette and Boerngen, 1984) in figure 21. Concentrations of Cr, Cu, Pb, Ni, and Zn, typical constituents of highway runoff (Young and

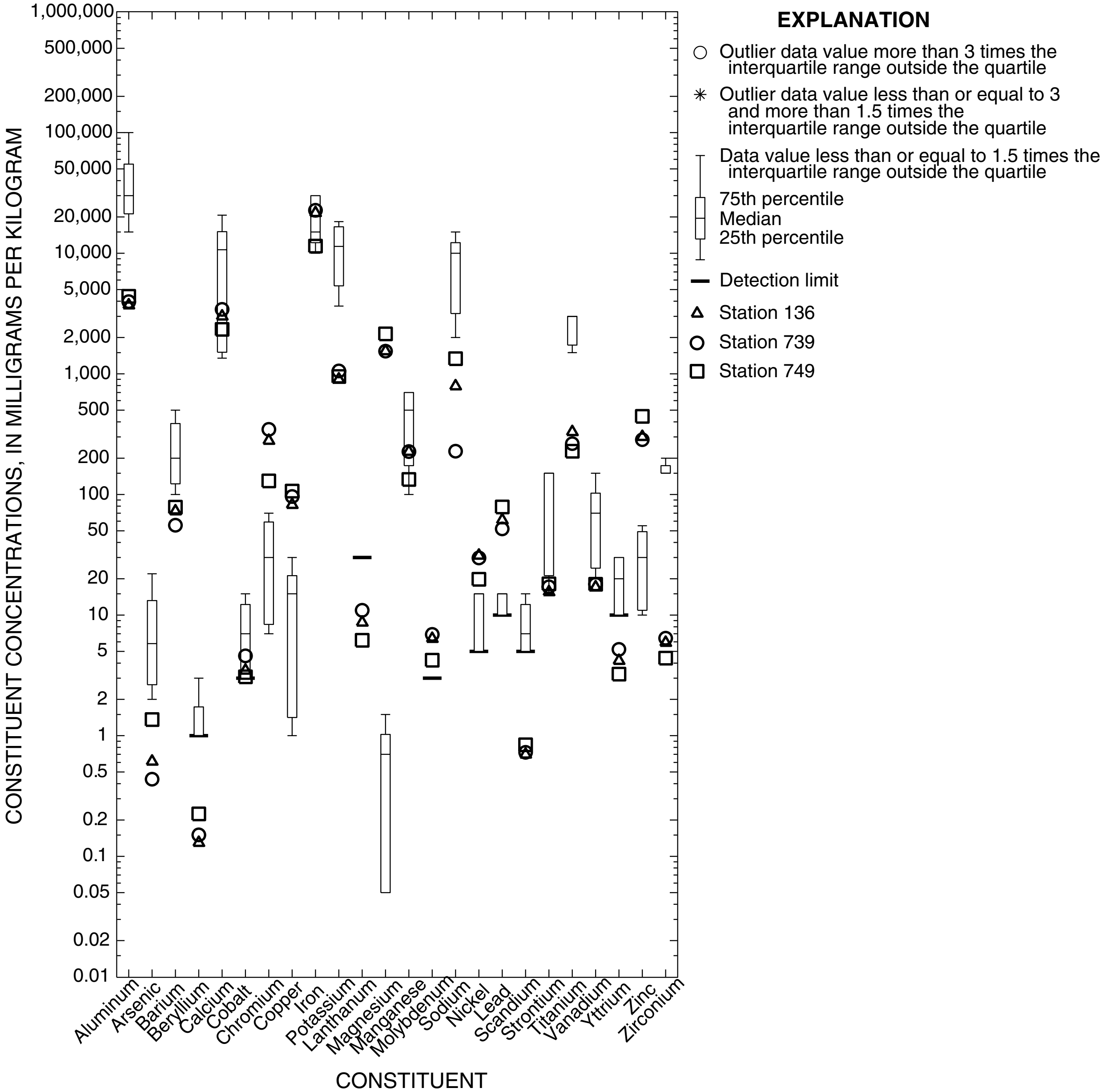

Figure 21. Comparison of local soil chemistry to samples collected from oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

others, 1996), were as much as one order of magnitude greater in the bottom sediments from the separators than in local soils. Magnesium (Mg) concentrations in bottom sediment were about 2,000 times greater than in local soils. Concentrations of other constituents were either within their ranges in the soil or were less than in the soil. These data indicate that about 15 percent of the highway-affiliated metals could be attributed to local soils.

Reduction of Chemical Constituent Loads Discharged in Storm Flows

Samples for the analysis of concentrations of inorganic and organic constituents were collected at the inlet and the outlet of each structural BMP during four runoff events that reflected most seasonal variations during the monitoring period. EMCs of chemical and biological constituents are presented in appendix 1, table 1*H*. Total precipitation for the storms ranged from 0.34 to 0.74 in.; most of the storms produced more precipitation than the average for all storms during the monitoring period. The individual and average RPDs between the inlet and the outlet (inlet minus outlet) concentrations for selected constituents for each structural BMP for four storms is illustrated in figure 22. The average RPD for concentrations of sediment-associated constituents for the catch basin ranged from -29 to +42 percent. The average RPD for concentrations of trace metals was about 25 percent. The average RPD for concentrations of organic constituents was typically less than 20 percent and even negative in several cases, except for oil and grease, which was near 30 percent. The average RPD for concentrations of sediment-associated constituents for the separators ranged from -129 to +44 percent at station 136, and -47 to +21 percent at station 739. The average RPD for concentrations of trace metals was about 30 percent at station 136, and about 15 percent at station 739. The average RPD for concentrations of organic constituents for both separators was commonly less than about 10 percent and negative in several cases.

