Characterization of Stormwater Runoff From Bridge Decks in Eastern Massachusetts, 2014–16

Scientific Investigations Report 2018–5033

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

Cover. Photograph of bridge-deck scuppers draining into the Charles River on State Route 2A in Boston near U.S. Geological Survey bridge-deck-monitoring station 422108071052501 during a rain storm.

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	metric ton (t)
ton, long (2,240 lb)	1.016	metric ton (t)

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

$$°F = (1.8 \times °C) + 32.$$

Datum

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

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

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

Abbreviations

AADT	annual average daily traffic
Al	aluminum
ANOVA	one-way analysis of variance
As	arsenic
Ba	barium
BMP	best-management practice
Cd	cadmium
Cr	chromium
Cu	copper
DN	total dissolved nitrogen
EPA	U.S. Environmental Protection Agency
HRDB	Highway-Runoff Database
LOI	loss on ignition of suspended solids
MassDOT	Massachusetts Department of Transportation
MIC	minimum irreducible concentration
Mn	manganese
Ni	nickel
NWIS	National Water Information System
p	attained significance level
Pb	lead
PC	particulate carbon
PIC	particulate inorganic carbon
PN	particulate nitrogen
POC	particulate organic carbon
RPD	relative percent difference
SD	standard deviation
SELDM	Stochastic Empirical Loading and Dilution Model
SS	suspended sediment
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TP	total phosphorus
USGS	U.S. Geological Survey
WWTP	wastewater treatment plant
Zn	zinc

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Abstract

The quality of stormwater runoff from bridge decks (hereafter referred to as "bridge-deck runoff") was characterized in a field study from August 2014 through August 2016 in which concentrations of suspended sediment (SS) and total nutrients were monitored. These new data were collected to supplement existing highway-runoff data collected in Massachusetts which were deficient in bridge-deck runoff concentration data. Monitoring stations were installed at three bridges maintained by the Massachusetts Department of Transportation in eastern Massachusetts (State Route 2A in the city of Boston, Interstate 90 in the town of Weston, and State Route 20 near Quinsigamond Village in the city of Worcester). The bridges had annual average daily traffic volumes from 21,200 to 124,000 vehicles per day; the land use surrounding the monitoring stations was 25 to 67 percent impervious.

Automatic-monitoring techniques were used to collect more than 160 flow-proportional composite samples of bridge-deck runoff. Samples were analyzed for concentrations of SS, loss on ignition of suspended solids (LOI), particulate carbon (PC), total phosphorus (TP), total dissolved nitrogen (DN), and particulate nitrogen (PN). The distribution of particle size of SS also was determined for composite samples. Samples of bridge-deck runoff were collected year round during rain, mixed precipitation, and snowmelt runoff and with different dry antecedent periods throughout the 2-year sampling period.

At the three bridge-deck-monitoring stations, median concentrations of SS in composite samples of bridge-deck runoff ranged from 1,490 to 2,020 milligrams per liter (mg/L); however, the range of SS in individual composites was vast at 44 to 142,000 mg/L. Median concentrations of SS were similar in composite samples collected from the State Route 2A and Interstate 90 bridge (2,010 and 2,020 mg/L, respectively), and lowest at the State Route 20 bridge (1,490 mg/L). Concentrations of coarse sediment (greater than 0.25 millimeters in diameter) dominated the SS matrix by more than an order of magnitude. Concentrations of LOI and PC in composite samples ranged from 15 to 1,740 mg/L and 6.68 to 1,360 mg/L, respectively, and generally represented less than 10 and 3 percent of the median mass of SS, respectively. Concentrations of TP in composite samples ranged from 0.09 to 7.02 mg/L; median concentrations of TP ranged from 0.505 to 0.69 mg/L and were highest on the bridge on State Route 2A in Boston. Concentrations of total nitrogen (TN) (sum DN and PN) in composite samples were variable (0.36 to 29 mg/L). Median DN (0.64 to 0.90 mg/L) concentrations generally represented about 40 percent of the TN concentration at each bridge and were similar to annual volume-weighted mean concentrations of nitrogen in precipitation in Massachusetts.

Nonparametric statistical methods were used to test for differences between sample constituent concentrations among the three bridges. These results indicated that there are no statistically significant differences for concentrations of SS, LOI, PC, and TP among the three bridges (one-way analysis of variance test on rank-transformed data, 95-percent confidence level). Test results for concentrations of TN in composite samples indicated that concentrations of TN collected on State Route 20 near Quinsigamond Village were significantly higher than those concentrations collected on State Route 2A in Boston and Interstate 90 near Weston. Median concentrations of TN were about 93 and 55 percent lower at State Route 2A and at Interstate 90, respectively, compared to the median concentrations of TN at State Route 20.

Samples of sediment were collected from five fixed locations on each bridge on three occasions during dry weather to calculate semiquantitative distributions of sediment yields on the bridge surface relative to the monitoring location. Mean yields of bridge-deck sediment during this study for State Route 2A in Boston, Interstate 90 near Weston, and State Route 20 near Quinsigamond Village were 1,500, 250, and 5,700 pounds per curb-mile, respectively. Sediment yields at each sampling location varied widely (26 to 25,000 pounds per curb-mile) but were similar to yields reported elsewhere in Massachusetts and the United States. Yields calculated for each sampling location indicated that the sediment was not evenly distributed across each bridge in this study for plausible reasons such as bridge slope, vehicular tracking, and bridge deterioration.

Bridge-deck sediment quality was largely affected by the distribution of sediment particle size. Concentrations of TP in the fine sediment-size fraction (less than 0.0625 millimeter in diameter) of samples of bridge-deck sediment were about 6 times greater than in the coarse size fraction. Concentrations for many total-recoverable metals were 2 to 17 times greater in the fine size fraction compared to concentrations in the coarse size fraction (greater than or equal to 0.25 millimeter in diameter), and concentrations of total-recoverable copper and lead in the fine size fraction were 2 to 65 times higher compared to concentrations in the intermediate (greater than or equal to 0.0625 to 0.25 millimeter in diameter) or the coarse size fraction. However, the proportion of sediment particles less than 0.0625 millimeter in diameter in composite samples of bridge-deck runoff was small (median values range from 4 to 8 percent at each bridge) compared to the larger sediment particle-size mass. As a result, more than 50 percent of the sediment-associated TP, aluminum, chromium, manganese, and nickel was estimated to be associated with the coarse size fraction of the SS load. In contrast, about 95 percent of the estimated sediment-associated copper concentration was associated with the fine size fraction of the SS load.

Version 1.0.2 of the Stochastic Empirical Loading and Dilution Model was used to simulate long-term (29–30-year) concentrations and annual yields of SS, TP, and TN in bridge-deck runoff and in discharges from a hypothetical stormwater treatment best-management practice structure. Three methods (traditional statistics, robust statistics, and L-moments) were used to calculate statistics for stochastic simulations because the high variability in measured concentration values during the field study resulted in extreme simulated concentrations. Statistics of each dataset, including the average, standard deviation, and skew of the common (base 10) logarithms, for each of the three bridges, and for a lumped dataset, were calculated and used for simulations; statistics representing the median of statistics calculated for the three bridges also were used for simulations. These median statistics were selected for the interpretive simulations so that the simulations could be used to estimate concentrations and yields from other, unmonitored bridges in Massachusetts. Comparisons of the standard and robust statistics indicated that simulation results with either method would be similar, which indicated that the large variability in simulated results was not caused by a few outliers. Comparison to statistics calculated by the L-moments methods indicated that L-moments do not produce extreme concentrations; however, they also do not produce results that represent the bulk of concentration data.

The runoff-quality risk analysis indicated that bridge-deck runoff would exceed discharge standards commonly used for large, advanced wastewater treatment plants, but that commonly used stormwater best-management practices may reduce the percentage of exceedances by one-half. Results of simulations indicated that long-term average yields of TN, TP, and SS may be about 21.4, 6.44, and 40,600 pounds per acre per year, respectively. These yields are about 1.3, 3.4, and 16 times simulated ultra-urban highway yields in Massachusetts; however, simulations indicated that use of a best-management practice structure to treat bridge-deck runoff may reduce discharge yields to about 10, 2.8, and 4,300, pounds per acre per year, respectively.

Introduction

Stormwater discharges from Massachusetts roadways can adversely affect the quality of receiving water and may result in the failure of a water body to meet Massachusetts surface-water-quality standards. Many studies have shown that highway runoff can be a source of suspended sediment (SS) and nutrients (Breault and Granato, 2000; Smith, 2002; Kayhanian and others, 2003; Smith and Granato, 2010). Data from focused bridge studies (Malina and others, 2005; Wagner and others, 2011) also indicate that concentrations of total phosphorus (TP) and SS in samples of stormwater runoff from bridge decks (hereafter referred to as “bridge-deck runoff”) are similar to concentrations in samples of runoff collected from open highways. In Massachusetts, bridge-deck runoff is collected in cast iron drainage inlets called “scuppers.” Scuppers typically drain to trunk-line conveyance systems, where the runoff is discharged to a structural source control near the bridge embankment. For some bridges, bridge-deck runoff is discharged directly to the underlying land surface or water body. The Massachusetts Department of Transportation (MassDOT) owns about 4,800 bridges, and 38 percent are over water (Henry Barbaro, Massachusetts Department of Transportation, written commun., 2014). Bridge-deck scuppers do not provide water-quality treatment of stormwater runoff, and thus discharge from bridges is of concern to regulating officials.

Data on the quality of bridge-deck runoff is limited in the northeastern United States, and the transferability of existing highway-runoff data to bridge decks is not well documented. To address this data gap, the U.S. Geological Survey (USGS) piloted a field study where composite samples of bridge-deck runoff were collected between August 2014 through August 2016 to document the quality of bridge-deck runoff for concentrations of SS, total nutrients, loss on ignition of suspended solids (LOI), and particulate carbon (PC) at three bridges maintained by the MassDOT in eastern Massachusetts. The integration of these data with a technically sound highway-runoff model can be used to guide, substantiate, and support highway planning, design, and maintenance decisions. The study findings aid in the interpretation of local, regional, and national bridge-deck runoff data including concentrations, loads, potential effects on receiving waters, and the potential effectiveness of various best-management practices (BMPs). This study is also a component of the implementation of MassDOT’s National Pollutant Discharge Elimination System, Small Municipal Separate Storm Sewer Systems general permit.

This report documents concentrations of SS, SS particle size, total nutrients, LOI, and PC measured in flow-weighted composite samples of bridge-deck runoff collected from bridge scuppers for three bridges in eastern Massachusetts during a 2-year monitoring period (2014–16). It also describes the physiochemical characteristics of samples of bridge-deck sediment and documents the monitoring and sample collection methods for all data contained within the report. The report discusses the relation between concentration data for the respective constituents among the three bridge-deck stations and compares the composition and quality of sediment in samples collected from bridge decks and highways in Massachusetts. The data presented in this report are integrated in the Highway-Runoff Database (HRDB; Version 1.0.0b) (Granato and Cazenas, 2009), which serves as a preprocessor for the Stochastic Empirical Loading and Dilution Model (SELDM) (Granato, 2013). SELDM yields of SS and total nutrients and examples of BMP analysis also are presented in this report.