Under ideal conditions, the RPD could be considered the main measure of efficiency of each structural BMP; however, the RPD does not represent the efficiency for the BMPs because the initial samples collected at the outlet do not represent water from the sampled storm, but water from the previous storm. Furthermore, the final inlet samples were not represented in the final outlet samples. For example, if we assume the following circumstances:

(a) the frequency of sampling was proportional to flow;

(b) each pair of samples represented one device volume; and

(c) the device exchanged its volume 20 times over the course of a storm,

Then the initial outlet sample would not be represented in the initial inflow sample and the final inflow sample would not be represented in the final outlet sample. Thus, as much as a 10 percent error (2 samples divided by 20) could be expected in the RPD. Furthermore, the total dissolved solid concentrations for the storm, which included all of the material that would never settle out of solution by gravity, should be similar for the inlet and outlet samples for each device under ideal sampling conditions. EMCs of total dissolved solids collected from the inlet and outlet at the separators, however, were commonly within 14 percent, and the EMCs of total dissolved solids collected from the inlet and outlet of the catch basin were as high as 57 percent; these large differences indicate that the samples represented different sources of water. This was further demonstrated during the March 17, 2000, storm, during which the rain turned to snow in the final hours of the storm and deicing compounds were applied to the roadway surface. The last two inlet samples at the separator at station 739 contained high concentrations of total dissolved solids which were not in the outlet samples; thus, the RPD for EMCs of total dissolved solids increased to nearly 80 percent.

The calculated RPD between inlet and outlet EMCs for sediment-associated constituents for each structural BMP was probably too large, because the concentration of suspended sediment in all four storms was greater than the median EMC of suspended sediment. The March storm accounted for about 18 percent of the total inlet load of suspended sediment for the catch basin for the 14-month monitoring period. The EMCs for suspended sediment for each BMP for these four storms accounted for 9 to 23 percent of the total load of suspended sediment measured during the monitoring period. Furthermore, the RPD for concentrations of each constituent for the separators does not include the effects of the primary stormwater treatment provided by the catch basins. For example, if the RPD between inflow and outflow EMCs of Pb for the catch basins within the drainage area of a separator is 30 percent, and the RPD between inflow and outflow EMCs of Pb for the separator itself is 20 percent, the actual reduction of initial highway concentrations of Pb by the separator is actually only 14 percent. Therefore, the RPDs between the inflow and the outflow EMCs of constituents sampled in this study should not be considered as the actual reduction of constituent concentrations by the separators.

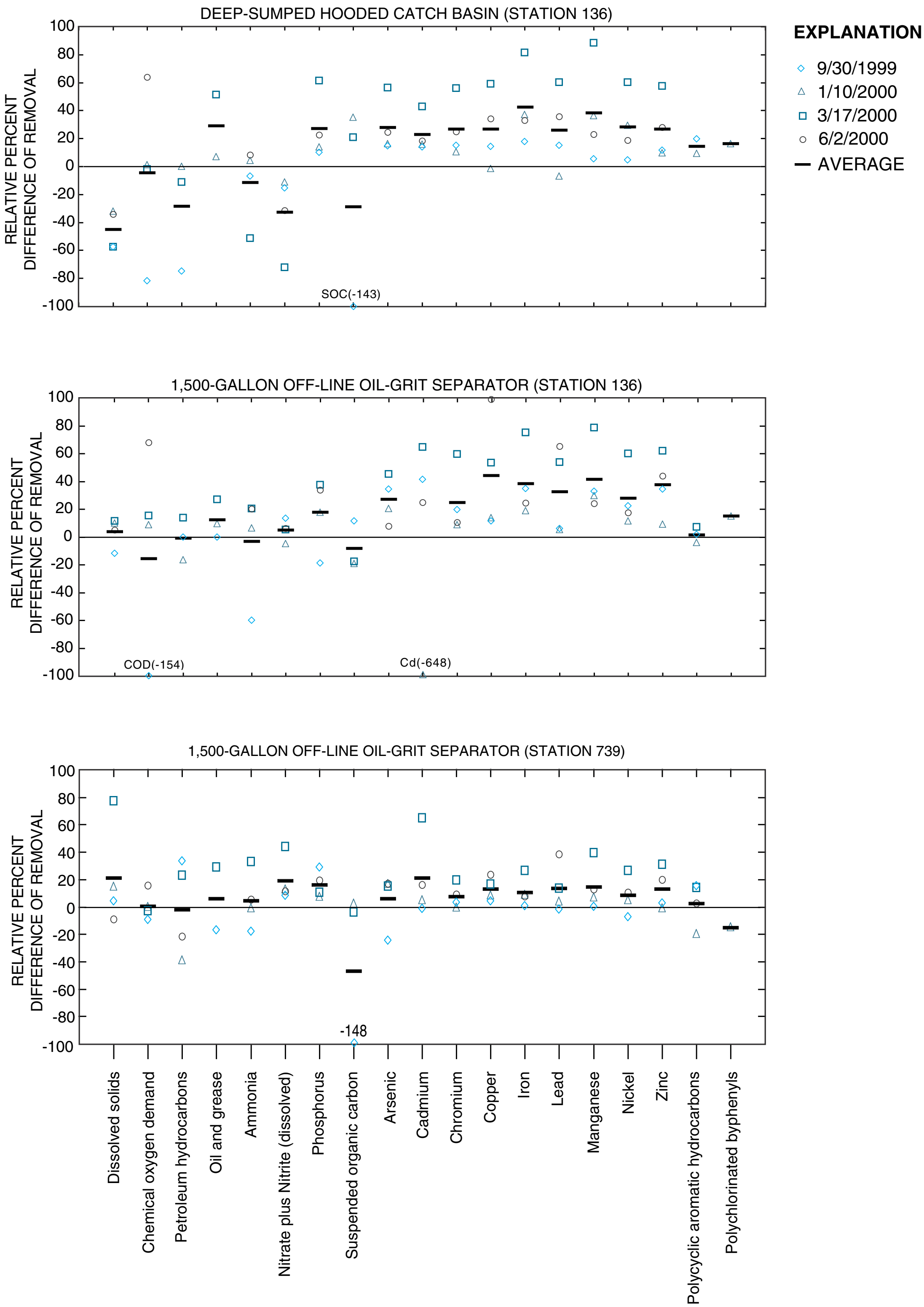

Figure 22. Relative percent differences between inlet and outlet event mean concentrations of selected highway runoff constituents for a deep-sumped hooded catch basin and two 1,500-gallon oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

Additionally, the RPD for EMCs of sediment-associated constituents for the separators was probably too large, because the sediment-associated constituent concentrations were not normalized (that is, they were not normalized to the average solid-phase constituent concentration in the water column); thus, sediment-associated constituents in the size fractions greater than 0.062 mm in diameter were not sampled in proportion to their average concentration. As discussed earlier, inlet loads of suspended sediment that were not normalized would be overestimated. This discrepancy is important because several of the storms produced above-average concentrations of suspended sediment containing large concentrations of coarse-grained particles. Although the size-fraction analysis of bottom sediment indicated that sediment-associated constituents had less affinity for the sediment-size fraction greater than 0.062 mm in diameter, coarse-grained sediments were readily retained by the separators; thus, overestimating the sediment-associated constituents related to the coarse-grained fraction creates a positive bias in the device efficiency.

The following example, which assumes the respective trace elements are sorbed entirely on the solid phase, explains these potential effects. Theoretical inlet EMCs of Cu, Pb, Mn, and Zn were estimated from sieved bottom-sediment concentrations collected from the separators, and from the EMCs of suspended sediment and from information about the particle-size distributions. The average RPDs for the theoretical and the observed concentrations at the inlet of the separator were 37 percent for Cu, 22 percent for Pb, 32 percent for Mn, and 18 percent for Zn for four storms. The average percent of each constituent estimated for the size fraction greater than 0.062 mm relative to the total solid-phase concentration would be about 13 percent for Cu, 13 percent for Pb, 30 percent for Mn, and 12 percent for Zn. During the January and March storms, the suspended-sediment concentrations and particle-size distributions were substantially different; the concentrations of each constituent estimated for the size fraction greater than 0.062 mm in diameter relative to the total solid-phase concentration were as high as 29 percent for Cu, 30 percent for Pb, 61 percent for Mn, and 29 percent for Zn. Normalizing the suspended-sediment fraction greater than 0.062 mm in diameter to the sampling point for each storm by using experimental water-column data, reduced the concentrations by up to 65 percent. Thus, the inlet concentrations of each constituent associated with particles greater than 0.062 mm normally retained by the device were overestimated. Consequently, the normalized RPD between the theoretical concentrations for the inlet of the separator and observed concentrations for the outlet of the separator for the January and March storms should theoretically be reduced by as much as an additional 15 percent for Cu, 11 percent for Pb, 10 percent for Mn, and 9 percent for Zn. The effect on the RPD for a given constituent depended upon the particle-size distribution of the sample and that constituent's association with particle size.