Site Selection

Sections of bridge deck on three highways in eastern Massachusetts were selected for this study because they represented varying traffic volumes and surrounding impervious density, factors that previously were determined to affect constituent concentrations (Smith and Granato, 2010). The USGS bridge-deck-monitoring stations were on State Route 2A (Massachusetts Avenue) in the city of Boston and over the Charles River spanning between the cities of Boston and Cambridge (station number 422108071052501; hereafter referred to as “State Route 2A monitoring station”), Interstate 90 (Massachusetts Turnpike) over the Charles River near the town of Weston (station number 422025071154501; hereafter referred to as “Interstate 90 monitoring station”), and State Route 20 near Quinsigamond Village in the city of Worcester over the Blackstone River (station number 421247071470201; hereafter referred to as “State Route 20 monitoring station”) (fig. 1).

The areas that drain to the monitoring stations range from 2,300 to 10,100 square feet (ft^2) and are 100 percent impervious. These values represent the area between scupper inlets to the crown of the roadway or to the opposite roadway shoulder. Posted speed limits range from 30 to 55 miles per hour and the annual average daily traffic (AADT) volumes range from about 21,200 to about 124,000 vehicles per day (Massachusetts Department of Transportation, 2017a) (table 1). The wearing bridge surface is asphalt, except for Interstate 90, which is concrete. The land use surrounding each monitoring station is primarily developed land (43.1 to 78.8 percent) (Homer and others, 2015) with accompanying high impervious area (25 to 67 percent; Massachusetts Office of Geographic Information System, 2007) (table 2). The Charles River, the largest water body near any of the bridges, accounts for 16 percent of the surrounding area at the State Route 2A monitoring station in Boston. The amount of development near each bridge decreases from east to west (table 2).

Prior to the monitoring period, bridge scuppers at each location were cleaned by MassDOT, except for the Interstate 90 bridge where the necessary maintenance equipment was not available at the beginning of the study. The Interstate 90 bridge scuppers were cleaned in October 2015. There were no major construction activities at the three bridges during the study period. Street sweeping was done once a week, weather permitting, on the State Route 2A bridge in Boston and as necessary on the other bridges. The application of winter maintenance materials was limited to salt. A sand or sand-salt mixture was not applied to the bridges.

Data Collection Methods and Results of Quality-Assurance Sampling

The methodology described herein includes a description of the design of each bridge-deck-monitoring station (herein referred to as “monitoring station”) and the collection and analysis methods for samples of bridge-deck runoff and bridge-deck sediment. At each bridge, a continuous monitoring and sampling system was installed and operated from August 2014 through August 2016. Samples of bridge-deck sediment were collected at five locations across each bridge following three dry antecedent periods during the study.

Continuous Monitoring of Bridge-Deck Runoff

Automatic-monitoring techniques were used to collect continuous measurements of water level in the runoff collection system and rainfall and to collect composite samples of bridge-deck runoff. Continuous monitoring data were collected from August 2014 through September 2016 at each bridge; composite samples of bridge-deck runoff were collected from August 2014 through August 2016 at each bridge. Runoff coefficients were calculated, in part, to determine practical flow thresholds for triggering the automatic samplers. Samples of bridge-deck runoff were collected by the automatic samplers on a flow-proportional basis.

Design of Bridge-Deck-Monitoring Systems

At each monitoring station, the outlet of a bridge-deck scupper was modified to divert runoff from the scupper outfall to a shelter containing an H flume rated for 2 cubic feet per second (ft^3/s) where flow data were collected (fig. 2). The H flume combines the sensitivity and accuracy of a sharp-crested weir and the self-cleaning features of a flume (Kilpatrick and Schneider, 1983). The capacity of the flumes was sufficient to characterize all flow rates at each monitoring station. Water level in the flume was measured by a gas-purge bubbler system and a National Institute of Standards and

Technology traceable pressure sensor. Redundant measurements of water level were made with an ultrasonic sensor at the same measurement location (fig. 3). These secondary level measurements were useful to detect debris or ice in the flume that caused the pressure sensor to measure erroneously high water levels. Continuous measurements of water level were converted to continuous flow values by programming the dataloggers with the stage-flow relation for the flume. Rainfall data were measured at the monitoring stations on Interstate 90 and State Route 20 with an unheated 8-inch (in.) diameter tipping-bucket sensor mounted about 7 feet (ft) above the ground surface. The area near the State Route 2A monitoring station was not suitable for the measurement of rainfall; instead rainfall data were available at USGS station 01104683 (Muddy River at Brookline, Massachusetts) about 1.5 miles southwest of the bridge-deck-monitoring station. Precipitation data (inclusive of mixed precipitation and snowmelt water) also were available at USGS station 422302071083801 (Fresh Pond in Gate House at Cambridge, Mass.), about 3.5 miles northwest of the bridge-deck-monitoring station but only used as a redundant data source. Rainfall was measured to estimate the total runoff for the drainage area for each station to estimate flow-proportional sampling thresholds. Each station was equipped with telemetry to transmit stored data and to enable the dataloggers to be remotely programmed.

Calculation of Runoff Coefficients

A runoff coefficient is the ratio of the volume of runoff to the volume of rainfall. Runoff coefficients for each rainfall event in this study were calculated by dividing the runoff total by the product of the measured rain total and the drainage area for each respective monitoring station. These runoff coefficients were used to select appropriate flow thresholds for triggering the automatic samplers, to identify potential errors related to measurements of rainfall or water level, and to identify changes in the contributing area. The ratio of the volume of runoff to the volume of rainfall for a given area will range from zero (no runoff) to one (100 percent of the precipitation is measured in the runoff); however, if a runoff coefficient exceeds a value of one, there likely is an error in the measurement of precipitation, flow, and (or) contributing area (Church and others, 1999). Changes in the contributing area can result when flow from an upgradient drainage area is diverted into the drainage area of interest, such as when the inlet of one or

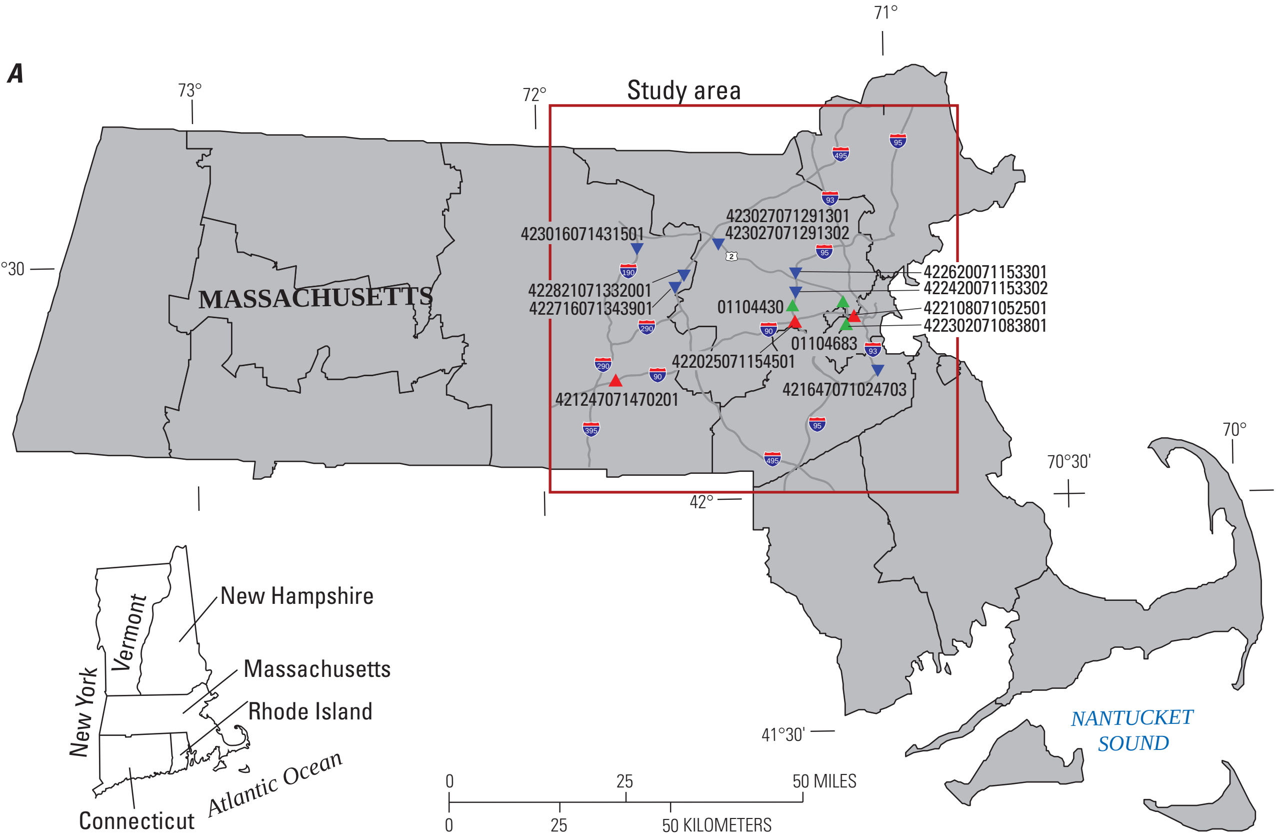
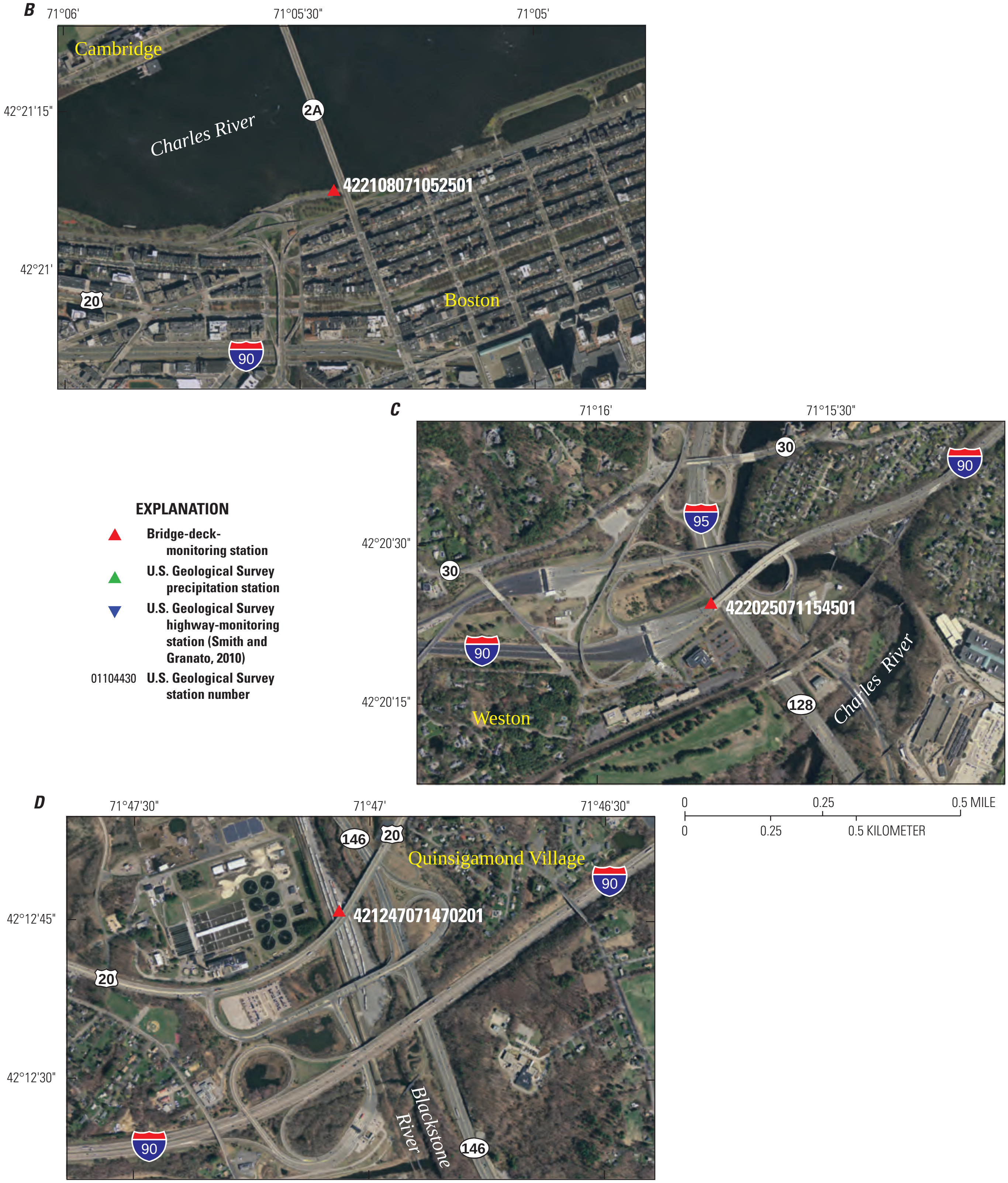


Figure 1. Locations of bridge-deck-monitoring sites in eastern Massachusetts, 2014–16. *A*, U.S. Geological Survey stations in this study. *B*, State Route 2A in Boston (422108071052501). *C*, Interstate 90 near Weston (422025071154501). *D*, State Route 20 near Quinsigamond Village (421247071470201).



Base from Massachusetts Office of Geographic Information (MassGIS) orthophotographs, 2012–14
Lambert conformal conic projection, North American Datum of 1983

Figure 1. Locations of bridge-deck-monitoring sites in eastern Massachusetts, 2014–16. *A*, U.S. Geological Survey stations in this study. *B*, State Route 2A in Boston (422108071052501). *C*, Interstate 90 near Weston (422025071154501). *D*, State Route 20 near Quinsigamond Village (421247071470201).—Continued

Table 1. Names, locations, and other bridge attributes for U.S. Geological Survey bridge-deck-monitoring stations in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. USGS, U.S. Geological Survey; ADT, average daily traffic (value in parenthesis represents year of measurement); traffic volume source: Massachusetts Department of Transportation (2017a)]

USGS station number	Highway	Town or city	Annual ADT	Annual ADT per lane	Number of the total lanes monitored	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area contributing runoff to scuppers (square feet)	Median barrier	Pavement type	Posted speed limit (miles per hour)	Approximate bridge length (feet)	Approximate bridge span area (acre)	River crossing
422108071052501	State Route 2A	Boston	36,900 (2010)	9,230	2 of 4	42.352	-71.0903	2,400	No	Asphalt, concrete walkway	30	2,200	2.6	Charles River
422025071154501	Interstate 90	Weston	124,000 (2013)	20,700	3 of 6	42.3402	-71.2626	2,300	Yes	Concrete	55 reducing to 30	1,030	1.9	Charles River
421247071470201	State Route 20	Quinsigamond Village in the city of Worcester	21,200 (2015)	5,300	2 of 4	42.2129	-71.7841	10,100	Yes	Asphalt	55	1,000	1.7	Blackstone River

Table 2. Land-use characteristics for a one-half mile radius around the bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. Land use and total impervious area are expressed as percentages of the total area. Land-use data source: Homer and others (2015). Impervious area data source: Massachusetts Office of Geographic Information (2007)]

Land-use category	Percentage of area in a one-half mile radius around each of the U.S. Geological Survey bridge-deck-monitoring stations		
	State Route 2A	Interstate 90	State Route 20
Open water	16.3	4.7	0.1
Developed open space	1.5	28.3	15.5
Developed land	78.8	43.1	46.3
Forest and shrub	0.4	18.9	28.8
Grassland and cropland	0.5	0.9	4.4
Wetland	2.5	4.1	4.9
Impervious area	67	25	26

more upgradient scuppers is partially or completely blocked by deposits of sediment, debris, or slush around the scupper grate (fig. 4*A*). In such cases, some or all of the water from a neighboring drainage area is diverted to a downgradient drainage system. Similarly, runoff that leaks through expansion joints in the bridge deck (fig. 4*B*) or obstructions to the inlet of scuppers in the monitored drainage area results in low runoff coefficients. Runoff coefficients also can vary during the winter months on the basis of available snowmelt water and scupper inlets that are frozen or blocked by snow (fig. 4*C*). Measurements of rainfall were not made locally at the State Route 2A monitoring station in Boston, and therefore the rainfall totals acquired from the nearby USGS stations 01104683 and 422302071083801 (fig. 1) may not always accurately reflect conditions at the bridge location.

There was a large amount of variability in the runoff coefficients during this study because the drainage areas are relativity small and blockages of scupper inlets were common; therefore, estimated constituent yields from storm runoff volume are not presented, and reported drainage area may not reflect actual contributing areas during different runoff events during the study period.

Collection and Analysis of Samples

Flow-proportional composite samples of bridge-deck runoff were collected automatically during storms. Samples for each runoff event were generally collected the following day, processed, and shipped overnight to the laboratory for analysis of concentrations of SS, TP, total dissolved nitrogen (DN), particulate nitrogen (PN), LOI, PC, particulate inorganic carbon (PIC), and particulate organic carbon (POC) (table 3). Samples of sediment in highway runoff also were sieved into specific particle-size ranges and analyzed for concentrations of TP and 10 total-recoverable metals (table 4).

Samples of Bridge-Deck Runoff

A range of 54–56 flow-proportional composite samples of bridge-deck runoff were collected automatically during rainfall, mixed precipitation, and snowmelt events between August 2014 and August 2016 at each of the monitoring stations. Composite samples of runoff were collected during runoff events that were characteristic of the range of antecedent dry periods and event rain totals (fig. 5) and a range of precipitation events (fig. 6) throughout the study period. Storm precipitation volumes during the study period were similar to storm precipitation volumes recorded during the prior 13-year period (November 2001 through July 2014) at U.S. Geological Survey station 01104430 (Hobbs Brook below Cambridge Reservoir near Kendall Green, Mass.) (fig. 6), which is approximately geographically centered among the three bridges and about 4 miles north of the Interstate 90 monitoring station (fig. 1).

Selection of Storms

Storm-event samples were selected to reflect seasonal and antecedent dry variations throughout the study period. Most of the storm precipitation volumes for sampled storms (predominately rainfall and mixed precipitation event) during this study were within the interquartile range of all storm precipitation volumes (rainfall, mixed precipitation, and snowmelt) greater than or equal to 0.05 in. recorded at each monitoring station (fig. 6). The distribution of storm precipitation volumes for sampled storms at State Route 2A monitoring station tended to be skewed higher than the distribution of storms during the study period; however, precipitation for this monitoring station was measured at USGS station 01104683 and may not always accurately reflect site conditions at the bridge.

In this study, runoff events are defined as a function of flow where sequential measurements of discharge greater than or equal to 0.005 ft^3/s are separated by 6 hours or more of discharge less than 0.005 ft^3/s. Runoff events consist of any form of runoff including rainfall, mixed precipitation, and snowmelt runoff. A discharge of 0.005 ft^3/s was chosen as a cutoff because it was the minimum value that was discernable between the presence of flow and no flow on the basis of the resolution of level sensors and the stage-discharge relation for each monitoring station.

Figure 2. Monitoring equipment at U.S. Geological Survey bridge-deck-monitoring stations on *A*, State Route 2A in Boston (422108071052501); *B*, Interstate 90 near Weston (422025071154501); and *C*, State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

Sample Collection

Samples of bridge-deck runoff for the analysis of SS and water chemistry were collected immediately upstream from the H flumes in the pipe by using an unrefrigerated automatic sampler controlled by a datalogger. Each autosampler was configured to hold four 3.75-liter (L) sample bottles that were pretreated with 4 milliliters (mL) of dilute sulfuric acid. The acid was added to maintain low pH in the samples and prevent dissolved phosphorus from partitioning to the bottle walls prior to sample collection by field crews. The first sample was collected when flow exceeded a minimum threshold (typically 0.005 to 0.008 ft^3/s), and subsequent samples were collected at flow-proportional intervals (samples collected at equal volumes of runoff) (fig. 7). After a runoff event was sampled and flow subsided below 0.005 ft^3/s for a minimum period of 6 hours, the datalogger was programmed to instruct the sampler to move the distributor arm to the next sample bottle. This method allowed for the collection of additional samples for subsequent runoff events without compromising the previously collected composite sample.

Approximately 50 subsamples of bridge-deck runoff were collected for an equivalent runoff of 1 in. of rain.

Figure 3. An H flume at U.S. Geological Survey bridge-deck-monitoring station on State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Location of station is shown on figure 1.