The removal of inorganic and organic constituents was impaired by the same factors that affected the removal of suspended sediment by the structural BMPs in this study. The removal efficiency for inorganic and organic constituents was probably less than the overall suspended-sediment removal efficiency, because the sediment fraction (less than 0.062 mm in diameter) onto which these constituents generally sorbed was not removed during flowing conditions in either device. Although higher concentrations of PCBs and PAHs were detected in the size fraction greater than 2.00 mm in diameter, concentrations of PCBs and PAHs are believed to be similar in the sediment fraction less than 0.062 mm in diameter due to the effects of increased available surface area. Because the retained particles greater than 2.00 mm in diameter represent about 21 percent of the total bottom material in the catch basin and about 6 percent of the total bottom material in the separators, and because both devices were not capable of retaining low-density floatables that contained high concentrations of TOC, the removal efficiency for organic constituents could have been an order of magnitude less than the overall suspended-sediment removal efficiency. Furthermore, given that specific conductance is a general measure of the total dissolved solids in solution, the lack of difference between the median and interquartile ranges of specific conductance values measured in samples of collected from the inlet and outlet of each structural BMP indicates that the devices were not effective at reducing dissolved constituents (fig. 23). It should be noted that other studies have found that a high proportion of trace metals in highway runoff are dissolved (Dupuis and others, 1985). In this study, about 35 percent of the Cr, 17 percent of the Ni, 15 percent of the Mg, 10 percent of the Cu, and 8 percent of the Zn as measured in EMCs from samples collected in January 2000 and processed

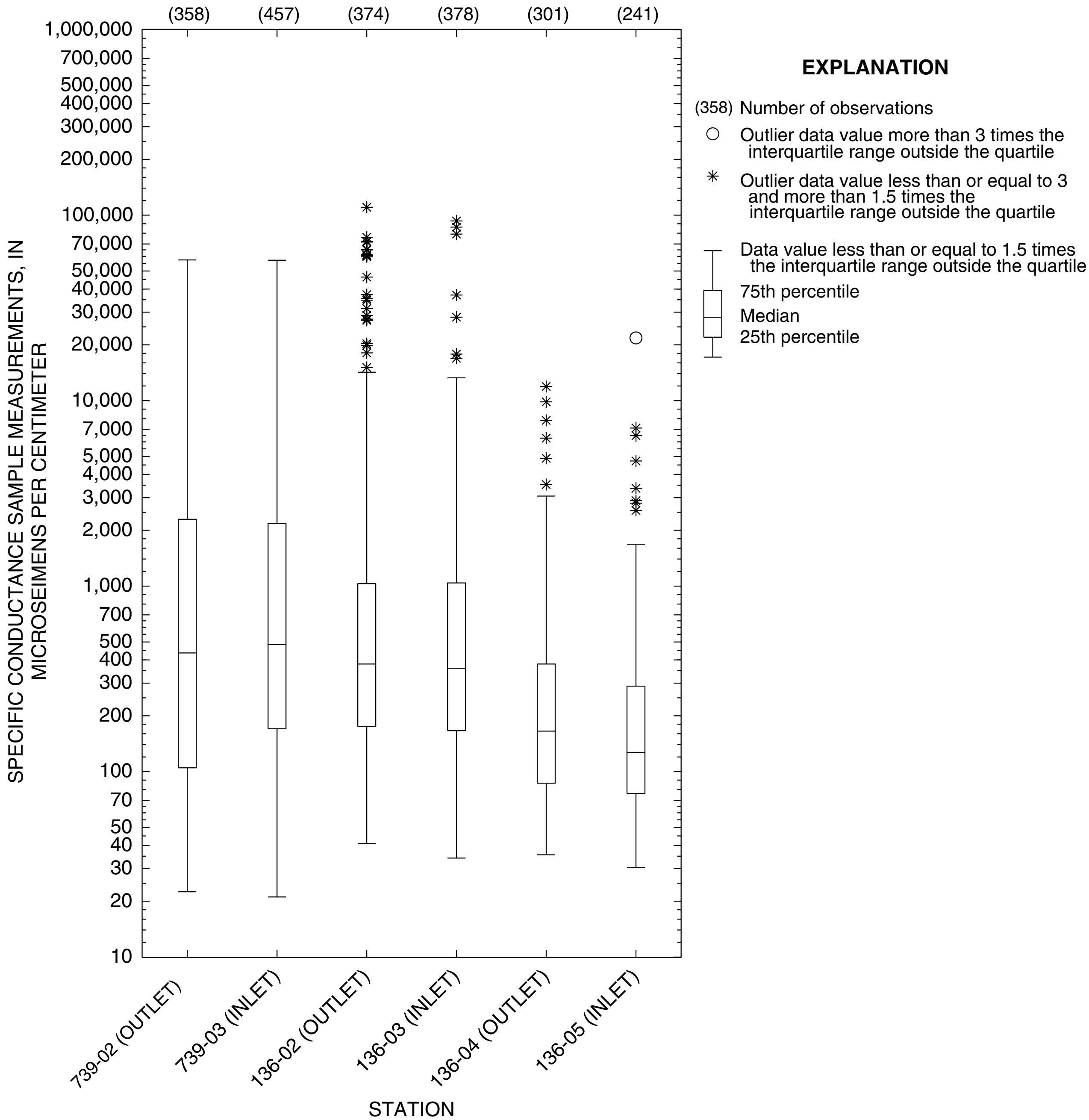

Figure 23. Specific conductance of suspended-sediment concentration samples collected from a deep-sumped hooded catch basin and two oil-grit separators located along the Southeast Expressway, Boston, Massachusetts.

within 24 hours of the initial sample collection were dissolved. In addition, the distribution of trace elements within the bottom sediment of the structural BMPs depends partly upon biochemical and geochemical conditions that increase concentrations of dissolved trace elements. For example, both Ellis and others (1987) and Morrison and others (1990) measured increases in dissolved concentrations of Cd, Cu, Pb, and Zn in catch-basin water caused by conditions resulting from decomposition of organic matter in the sump sediment.