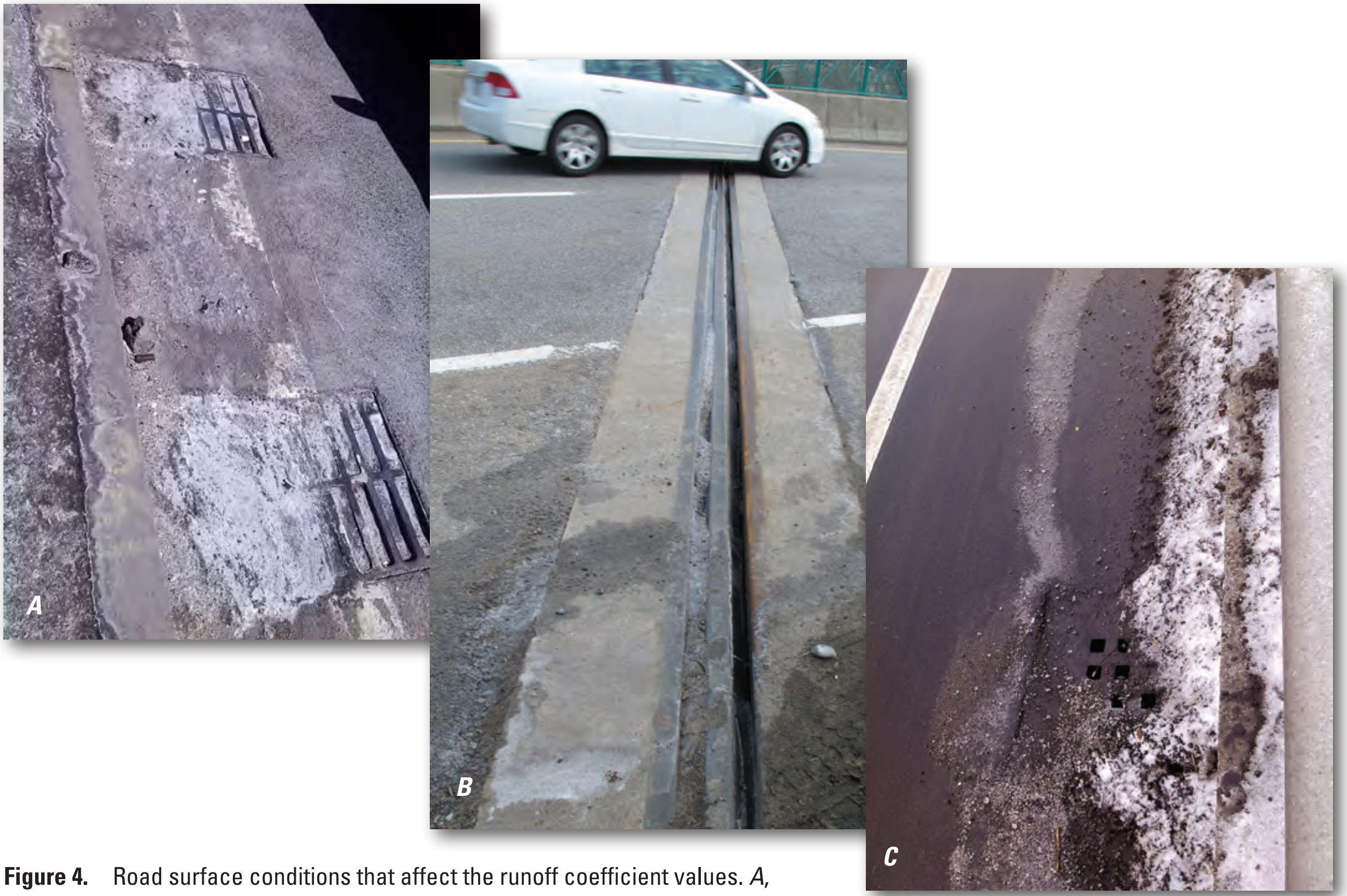


Figure 4. Road surface conditions that affect the runoff coefficient values. *A*, pair of blocked scupper inlets on Interstate 90 upgradient from the U.S. Geological Survey bridge-deck-monitoring station 422025071154501; *B*, expansion joint on State Route 20 upgradient from the U.S. Geological Survey bridge-deck-monitoring station 421247071470201; and *C*, partially blocked scupper inlet on State Route 2A near U.S. Geological Survey bridge-deck-monitoring station 422108071052501, Massachusetts, 2014–16. Locations of stations are shown on figure 1.

Flow-proportional thresholds, at which point the datalogger triggered the automatic water sampler, were fixed at each site throughout the study irrespective of expected storm characteristics; only the volume for each subsample was altered. Generally, a composite of bridge-deck runoff consisted of multiple 200-mL aliquots; however, the aliquot volume for the subsamples was reduced for storms with forecasted rain amounts greater than 1.0 in. to increase the total number of potential samples, so that the 3.75-L sample bottle would be adequate in size to represent the entire storm. In some cases, the forecasted rainfall volume was underestimated and resulted in a composite of two or more bottles. For small storms with forecasted rainfall amounts less than 0.5 in., the aliquot volume for each subsample was increased to ensure that sufficient water volume was collected to satisfy analytical requirements. Because the frequency for the collection of the subsamples was a function of a flow threshold derived from an equivalent runoff of 1 in. of rain from each site, the density of subsamples forming the composite of bridge-deck runoff was comparable from storm to storm and from site to site.

Various factors were considered during the selection and construction of the sites to ensure the best possible performance of the automatic samplers. Vertical distances from fixed sampling points to the sampler-pump heads were only about 2 ft and within optimal suction limits (Bent and others, 2001). All sampler lines were mounted in a sloping manner to allow for the complete purging and draining of sample water between samples. Sampler intakes were fixed to static mixers designed specifically for this project at each sampling point for all sampling locations (fig. 8). The purpose of the static mixer was to provide a secure and consistent mount for the sampler intake, reduce transport velocity, and provide agitation to produce a sample that represented the average concentration of SS (Smith, 2002; Smith and Granato, 2010). 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

Table 3. Constituents and physical properties measured in composite samples of bridge-deck runoff, reporting levels, analytical techniques, and parameter codes, 2014–16.

[Total dissolved nitrogen processed through a 0.3-micrometer glass fiber filter. mg/L, milligram per liter; USGS, U.S. Geological Survey; EPA, U.S. Environmental Protection Agency; NWQL, National Water Quality Laboratory; KY, USGS Kentucky Water Science Center Sediment Laboratory]

Physical property or constituent	Reporting level (mg/L)	Analytical technique	Analyzing laboratory	Reference	USGS parameter code
Total phosphorus	0.01	Alkaline persulfate digestion	NWQL	Patton and Kryskalla, 2003	00655
Total dissolved nitrogen	0.03	Alkaline persulfate digestion	NWQL	Patton and Kryskalla, 2003	62854
Particulate nitrogen	0.03	EPA 440.0	NWQL	Zimmerman and others, 1997	49570
Particulate organic carbon	0.05	EPA 440.0	NWQL	Zimmerman and others, 1997	00689
Particulate inorganic carbon	0.03	EPA 440.0	NWQL	Zimmerman and others, 1997	00688
Particulate carbon [inorganic plus organic]	0.05	EPA 440.0	NWQL	Zimmerman and others, 1997	00694
Suspended sediment	0.5	Filtration/gravimetry	KY	Guy, 1969; Shreve and Downs, 2005	80154
Suspended sediment, percent finer percent smaller than 0.0625 millimeter in diameter	Percent	Filtration/sieving/gravimetry	KY	Guy, 1969; Shreve and Downs, 2005	70331
Suspended sediment, percent finer percent smaller than 0.25 millimeter in diameter	Percent	Filtration/sieving/gravimetry	KY	Guy, 1969; Shreve and Downs, 2005	70333
Loss on ignition of suspended solids	0.5	Method I-3765	KY	Fishman and Friedman, 1989	00535

Table 4. Constituents measured in samples of bridge-deck sediment in milligrams per kilogram, reporting levels, analytical techniques, and parameter codes, 2014–16.

[Samples analyzed by RTI Laboratories, Inc., in Livonia, Michigan. USGS, U.S. Geological Survey; SM, standard method]

Constituent	Minimum detection level	Analytical technique	Reference	USGS parameter code
Phosphorus as phosphorus	0.8	SM 4500-P F	Clesceri and others, 1998	68075
Aluminum	10	Digestion method 3050B; inductively coupled plasma-atomic emission spectrometry, method 6010C	U.S. Environmental Protection Agency, 1996; U.S. Environmental Protection Agency, 2000	65196
Arsenic	4			67876
Barium	4.6			67877
Cadmium	3.4			67880
Chromium	7.6			67882
Copper	5.3			67884
Lead	3.1			64181
Manganese	21			67888
Nickel	13			67890
Zinc	19			64180

allows the sampler to collect a more representative sample of the course load (Edwards and Glysson, 1999). The static mixers were constructed from a 0.75-in. low-density polyethylene.

Each automatic sampler was configured to hold four 3.75-L polyethylene sample bottles. Sample bottles were cleaned with phosphate-free, laboratory-grade soap and tap water; then immersed in a 5-percent solution of hydrochloric acid for a period of at least 6 hours; and finally rinsed with deionized water until the specific conductance of the waste rinse water was less than 1 microsiemens per centimeter. The sampler's intake lines consisted of 0.5-in. polyethylene tubing attached to silicon pump-head tubing and a discharge tube. Prior to the initial installation of the sampling equipment, the various tubing was cleaned as described above; however, the tubing was only cleaned with phosphate-free, laboratory-grade soap and deionized water between sample collection. As part

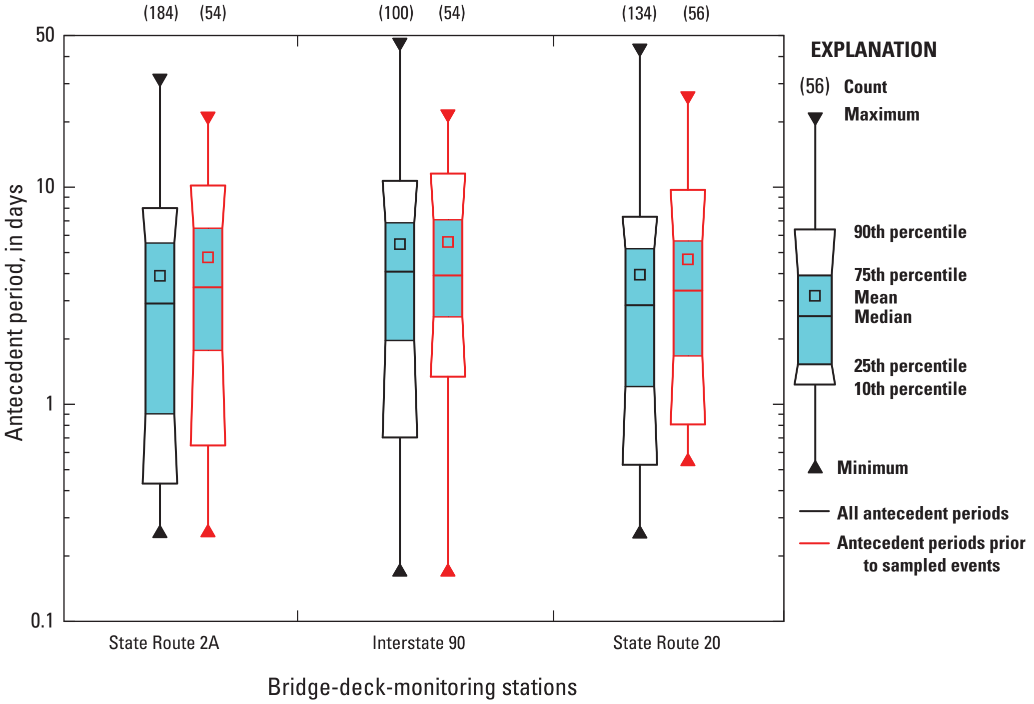


Figure 5. Distribution of all antecedent dry periods and the antecedent dry periods for runoff events during which runoff samples were collected at U.S. Geological Survey monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

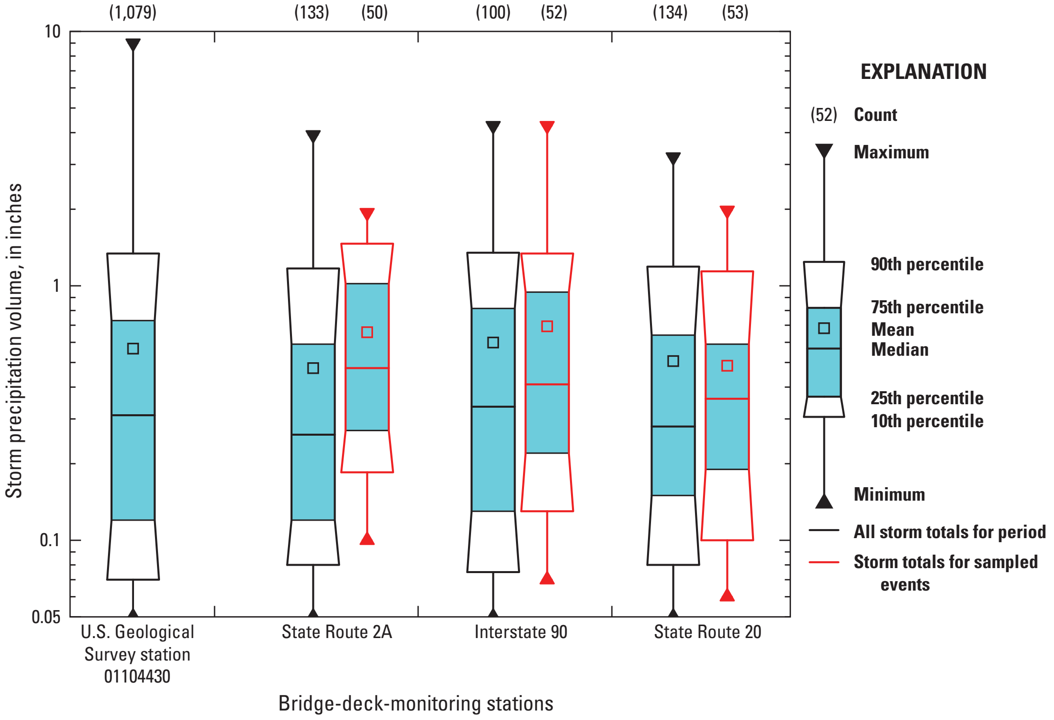


Figure 6. Distribution of storm totals equal to or greater than 0.05 inch recorded at U.S. Geological Survey station 01104430 during November 2001 through July 2014 and precipitation totals for storms during which samples were collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, August 2014 through September 2016. Precipitation totals for State Route 2A in Boston were recorded at U.S. Geological Survey station 01104683. Locations of stations are shown on figure 1.