Loads for chemical and biological constituents were not estimated because insufficient data were collected to accurately characterize the temporal and spatial variability in the runoff. For example, the suspended-sediment concentrations for the four storms, which were also sampled for chemical and biological constituents, represented about 5 percent of the storms that occurred during the monitoring period, but as much as 21 percent of the overall suspended-sediment load during the monitoring period. Because the ratio of chemical loads to suspended-sediment loads, however, was likely similar to the ratio of chemical concentrations to suspended-sediment concentrations, use of the limited chemical data would overestimate the chemical loads.

Reduction of Fecal-Indicator Bacteria

Concentrations of fecal and *Enterococci* bacteria were found throughout the storms at the inlet of each oil-grit separator. This result indicates that the pavement washoff process was inefficient or that there was continuous source of bacteria in the drainage area. Discrete concentrations of fecal and *Enterococci* bacteria collected during five storms are presented in appendix 1, table 1*I*. EMCs of *Enterococci* bacteria for samples collected during individual storms were within 36 percent of each other, and EMCs of fecal bacteria were within 90 percent of each other. In general, subcomposites of *Enterococci* bacteria for samples collected during individual storms varied from each other by as much as 500 percent and subcomposites of fecal bacteria varied from each other by 200 percent to more than an order of magnitude.

Concentrations of fecal-indicator bacteria were greatest in the fall and the early winter. An abrupt decrease in fecal and *Enterococci* bacteria concentrations in samples collected in March coincided with winter applications of deicing compounds. EMCs of fecal and *Enterococci* bacteria for samples collected in March were as much as an order of magnitude and 95 percent lower than EMCs of fecal and *Enterococci* bacteria collected in the fall, respectively. Since deicing applications ceased around April, warmer and longer antecedent conditions may have affected June bacteria concentrations. This temporal distribution of fecal-indicator bacteria is similar to that found in other highway runoff studies (Kobriger and Geinopolos, 1984). In about half of the storms, concentrations of fecal-indicator bacteria were lower in initial first-flush samples. One possible explanation is the initial water entering the separators was essentially the supernatant of the catch basins, and sediment-affiliated bacteria may have settled during the antecedent period. Subsequent bacteria concentrations increased because pavement water mixed with the catch-basin water, and possibly disturbed bottom sediments. The catch basin, and the separator particularly provide an environment that is thermally stable, free from ultraviolet light, and enriched in TOC and nutrients—factors that normally enhance bacteria survivability. Bacteria have been found to survive in storm sewers for at least 13 days and in sediment exposed to air for up to 49 days (Kobriger and Geinopolos, 1984). Thus, the potential for resuspension of sediments in each device and mobilization of roadside sediment may provide a continuous source of bacteria.

The efficiency of the structural BMPs tested in this study to reduce fecal-indicator bacteria concentrations was not quantified; however, these devices are most likely ineffective for this purpose. Bacterial removal efficiency is affected by the BMPs' short retention time and inability to remove suspended sediment less than 0.062 mm in diameter. Individual fecal coliform bacteria cells are less than 0.002 mm in diameter (Schueler, 1999) and have settling characteristics similar to clay particles (Coyne and others, 1995). Schillinger and Gannon (1982) reported that 50 percent of the bacteria in stormwater were not associated with sediments, and about 70 to 85 percent of associated bacterial cells adhered to sediment particles less than 0.030 mm in diameter. Consequently, each BMP is likely to retain a quantity of fecal-indicator bacteria proportional to its volume after a storm. Absolute removal is dependent on the survivability of fecal-indicator bacteria prior to the subsequent storm and potential for export during the subsequent storm.

SUMMARY

The USGS, in cooperation with the Federal Highway Administration and the Massachusetts Highway Department (MassHighway), began a study in November 1998 to determine the effectiveness of three best management practices (BMPs) in reducing suspended-sediment loads and related constituents along the Southeast Expressway in Boston, Massachusetts. The study area included about 2 mi of the Southeast Expressway, which represents about 0.06 percent of the total area of the Neponset drainage basin and the Boston Harbor Coastal Subbasin. Primary treatment for highway stormwater runoff was provided by 209 catch basins. One 3-chambered 4,500-gal off-line oil-grit separator, and four 2-chambered 1,500-gal off-line oil-grit separators provided additional stormwater treatment. Each separator includes a diversion weir positioned near the inlet of the separator that directs a portion of the flow to a bypass pipe during high flows. Mechanized street sweeping is conducted annually following the winter maintenance period. The BMPs examined in this study included a single catch basin, three 1,500-gal oil-grit separators, and mechanical street sweeping.