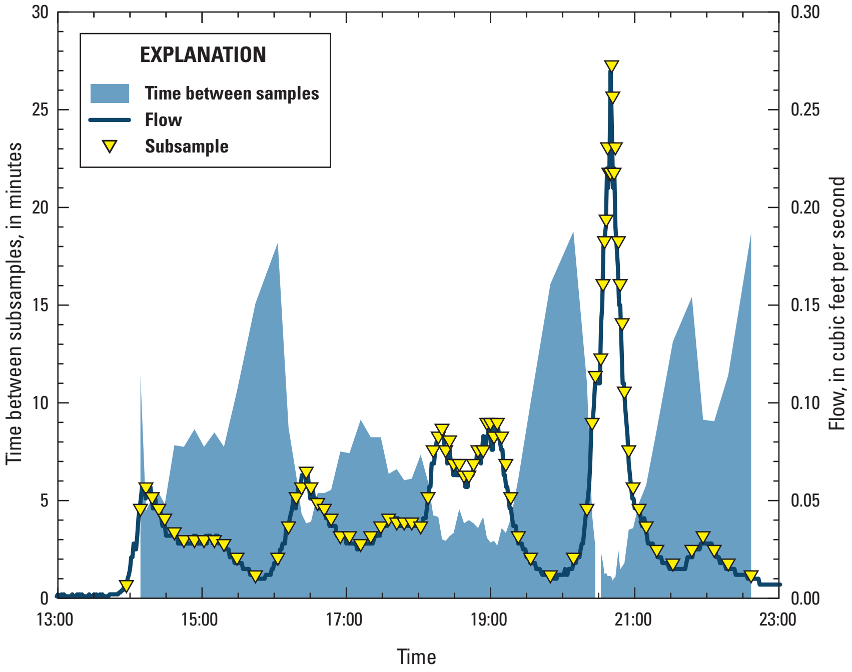


Figure 7. Example of automated flow-proportional collection of stormflow subsamples at U.S. Geological Survey bridge-deck-monitoring station at State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, December 17, 2015. Location of station is shown on figure 1.

Figure 8. A static mixer assembly at U.S. Geological Survey bridge-deck-monitoring station on State Route 2A in Boston (422108071052501) in eastern Massachusetts, 2014–16. Location of station is shown on figure 1.

of the routine cleaning practice, lint-free wipes were forced hydraulically through the sampler's tubing to remove internal deposits or films that were difficult to remove by circulating solution alone. Afterward, the sample tubing was purged with 2 L of deionized water. The sampler's pump-head tubing was routinely replaced with new tubing throughout the project as the tubing performance deteriorated.

Sample Processing

Water samples were processed in the USGS New England Water Science Center laboratory in Northborough, Mass., typically during the day following the conclusion of the runoff events. The pH of the entire sample volume was adjusted to be between 1.6 and 1.95 prior to processing to meet preservation requirements for nutrient analysis. Subsamples for the analysis of SS, TP, DN, PN, LOI, and PC were split by pouring the contents of each composite sample bottle fitted with a funnel cap into a Deka port cone splitter (Capel and others, 1995) modified to accept 0.5-in. tubes. The modification of the cone splitter to accept tubes of the same diameter as the sampler was necessary to ensure that all particles in the runoff samples would pass through the splitting device. Results of experimental tests by the USGS (Capel and others, 1995; Capel and Larson, 1996) indicate that subsamples containing coarse sediment are more precisely processed with a cone splitter compared to other splitting devices. In many cases, it was necessary to split subsamples multiple times to reduce the volume sufficiently to satisfy analytical requirements when the sample volume was large. Sample-water particulates were processed by passing a known volume of sample water through a Teflon™ filter assembly and a 25-millimeter (mm) glass-microfiber filter with a 0.3-micrometer (µm) pore size (U.S. Geological Survey, variously dated). The filters were analyzed for PN, PC, PIC, and POC. The filtrate from this procedure was analyzed for DN.

Sample Analysis

Samples for analysis of nutrients and carbon constituents were preserved with Optima-grade sulfuric acid 4.5-normal solution and chilled. Other samples only required refrigeration. Samples for the analysis of nutrients and carbon constituents were double bagged after processing and stored on ice for overnight delivery to the USGS National Water Quality Laboratory in Denver, Colorado, where they were analyzed (table 3). Samples were analyzed for SS, distribution of particle size, and LOI at the USGS Kentucky Water Science Center Sediment Laboratory (table 3). Constituent concentrations for the composite samples of bridge-deck runoff are available through the USGS National Water Information System (NWIS; U.S. Geological Survey, 2016).

Samples of Bridge-Deck Sediment

A composite sample of bridge-deck sediment for analysis of sediment quality was collected directly from the bridge surface, scuppers, or flumes on each bridge. These composite samples were wet sieved into three particle-size ranges (less than 0.0625 mm in diameter, greater than or equal to 0.0625 to 0.25 mm in diameter, and greater than 0.25 mm in diameter), and each size range was analyzed for concentrations of TP and 10 total-recoverable metals (table 4).

Sample Processing

Samples of bridge-deck sediment for analysis of sediment quality were wet sieved with bridge-deck runoff water specifically collected for this purpose through precleaned 0.25-mm and 0.0625-mm nylon-mesh sieves. The sieves, and polyethylene settling bags, were cleaned by immersing them in a 5-percent solution of hydrochloric acid for a period of about 6 hours and thoroughly rinsing them with deionized water. Sediment greater than or equal to 0.0625 to 0.25 mm in diameter and sediment greater than 0.25 mm in diameter for each bridge was set aside in separate clean polyethylene bags. Sediment particles less than 0.0625 mm in diameter were collected in polyethylene bags with native water and allowed to settle undisturbed in a laboratory refrigerator in the USGS New England Water Science Center laboratory in Northborough, Mass., for at least a week. After the sediment settled, the supernatant was decanted and discarded, and the sediment was retained for chemical analysis.

Sample Analysis

Samples for sediment quality containing particles less than 0.0625 mm in diameter, greater than or equal to 0.0625 to 0.25 mm in diameter, and greater than 0.25 mm in diameter were submitted to RTI Laboratories, Incorporated in Livonia, Michigan, for analysis of TP and 10 total-recoverable metals (table 4). Concentrations of TP were determined by automated ascorbic acid reduction (Clesceri and others, 1998). Concentrations of total-recoverable metals were determined with the use of U.S. Environmental Protection Agency (EPA) digestion method 3050B (U.S. Environmental Protection Agency, 1996) and inductively coupled plasma-atomic emission spectrometry (U.S. Environmental Protection Agency, 2000). Bridge-deck sediment quality data are available through the NWIS database (U.S. Geological Survey, 2016).

Distribution of Bridge-Deck Sediment

The bridges contain numerous scuppers, and most scupper outlets are over water or are too high to access. As a result, bridge-deck runoff monitoring was limited to a single scupper on each bridge. Characterizing the distribution of the mass of bridge-deck sediment on the surface of the roadway at different points across each bridge is necessary to qualify the results obtained at the monitored scupper.

To determine the distribution of sediment on the bridge decks, samples of sediment along the curb were collected with portable vacuums at five evenly distributed locations across each of the bridges. The nozzle width of the vacuum and the number and lengths of the vacuumed sections were recorded, and samples were returned to the New England Water Science Center laboratory in Northborough, Mass., where they were extracted from the vacuums and a mass per curb length was determined for each set of samples.

Sample Collection and Processing

Three sampling events were conducted on each bridge deck between April 2015 and September 2016. Samples of bridge-deck sediment were collected at five evenly distributed locations across each bridge deck (table 5). Dedicated hand-held battery-powered vacuums were used to collect bridge-deck sediment samples at each of the five sampling locations. Fixed sampling locations included the center of each bridge and adjacent locations that represent about 10 and 30 percent of the total length of each bridge span. Each of the five samples was a composite of two to five vacuumed strips that were the width of the vacuum nozzle (0.22 ft), 3 ft long, and perpendicular to direction of traffic flow from the rightmost curb edge (fig. 9). The number of strips vacuumed at each location was determined by the amount of sediment available on the bridge deck at the time of sample collection. Sediment was removed from pre-tared vacuum tanks and each filter was dried in pre-tared stainless-steel trays at 105 degrees Celsius (°C) to a constant weight, or until the weight change from the previous recorded weight was less than 0.5 milligram (mg) (Clesceri and others, 1998) at the USGS New England Water Science Center laboratory in Northborough, Mass. The resultant bridge-deck sediment mass, in grams, for each bridge and sampling event is listed in table 5. Previous studies have shown that this method of street sediment collection provides good precision and that these sample-collection techniques do not likely introduce additional variability (Pitt, 1979; Bannerman and others, 1983; Selbig and Bannerman, 2007; Sorenson, 2013).

Sample Analysis

Sediment yield in pounds per curb-mile was estimated from the dry mass of bridge-deck sediment at each sampling location (eq. 1). These estimated yields provide a semiquantitative account of the mass of sediment at fixed points across each bridge. The mass of sediment used to estimate the linear yield was collected within 3 ft of the curb. Data from several studies indicate that between 75 and 90 percent of the street sediment is near the curb (Sartor and Boyd, 1972; Pitt, 1979; Selbig and Bannerman, 2007), and this also was observed on the bridge sites through visual observations during routine sample collection (fig. 9*B*). Sample composite yields for each bridge are summarized in table 6.

$$P = \frac{g \times 0.0022}{W \times N \times M} \tag{1}$$

where

P is the mass of the sediment for a bridge-deck sampling location, in pounds per curb-mile;
g is the total dry mass of sampled bridge-deck sediment, in grams;
0.0022 is the unit conversion factor between grams and pounds;
W is the width vacuumed for each sample strip (vacuum nozzle width), in feet;
N is the total number of sample strips at each of the bridge-deck sampling location; and
M is the conversion from the width vacuumed, in feet, to miles.

Data Quality

The accuracy and precision of the data collected in this study were evaluated by making quality-control measurements at each of the monitoring stations and collecting various types of quality-control samples. Quality-control samples include field blanks and replicate-split samples. The identification of random error and systematic bias can be achieved through the collection and analysis of quality-control data. These analyses provided the basis for the interpretation of sediment and chemical data collected in this study.

Bridge-Deck Flow

Quality-assurance data were collected at each monitoring station to evaluate the accuracy of the theoretical water-level/flow relation of each flume. This relation was tested by simultaneously measuring flow from a 9,600-gallon-per-hour centrifugal pump with an in-line flowmeter and measuring the water level in the flume. Pump and theoretical flow values were recorded after pump flow and flume water level were stable across a range of pumping rates. This process was

Table 5. Sample location, in percent of total bridge span, and mass of bridge-deck sediment samples in grams collected at five bridge locations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2015–16.

[Locations of stations are shown in figure 1. Shaded areas indicate bridge sample location nearest to scupper where runoff samples were collected. Bridge-deck sample location expressed as a percent of total bridge span length measured from nearest bridge abutment from east to west. mm, month; dd, day; yyyy, year; °, decimal degrees]

Collection date (mm/dd/yyyy)	Number of strips vacuumed (0.22 foot wide)	Sample mass of bridge-deck sediment in grams for five equidistant locations									
		10 percent		30 percent		Center		70 percent		90 percent	
		Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude
State Route 2A in Boston, Massachusetts											
		42.35245°	-71.09032°	42.35347°	-71.09081°	42.35447°	-71.09132°	42.35547°	-71.09182°	42.35645°	-71.09232°
04/02/2015	3	**89.6**		198		342		274		79.5	
09/01/2015	3	**5.70**		33.3		6.60		49.0		37.3	
11/23/2015	3	**19.6**		18.0		18.6		69.7		48.8	
Interstate 90 near Weston, Massachusetts											
		42.34172°	-71.25998°	42.34138°	-71.26073°	42.34093°	-71.26152°	42.34088°	-71.26202°	42.34027°	-71.26247°
09/03/2015	3	2.10		7.10		5.90		5.40		**6.10**	
12/15/2015	5	5.02		78.2		58.8		83.5		**42.6**	
09/20/2016	3	1.48		5.05		5.89		6.93		**8.43**	
State Route 20 near Quinsigamond Village, Massachusetts											
		42.2141°	-71.78323°	42.21365°	-71.78358°	42.21322°	-71.78392°	42.21277°	-71.78428°	42.21235°	-71.7847°
04/01/2015	2	934		**725**		405		605		198	
8/27/2015	3	63.9		**67.7**		45.1		55.9		45.4	
11/27/2015	3	58.7		**86.0**		47.1		75.8		59.5	

Figure 9. *A*, collection of bridge-deck sediment sample and *B*, vacuumed strip adjacent to 3-foot ruler after collection of sediment sample on Interstate 90 near Weston (422025071154501). Location of station is shown on figure 1.

repeated until the pump reached its maximum rate of flow. Pump flow values typically were within the range of flow estimated from a water level of plus or minus 0.01 ft around the theoretical water level-flow relation (fig. 10). This range (plus or minus 0.01 ft) in water level represents the typical error for the measurement of water levels in the flume. Errors in flow at the low end of the relation may be larger as a result of minor physical imperfections in the flume than that in the theoretical water-level/flow relation. Maximum pump flow values exceeded all peak flows measured during sampled events, except for the monitoring station at State Route 20, which had the largest drainage area. At State Route 20, about 80 percent of the flows measured during sampled events were within the range of flows tested with the pump (fig. 10). Nevertheless, there was no indication that flow greater than the test range deviated from the theoretical level-flow relation at this monitoring station. These water level-flow pump tests indicate that the theoretical relation for each flume provided accurate estimates for flow.

Sediment and Chemical Quality

Quality-control samples, including field blank and replicate-split samples, were collected to identify potential bias in sampling and processing methods and contamination resulting from the sampling equipment and from the sample-collection, processing, and analysis processes. These quality-control samples are listed in table 7 in the back of the report.

Field Blank Samples

A field blank is used to test for positive bias that can result from contamination at any stage of sample collection, processing, or analysis, as well as from the sampling equipment itself. Source-solution blanks were prepared from deionized water produced by a laboratory-grade water-purification system that uses ion-exchange packs and reverse osmosis. The source-solution water was transported to the monitoring stations in precleaned polyethylene cubits. Field blanks were collected throughout the study period and at every monitoring station. These samples were collected by pumping blank water through the automatic sampler tubing and into the collection bottle, and processing it in a manner consistent with the collection of environmental samples of bridge-deck runoff.

During the study period, 10 field blanks were collected and submitted for chemical and sediment analysis. Measurable concentrations for each constituent in field-blank samples were compared to the USGS National Water Quality Laboratory and sediment laboratory reporting limit and environmental concentration data collected during the study (table 8). For analytes not detected in samples, such as PIC, PN, and TP, a concentration equal to the laboratory reporting limit is reported with a “less than” (<) remark code in all data tables in this report. Concentrations of SS in field blanks were slightly greater than the laboratory reporting limit in 7 of 10 field blank samples, with the maximum concentration in the field blanks being less than 2 percent of the minimum environmental concentration. Concentrations of LOI, PC, and POC were detected less often in field blank samples, and the maximum concentrations in the field blanks were 11, 11, and 2 percent of minimum environmental concentrations in samples of bridge-deck runoff respectively. Only 1 of the 10 field blanks had a detection of DN at a level that was below the minimum environmental concentration for that constituent. Low levels of contamination may be acceptable if the level of contamination is within the measurement error of the analytical method or is well below the concentrations of the constituent in the environmental samples. For example, the maximum concentration for SS in the field blanks was more than an order of

Table 6. Bridge-deck sediment yields, in pounds per curb-mile, for five bridge locations for bridges on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2015–16.

[Locations of stations are shown in figure 1. Shaded areas indicate bridge sample location nearest to scupper where runoff samples were collected. Bridge-deck sample location expressed as a percent of total bridge span length measured from nearest bridge abutment from east to west. mm, month; dd, day; yyyy, year; °, decimal degrees]

Collection date (mm/dd/yyyy)	Bridge-deck sediment yields, in pounds per curb-mile										Mean
	10 percent		30 percent		Center		70 percent		90 percent		
	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	
State Route 2A in Boston, Massachusetts											
	42.35245°	-71.09032°	42.35347°	-71.09081°	42.35447°	-71.09132°	42.35547°	-71.09182°	42.35645°	-71.09232°	
04/02/2015	**1,600**		3,500		6,000		4,800		1,400		3,500
09/01/2015	**100**		590		120		860		660		470
11/23/2015	**350**		320		330		1,200		860		610
Mean	**680**		1,500		2,200		2,300		970		1,500
Interstate 90 near Weston, Massachusetts											
	42.34172°	-71.25998°	42.34138°	-71.26073°	42.34093°	-71.26152°	42.34088°	-71.26202°	42.34027°	-71.26247°	
09/03/2015	37		130		100		95		**110**		90
12/15/2015	53		830		620		880		**450**		570
09/20/2016	26		89		100		120		**150**		100
Mean	39		350		270		370		**240**		250
State Route 20 near Quinsigamond Village, Massachusetts											
	42.2141°	-71.78323°	42.21365°	-71.78358°	42.21322°	-71.78392°	42.21277°	-71.78428°	42.21235°	-71.7847°	
04/01/2015	25,000		**19,000**		10,700		16,000		5,200		15,000
8/27/2015	1,100		**1,200**		800		990		800		980
11/27/2015	1,000		**1,500**		830		1,300		1,000		1,100
Mean	9,000		**7,200**		4,100		6,100		2,300		5,700

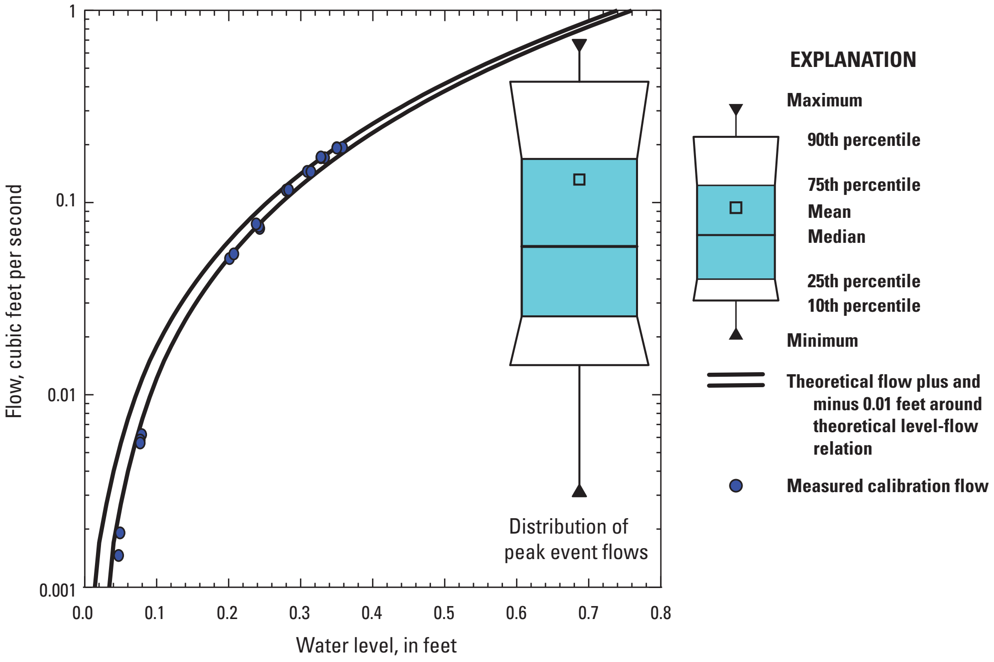


Figure 10. Discrete measurements of pump flow in relation to the theoretical water-level/flow relation (offset by plus or minus 0.01 feet) for the H flume compared to the distribution of peak flows recorded during sampled events at U.S. Geological Survey bridge-deck-monitoring station on State Route 20 near Quinsigamond Village (421247071470201), eastern Massachusetts, 2015–16. Location of station is shown on figure 1.

magnitude lower than the minimum concentration measured in samples of bridge-deck runoff. In general, contamination bias was low for all constituents.

Concurrent Replicate-Split Runoff Samples

Concurrent replicate-split samples are thought to be identical in composition to the environmental samples and are collected simultaneously during sample processing. Replicate-split samples provide a measure of bias and variability for the method of sample processing (splitting, filtering, and preservation), laboratory analysis, and effects such as analyte degradation that can happen prior to laboratory analysis. Concurrent replicate-split samples were collected throughout the year and over a range of varying concentrations that occurred during the study (fig. 11).