Automatic-monitoring techniques were used to characterize the temporal and spatial variability in suspended-sediment transport through each structural BMP. Water samples were collected, and continuous measurements of selected hydrologic, water-quality, and meteorology parameters were made from April 1999 through June 2000 for the catch basin and one of the separators (station 136), and from August 1999 through June 2000 for the second separator (station 739). The third separator was not continuously monitored. Samples for the analysis of suspended sediment and water quality were collected flow-proportionally at the inlet and outlet of each structural BMP automatically. The inlet and outlet flows for each device were sampled during four storms for analysis of chemical constituents. Discrete samples for the analysis of bacteria were collected flow-proportionally from a second dedicated automatic sampler at the inlet of each separator during five storms. Samples of large buoyant particles and other debris (greater than 6 mm in diameter) were collected at the outlet of a separator (station 739) during 12 storms.

Samples of bottom material were collected from three separators in November 1998, and from December 1999 through January 2000. The depth of bottom material was assessed in each structural BMP prior to the first scheduled cleaning, during the collection of bottom material, and at the conclusion of the monitoring period. Samples of bottom material for determinations of density were collected in the catch basin and each chamber of the separators. Samples of bottom sediment collected for chemical analysis from each separator in November 1998 were composited in proportion to the estimated volume of retained material in each separator. Samples of bottom sediment (excluding litter and identifiable metal objects) collected for chemical analysis in December 1999 through January 2000 were wet-sieved into size classes of less than 0.062 mm in diameter, between 0.062 mm and 2.00 mm in diameter, and greater than 2.00 mm in diameter. The contents of the bottom material were visually identified and placed in general categories. Samples of street sweepings were collected from mechanical sweepers while in the vicinity of the monitoring stations.

Quality-control data indicated that most data were within the accumulative uncertainties of the various measurement, sampling, and analytical processes. Those data also indicated that particles greater than 0.062 mm in diameter were not evenly distributed throughout the water column at the inlet of the separators. Loads of suspended sediment at the inlets of the separators would have been overestimated without an adjustment in concentration. Therefore, an adjustment equation was developed to normalize the mean concentration of suspended sediment in water samples collected at the fixed sampling location at the inlet of the separators. This equation was based on concentration and particle-size distribution of suspended sediment collected in the water column of the drainage pipe at flows characteristic of observed field conditions.

A distinct pattern of bottom-material deposition was initially observed for each separator; however, as the volume of material in each chamber increased over

time, the distribution of the bottom material became more uniform. The estimated volume of retained bottom material in the separators at the conclusion of the study in contrast to the estimated volume of retained bottom material in the separators after three-years of operation without any maintenance indicate that the estimated rate of bottom-material accumulation was about two times greater during the study period at station 136 and at station 739 and about seven times greater at station 749, than during the first three years of operation. The actual increase in the estimated rate of bottom-material accumulation is uncertain because the density of the bottom material for the first three years of operation was unknown and suspended-sediment data were not available prior to this study. One possible explanation for the increase in the rate of bottom-material accumulation during the study, or perhaps more specifically, the lack of accumulation during the first three years of operation, is that a single (or multiple) storm(s) resuspended a portion of the bottom material retained in the separators during the first three years of operation and flushed the suspended materials from the device; thus, the rate of accumulation would have been distorted by the loss of retained bottom material.

The particle-size distribution of bottom material varied substantially between the catch basin and the separators. Most bottom material in the catch basin (about 83 percent) and in the primary chamber of the separators (a weighted average of 85 percent) was coarse-grained (greater than 0.25 mm in diameter), whereas a greater amount of sediment in the secondary chamber of the separators was fine-grained (a weighted average of about 50 percent was less than 0.25 mm in diameter). The percentages of sediment particles found in each size class were similar, with respect to sample location, for each separator. In contrast, the percentages of particles found in each size class, for classes less than 0.062 mm in diameter and greater than 0.5 mm in diameter, were substantially different for the two chambers of the separators. In general, the primary chamber of the separators contained higher percentages of coarse material, whereas finer and less dense particles were found in the second chamber. About 17 percent of the material found in the separators and about 7 percent of the material found in the catch basin was less than 0.062 mm in diameter.

Visual observations suggested that the separators were effective in removing floatable debris; however, the distribution of potentially floatable debris in bottom materials relative to each chamber, and the quantity of debris collected at the outlet of a separator, indicated that the devices can be effective only if they are cleaned regularly. The absence of debris in the catch basin at the conclusion of the monitoring period and the presence of floatable debris found in each separator indicated that the catch-basin hoods were not effective in reducing floatable debris.

The concentrations of suspended sediment in discrete samples of runoff collected from the inlets of the separators ranged from 8.5 to 7,110 mg/L, and concentrations of suspended sediment in discrete samples of runoff collected from the inlet of the catch basin ranged from 32 to 13,600 mg/L. The concentrations of suspended sediment in discrete samples of runoff collected from the outlets of the separators ranged from 5 to 2,170 mg/L, and concentrations of suspended sediment in discrete samples of runoff collected from the outlet of the catch basin ranged from 25.7 to 7,030 mg/L. The particle-size distribution of samples collected from the inlet of each structural BMP indicated that more than half of the suspended sediment consisted of particles less than 0.062 mm in diameter.