Concurrent replicate-split samples were collected from 33 bridge-deck composite samples. Bridge-deck composite runoff samples were split into smaller representative aliquots, as described previously, to satisfy the different analytical

Table 8. Summary of field-blank data and comparison to composite bridge-deck runoff samples, in milligrams per liter, collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. USGS, U.S. Geological Survey; NWQL, National Water Quality Laboratory; <, less than]

Constituent	USGS parameter code	Sample count	NWQL reporting limit	Number of detections in field blanks	Maximum concentration in field blank	Minimum concentration in bridge-deck runoff	Maximum concentration in bridge-deck runoff
Loss on ignition of suspended solids	00535	7	0.5	4	2	19	1,740
Particulate carbon [inorganic plus organic]	00694	10	0.05	4	0.76	6.68	1,360
Particulate organic carbon	00689	8	0.05	2	0.11	6.57	1,100
Particulate inorganic carbon	00688	8	0.03	0	<0.03	<0.03	255
Particulate nitrogen	49570	10	0.030	0	<0.030	0.179	26.7
Total phosphorus	00665	10	0.01	0	<0.01	0.09	7.02
Total dissolved nitrogen	62854	10	0.05	1	0.07	0.18	5.63
Suspended sediment	70331	10	0.5	7	2	44	142,000

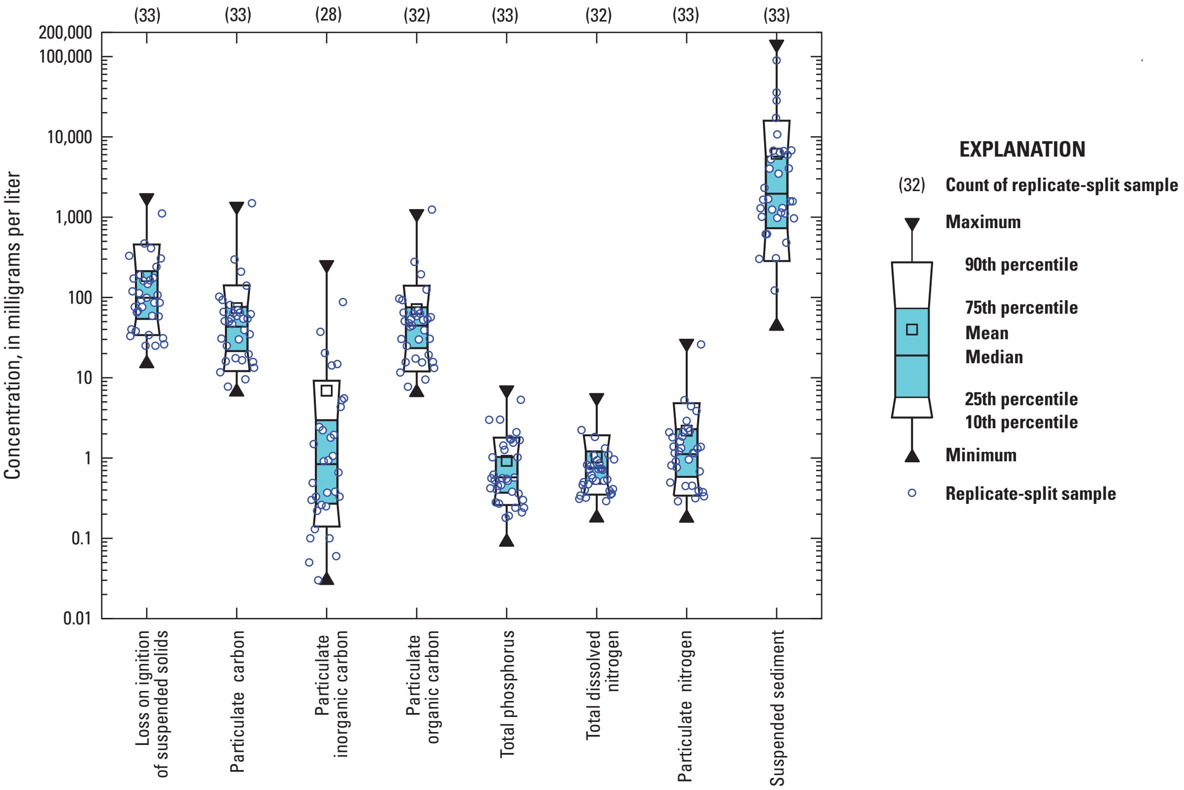


Figure 11. Distribution of concentrations of constituents measured in composite samples of bridge-deck runoff and in concurrent replicate-split samples collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

methods. The absolute relative percent difference (RPD) was calculated for each sample pair (concurrent replicate-split sample and composite runoff sample). The median RPD for concentrations of SS- and particle-associated constituents ranged from 10 to 25 percent, except for the median RPD for concentrations of PIC, which was about 65 percent (fig. 12). The maximum RPD for SS and LOI was 59 and 45 percent, respectively; about 75 percent of the RPDs for each constituent were less than 20 percent. The maximum RPD for PC, POC, TP, and PN was about 100 percent for each constituent; about 75 percent of the RPDs for each constituent were less than 42 percent. The RPD for PIC was much greater compared to the RPD for other carbon constituents. Concentrations of PIC were an order of magnitude lower than concentrations of PC and POC (fig. 11) and may explain the higher variability in the RPD values. Dissolved constituents generally are not affected by splitting; however, the low RPD for DN (less than 8 percent for all sample pairs; median less than 2 percent for all sample pairs) also is an indication that the analytical method performance was generally precise.

The collection of representative aliquots from composite samples containing high concentrations of sand-size particles is difficult, and the results are often imprecise (Selbig and others, 2007; Smith and Granato, 2010). Under experimental conditions, the relative standard deviation for concentrations of sand-size particles in aliquots obtained by processing two artificial samples containing known concentrations of SS (50 and 200 milligrams per liter [mg/L]) through a Deka port cone splitter ranged from 12 to 45 percent (Capel and others, 1995). The relative standard deviation for the RPDs of 33 SS pairs in this study was higher at 99 percent. Concentrations of SS in composite samples collected in this study varied by more about three orders of magnitude (fig. 11), and the sediment matrix was dominated by sand-size particles. The lower precision for SS and particle-associated constituent concentrations observed in concurrent replicate-split sample aliquots in this study may be explained, in part, by the variability and high concentrations of SS in composite samples of runoff collected from the bridge decks where the concentration of SS in 96 percent of the sample pairs was substantially greater than the concentrations of SS in the two artificial samples described in the Deka port cone splitter experiment (Capel and others, 1995). Furthermore, sample composite volumes in this study ranged from 1 to 16 L; thus composite samples often were split two or three times to reduce the aliquot volume sufficiently, and this also could have attributed to lower sample splitting precision for SS and particle-associated constituent concentrations. The relation between the RPDs of sample pairs and the associated

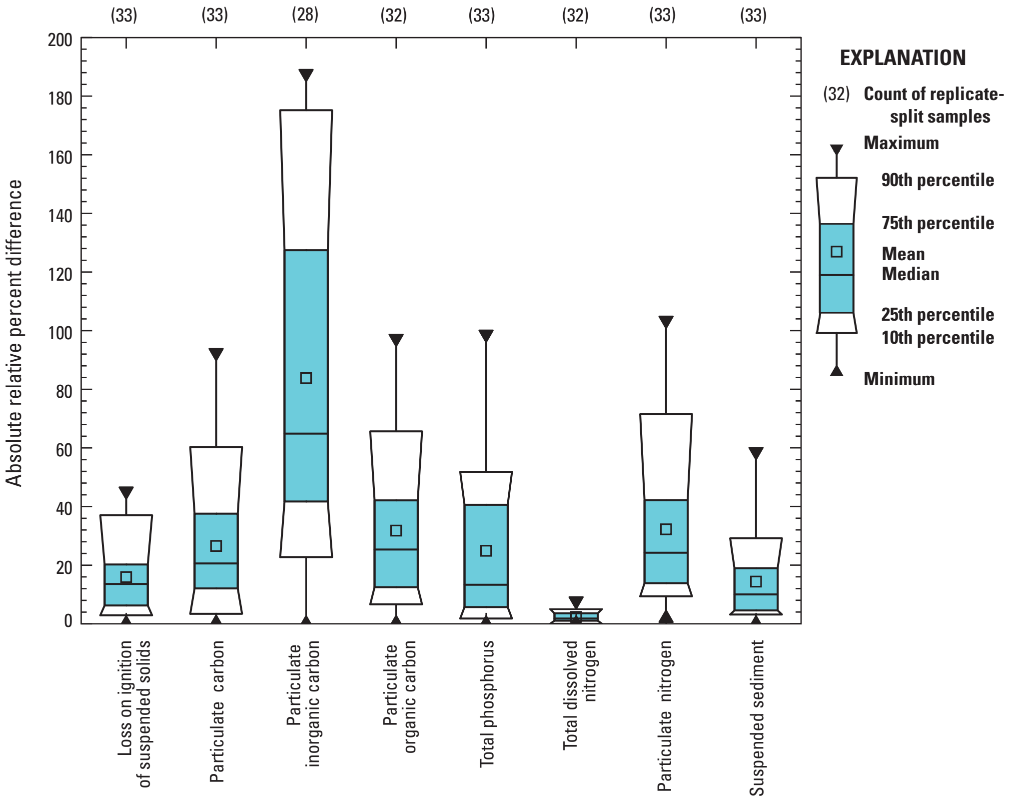


Figure 12. Distribution of absolute relative percent difference values between replicate-split samples and composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

concentrations of SS was poor, indicating the precision was random across the range of concentrations measured in composite samples of bridge-deck runoff.

Replicate Samples of Bridge-Deck Sediment

One replicate sample, representing one of three particle-size classes of bridge-deck sediment, was collected at each bridge site to determine the precision of the concentration data associated with the particle-size classes less than 0.0625 mm in diameter, greater than or equal to 0.0625 to 0.25 mm in diameter, and greater than 0.25 mm in diameter. The RPD between concentrations of TP and total-recoverable metals in many replicate-split samples and bridge-deck sediment samples tended to be lower (less than 12 percent) in the fine-sediment fraction and increased with particle-size diameter (table 9). In general, many constituents affiliated with SS tend to be concentrated on the particles less than 0.0625 mm in diameter, and the relation becomes less homogenous as sediment diameter increases (Breault and others, 2005; Smith, 2005; Smith and Granato, 2010). Aside from arsenic (As) and copper (Cu), the RPD for the other metals in the coarser size fractions ranged from 0 to 64 percent. The RPDs for concentrations of As and Cu were the least precise in the two larger size fractions. The RPD for concentrations of chromium (Cr) was the most precise in all three particle-size ranges.

Analysis Methods

The Anderson-Darling test, which compares the fit of an observed cumulative distribution function to an expected cumulative distribution function, was used to test for normality of each dataset (Minitab, Inc., 2010). The Spearman rho test was used to evaluate monotonic relations between concentrations of constituents collected at the bridges (Helsel and Hirsch, 2002). The Spearman rho test is based on the ranks of the data and, therefore, is resistant to effects caused by outliers (Helsel and Hirsch, 2002). Test results range from −1 (negative relation) through 0 (no relation) to +1 (positive relation). A negative coefficient indicates that one variable tends to increase as the other decreases, and a positive coefficient indicates that the two variables tend to increase together; however, the variables may not necessarily change at a constant rate in a monotonic relation. The absolute value of the correlation coefficient indicates the strength of the relation between variables. For the Anderson-Darling and the Spearman rho test, the significance level (α) was equal to 0.05. When the attained significance level of the test (*p*-value) was less than 0.05, the null hypothesis of “data is normally distributed” (Anderson-Darling) or “no correlation in ranked data” (Spearman) was rejected.