The two separators treated about 98 percent of the stormwater within their contributing area. The individual suspended-sediment removal efficiencies ranged from between -98 to +95 percent at station 136, and -94 percent to +90 percent at station 739. The operating efficiencies for the respective monitoring periods for the separators were 35 percent at station 136 and 28 percent at station 739. The average removal-efficiency associated with storms less than 0.2 in., however, ranged from about 32 to 81 percent. This increase in efficiency was a function of retention time rather than active treatment of the stormwater. The separator at station 136 retained 477 kg and the separator at station at 739 retained 190 kg of solids. The efficiency computed from the measured mass of material retained in the separators at the conclusion of the monitoring period and from the total outflow load of suspended sediment was 32 percent at station 136 and 24 percent at station 739. The small difference between the two methods used to estimate the efficiency of the separators indicated that the flow-weighted normalization of the inflow loads was a reasonable approach. The estimated mass-balance difference was within the cumulative uncertainties of the various measurement processes. The primary factor controlling the suspended-sediment-removal efficiency of each structural BMP was retention time. In the combined treatment system in this study, where catch basins provided primary suspended-sediment treatment, the separators reduced the mass of the suspended sediment from the pavement by about an additional 18 percent (with an assumed average catch-basin efficiency of about 41 percent).

Despite the presence of a bypass pipe at the inflow to the separator, previously captured sediments were resuspended and discharged from the separators nine times at station 136 and seven times at station 739. Resuspension of sediments was detected at and above rainfall intensities of 0.04 in. per 5-minute interval and flows greater than about 0.46 ft^3/s at each station. Stormflows from the separator at station 136 exceeded 0.46 ft^3/s 33 times compared to 22 times for station 739 during the monitoring period. The stormflows from separator 136 exceeded 0.46 ft^3/s 24 times during the same 10-month operating period. The amount of resuspended sediment estimated for both separators represented about 8 percent of the suspended-sediment loads retained at the end of the monitoring period. The estimated quantity of suspended sediment that bypassed the separators at station 136, where bypass flow occurred more frequently, and station 739 was about 20 percent higher and about 16 percent lower, respectively, than the amount of sediment (less than 0.062 mm in diameter) resuspended. Without the ability to limit flows through the device to 0.46 ft^3/s or less, changes in the diversion-weir height would not substantially affect the device performance. Sediments subject to resuspension represented a small fraction of the retained bottom-material composition, and a portion of coarse-grained sediments, readily retained by the separator and mobilized during peak flows, would bypass the device. Resuspension could be virtually eliminated by reducing the device drainage area by a factor of about five or performing maintenance (cleaning) between storms, but neither option is cost effective or practical.

The individual removal efficiencies for the catch basin ranged from -114 to +97 percent. The average catch-basin retention time was about 1 hour; however, retention times were as low as 37 seconds during brief periods of flow. Resuspension of bottom sediments was detected during several storms, although the depth of bottom sediment retained in the catch basin was less than 25 percent of the sump depth at the conclusion of the monitoring period. The frequency of cases in which resuspension was detected did not increase with an increase in captured sediment. The estimated amount of resuspended sediment represented 18 percent of the final mass of retained sediment.

The operating efficiency for the 14-month monitoring period for the catch basin was 39 percent, and the catch basin retained an estimated 234 kg of solids. The relative mass-balance error for the catch basin was -14 percent. There was no substantial difference between combined loads of suspended sediment from the catch-basin discharges, estimated from the separator inflows, several weeks before and after annual catch-basin cleaning. This finding indicated that the volumes of retained bottom material in the catch basins within the drainage areas of station 136 and 739 were not sufficient to substantially affect catch-basin performance. Removal of bottom sediments in the late winter or spring may be more beneficial than at other times because high intensity rainfall, characteristic of summer thunderstorms, can cause resuspension of bottom sediments in catch basins, even when the volume of bottom material represents less than 25 percent of the catch-basin sump.

In this combined system, the efficiencies of the catch basin and separator were inversely related. The suspended-sediment removal efficiency of the catch basin decreased with an increase in discharge, which decreased retention time. Conversely, the separator performance improved with an increase in discharge in spite of a decrease in retention time. This was due, in part, to a change in the particle-size distribution during periods of greater flows. During low flow, larger particles settled in the catch basins while finer material entered the separator. While the separator volume was greater than that of a single catch basin, the combined flow from multiple catch basins discharged to each separator, which reduced the retention time and inhibited the capture of fine material. As flow increased, however, sediment from roadway and particle size tended to increase as coarse-grained material was discharged from the catch basin, which subsequently improved the separator performance.

Suspended-sediment loads for the entire study area were estimated on the basis of the long-term average annual precipitation and the estimated inlet and outlet loads of the two separators. The estimated annual suspended-sediment load for the entire study area was about 29,000 kg. About 24,000 kg of this total discharged near Malibu Beach and Tenean Beach embayments, and the remaining 5,000 kg discharged to the land surface, where it infiltrated into the ground. These loads do not include an estimated 2,000 kg of sediment retained by the five separators.

The effectiveness of mechanical street sweeping was assessed by evaluating the differences between suspended-sediment loads of structural BMPs before sweeping and after sweeping relative to storm precipitation totals. The effectiveness was also assessed by evaluating the differences between the particle-size distribution of sweeper samples and bottom-sediment samples collected in the catch basin and the weighted average of bottom-sediment samples collected from the three separators. The particle-size distribution of sweeping samples closely resembled the particle-size distribution of the catch-basin sediments in all size classes below 4 mm in diameter. The concentration of particle sizes greater than 0.5 mm in diameter in sweeper samples was higher than averaged concentrations of bottom sediment collected from the separators. On the basis of these data, the greatest benefit of annual street sweeping was the removal of particles greater than 8 mm in diameter that were not mobilized routinely during storm flows. Except for reducing the frequency of cleaning of catch basins and separators, frequent pavement sweeping (several times a month) would probably provide little additional water-quality benefit beyond those of the existing structural BMPs along the Southeast Expressway, due in part to the lack of curbing at the highway edge that would provide a physical boundary to trap debris and sediment. Also the sweeper was not effective at removing particles less than 0.062 mm in diameter, which composed the dominant particle-size group on the roadway surface.

Concentrations of inorganic constituents in sieved bottom sediments from three separators were typically higher for sediments less than 0.062 mm in diameter. Concentrations of total organic carbon (TOC) in sieved bottom sediments were similar for sediments less than 0.062 mm in diameter and sediments greater than 2.00 mm in diameter. Conversely, concentrations of polychlorinated biphenyls (PCB) and polyaromatic hydrocarbons (PAH) were typically higher for sediments greater than 2.00 mm in diameter. A substantial difference in the TOC content of sediments greater than 2.00 mm in diameter and less than 2.00 mm in diameter may explain the PCB and PAH distribution and further indicate that the PCB and PAH concentrations in bottom sediments less than 0.062 mm in diameter are similar to the concentrations in the bottom sediments greater than 2.00 mm in diameter, if not greater because of the effects of the surface area. Therefore, the potential effectiveness of the catch basins and the separators to reduce loads of inorganic and organic constituents was several times less (as much as an order of magnitude) than their ability to reduce loads of suspended sediment (consisting of natural organics, and fine- and coarse-grained material) because (a) most of the suspended sediment entering the structural BMPs was less than 0.062 mm in diameter, (b) only about 21 percent of the retained bottom material in the catch basin and 6 percent of the retained bottom material in the separators was greater than 2 mm in diameter, and (c) neither type of device was completely capable of retaining low-density floatable debris that contained concentrated levels of TOC and organic compounds.

The average relative percent difference (RPD) for concentrations of trace metals and organic constituents between the inlet and the outlet (inlet minus outlet) of the catch basin ranged from -29 to +42 percent. The average RPD for concentrations of sediment-associated constituents for the inlet and the outlet of the separators ranged from -129 to +44 percent at station 136, and -47 to +21 percent at station 739. The average RPD for concentrations of trace metals was about 30 percent at station 136, and about 15 percent at station 739. The average RPD for concentrations of organic constituents for both separators was commonly less than about 10 percent and negative in several cases. These RPDs were probably larger than normal because the precipitation totals for the four storms were greater than the average precipitation total for storms during the monitoring period, and likewise, the EMCs of suspended sediment for each structural BMP in all four storms were greater than the median EMCs of suspended sediment for each BMP during the monitoring period. In fact, the quantity of suspended sediment during the four storms accounted for 9 to 23 percent of the overall suspended-sediment load for each BMP during the monitoring period. Additionally, because sediment-associated constituents collected from the inlet of the separators were not normalized to the water column, the portion of constituents associated with sediments greater than 0.062 mm in diameter was not sampled in proportion to the mean concentration. Examination of constituent-sediment relations suggests that a substantial amount of highway-related constituents was either in the dissolved form and not subject to treatment by simple gravity separation, or was associated with particles less than 0.062 mm in diameter, which commonly passed through these structural BMPs. Loads for chemical and biological constituents were not estimated because insufficient data were collected to characterize the temporal and spatial variability accurately; however, the ratio of chemical loads to suspended-sediment loads was likely similar to the ratio of chemical concentrations to suspended-sediment concentrations.

The efficiency of the structural BMPs tested in this study to reduce concentrations of fecal-indicator bacteria was not quantified; however, the structural BMPs are probably ineffective in reducing fecal-indicator bacteria concentrations because bacteria share the same settling characteristics as particles less than 0.062 mm in diameter. Absolute bacteria removal in each device is dependent on the fecal-indicator bacteria survivability prior to the storm and the potential for exportation during the storm. Fecal and *Enterococci* bacteria were found throughout the entire storm at the inlet of each separator; this finding indicated that the pavement-washoff process was inefficient or that there was continuous source of bacteria in the drainage area.

The findings of this study on the effectiveness of deep-sumped hooded catch basins, 1,500-gal off-line oil-grit separators, and mechanized street sweeping were based on the physical and environmental conditions during the study. Many of the conditions at this site were unique in Massachusetts, specifically the movable zipper barrier and the substantial average daily traffic volume. Studies of other highways that have lower traffic volumes, different particle-size distributions, and different concentrations of suspended sediment may produce other results.

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