Data collected in this study were analyzed to determine if the quality of bridge runoff differed significantly from bridge to bridge and if the quality of bridge runoff differed

Table 9. Concentrations and absolute relative percent difference between three replicate-split and environmental composite samples of bridge-deck sediment collected from U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. Values calculated from a single pair of composite samples for each particle-size class. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. USGS, U.S. Geological Survey; Composite, composite runoff sample; Replicate, concurrent replicate-split sample; RPD, absolute relative percent difference; <, less than; ND, not detected in particle-size range]

Sample type	Particle-size range	Concentration, dry weight, in milligrams per kilogram										
		Phosphorus (p68075)	Aluminum (p65196)	Arsenic (p67876)	Barium (p67877)	Cadmium (p67880)	Chromium (p67882)	Copper (p67884)	Lead (p64181)	Manganese (p67888)	Nickel (p67890)	Zinc (p64180)
USGS station 421247071470201												
Composite	Greater than 0.25 millimeter in diameter	44	7,400	2	37	0.11	22	<4.5	8.8	220	23	73
Replicate		44	3,800	9	28	0.11	22	<4.0	4.8	330	14	58
RPD		0	64	127	28	0	0	ND	59	40	49	23
USGS station 422025071154501												
Composite	Greater than or equal to 0.0625 to 0.25 millimeter in diameter	35	6,200	6.8	100	0.4	56	5	120	290	34	300
Replicate		45	5,600	17	66	0.56	59	190	94	340	31	380
RPD		25	10	86	41	33	5	190	24	16	9	24
USGS station 422108071052501												
Composite	Less than 0.0625 millimeter in diameter	280	22,000	32	190	1.5	120	140	100	560	57	1,100
Replicate		310	23,000	32	170	1.5	120	140	92	560	55	1,100
RPD		10	4	0	11	0	0	0	8	0	4	0

significantly from the quality of highway runoff collected in eastern Massachusetts (Smith and Granato, 2010). Nonparametric rank-based methods were used for comparison of constituent concentrations collected on bridges or highways. Analysis of rank-transformed data is more robust compared to the analysis of raw data that are not normally distributed, and the mean rank represents an estimate of the median (Helsel and Hirsch, 2002). Bridge-deck runoff concentration data were analyzed by using the one-way analysis of variance (ANOVA) test on the ranks of the data (Minitab, Inc., 2010). Subsequently, the Tukey pairwise comparison method test was used to identify statistically significant differences (p-value less than 0.05) between datasets from each bridge (Minitab, Inc., 2010).

The Tukey method controls the overall specified error rate (95-percent joint confidence level) for all pairwise comparisons, and it is applicable to the uneven sample sizes (Helsel and Hirsch, 2002). The Mann-Whitney test, also referred to as the rank-sum test, was used to determine whether constituent concentrations collected from bridges differed statistically (p-value less than 0.05) from paired constituent concentrations collected from highways (Helsel and Hirsch, 2002). The Mann-Whitney test is a nonparametric method that makes no assumptions about the distribution of data and is used to determine if groups of data come from the same population or, alternatively, if the median values are different (Helsel and Hirsch, 2002).

Bridge-Deck Runoff Simulations

Model simulations of runoff quality can provide important information for engineers and managers when choosing BMPs that are most effective in consistently reducing the target. The Stochastic Empirical Loading and Dilution Model (SELDM) was used to simulate bridge-deck runoff quality (Granato, 2013, 2016). These simulations demonstrate water-quality risk analysis and simulate annual bridge-runoff yields with and without use of stormwater control measure BMPs. Standard methods and variables described by Granato (2013) and statistics from the National Weather Service long-term precipitation monitoring sites in ecoregion 59 (the Northeastern Coastal Zone) were used for the hydrologic simulations.

Version 1.0.2 of SELDM was used to perform long-term (29–30-year) simulations of bridge-deck runoff quality. SELDM can be used to model sites with different land uses and sites in different settings because it is a lumped parameter model that simulates runoff by using representative input values for conditions at a site of interest. Although SELDM is primarily designed to indicate the risk for stormwater event-mean composites, flows, and loads to be above user-selected water-quality goals for individual storm events, it also calculates annual yields. SELDM is not calibrated by fitting input values to a historical record; it is calibrated by selecting statistics for runoff-quality variables and BMP-treatment variables from robust and representative datasets (Granato, 2013, 2014; Granato and Jones, 2015, 2016, 2017). The input statistics that are selected can have a substantial effect on the potential number of water-quality exceedances in a simulation and the estimated annual yields.

Simulating Bridge-Deck Hydrology

Although standard methods and variables described by Granato (2013) were used for the simulations in this study, information about the timing of runoff from the highway is not needed for annual-loads analyses. Therefore, the only bridge-site hydraulic variables needed for these analyses were the drainage area and the impervious fraction. A drainage area of 1 acre and an impervious fraction of one (100 percent) were selected so the loads would be computed as annual yields in pounds per acre of pavement per year. The primary hydrologic variables used by SELDM to simulate runoff are the volume, duration, and the number of hours between event midpoints for runoff-generating storm events. Storm events are generated stochastically by using the two-parameter exponential distribution. The numbers of hours between event midpoints for runoff-generating storm events are summed from event to event until the total elapsed time exceeds either 365 or 366 days, and then all the events within this period are lumped into an annual load accounting year. This process continues until the minimum threshold is exceeded and the last full year is simulated (Granato, 2013). The average of statistics from the 31 National Weather Service long-term precipitation monitoring sites in ecoregion 59 (the Northeastern Coastal Zone) were used for the simulations. These average values for storm-event depth, duration, and the number of hours between event midpoints are 0.704 in., 9.69 hours, and 155 hours, respectively (Granato, 2010, 2013). Stochastic variations in precipitation-event values resulted in 8 simulations with 29 annual-load accounting years and 3 simulations with 30 annual-load accounting years. SELDM simulates runoff from precipitation by using stochastic runoff coefficients simulated with the Pearson type III distribution (Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988). The stochastic-runoff coefficient statistics used in the analysis were calculated by using the standard SELDM values for the average (0.785), standard deviation (SD; 0.1917), and skew (−1.19) of runoff coefficients for sites that are fully impervious; these statistics were calculated by using rainfall-runoff data from 58 highway-runoff monitoring sites (Granato, 2013).

Simulating Bridge-Deck Runoff Concentrations

SELDM was used to simulate long-term concentrations and yields of SS, TP, and total nitrogen (TN) in bridge runoff. These values were simulated by using the log-Pearson type III distribution with the average, SD, and skew of the common (base 10) logarithms of SS, TP, and TN concentrations. In this study, these constituents were simulated by using the logarithms of concentrations because such data commonly fit a lognormal or log-Pearson type III distribution (Di Toro, 1984; Novotny, 2004; Granato and others, 2009; Granato, 2013). If data were simulated as lognormal, the skew was set equal to zero, which linearized the distribution of generated data with respect to the logarithmic and probability axes. In comparison, datasets with negative skews were concave down, which resulted in lower values at both ends of the distribution than would be produced with a lognormal distribution. Datasets with positive skews were concave up, which resulted in higher values at both ends of the distribution than would be produced with a lognormal distribution. Large positive skew values, when coupled with large SD values, may produce unrealistic concentrations, flows, and loads if an extreme random number is generated. Because monitoring data were limited, with many datasets commonly having fewer than 20 events per site, generating a long-term record set of many events (usually more than 1,600 in the Northeastern Coastal Zone) required extrapolation beyond the percentiles of the original data; therefore, careful selection of representative statistics was warranted.

Three methods for estimating sample statistics were used to evaluate input values for these long-term simulations. The first method was to use the traditional statistics for estimating the average, SD, and skew because they are most commonly used in hydrology and statistics (Haan, 1977; Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988; Hosking, 1990; Stedinger and others, 1993; Helsel and Hirsch, 2002). The second method was to use robust regression on order statistics to estimate the average and SD and Pearson’s second skew as a robust estimate of skew (Haan, 1977; Helsel and Hirsch, 2002). The third method was to use L-moments, which also are considered robust estimates of sample statistics (Hosking, 1990; Stedinger and others, 1993).

The traditional methods for estimating the average, SD, and skew have some limitations when these statistics calculated from limited datasets are used to simulate more values than are available (Haan, 1977; Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988; Hosking, 1990; Stedinger and others, 1993; Helsel and Hirsch, 2002). Although the average is the best estimate of the center of the distribution, the value of the average can be substantially biased by either high or low outliers in small datasets. Estimates of the average values tend to stabilize more rapidly with each additional sample and are less biased by outliers than the SD or skew because these statistics are calculated by using the sum of squared differences between each value and the average and the sum of cubed differences between each value and the average, respectively.

Robust regression on order statistics and Pearson’s second skew were used to estimate sample statistics because values calculated by using these methods may be less biased by outliers than values calculated by using traditional methods (Haan, 1977; Helsel and Hirsch, 2002). If the logarithms of data are plotted against the normal quantiles of the plotting position of each data point, then the intercept and slope of a regression line based on these points are estimates of the average and SD of a lognormal distribution of these data (Haan, 1977; Helsel, 2004; National Institute of Standards and Technology, 2012). For this study, the Kendall-Theil Robust Line software (Granato, 2006) was used to obtain the estimates of the average and SD with the composite sample runoff data because this regression method is resistant to outliers. The TP concentrations from composite runoff samples from the State Route 20 bridge-deck-monitoring station are presented in figure 13 as an example. The average was estimated by adding the median error to the intercept because the intercept of the Kendall-Theil Robust Line is an estimate of the median not the average (Granato, 2006). Pearson’s second skew was used to estimate the value of skew because it is less affected by outliers than the traditional measure of skewness. The traditional equation for skewness is calculated by using the sum of cubed differences from the mean and the cubed SD; therefore, a few extreme values can have a substantial effect on this estimate of skew (Haan, 1977; Stedinger and others, 1993; Helsel and Hirsch, 2002; National Institute of Standards and Technology, 2012). Pearson’s second skew, however, is calculated by subtracting the median from the mean, multiplying the difference by 3, and dividing by the SD, which avoids the use of cubed values (Haan, 1977; Stedinger and others, 1993; Helsel and Hirsch, 2002; National Institute of Standards and Technology, 2012).

L-moments also were used to estimate sample statistics for potential use in SELDM simulations. L-moments are linear combinations of probability-weighted moments (Hosking, 1990; Stedinger and others, 1993). The average L-moment statistic is calculated by using the same equation as the traditional average; however, the L-moments statistics which are analogous to the SD and skew statistics are considered unbiased estimators of sample statistics because these L-moment statistics are not calculated by using the squared or cubed differences from the average value. Calculation of these statistics is described by Stedinger and others (1993).

Selecting runoff-quality statistics from monitored sites to represent runoff quality at an unmonitored site is not a well-defined process. Although AADT counts have been reported as a predictive variable, such relations commonly are categorical, and the differences among sites may be attributable to the increasing development of surrounding areas that is associated with increasing traffic counts (Driscoll and others, 1990; Smith and Granato, 2010; Wagner and others, 2011; Taylor and others, 2014). Differences in monitoring statistics among sites may not be meaningful without availability of extremely large datasets (for example, 25 to 100 events) because of the variability of highway and urban runoff quality (Burton and Pitt, 2002; California Department of Transportation, 2009; Granato, 2013).

Robust methods are needed to use available data from monitored sites to estimate potential effects of runoff at unmonitored sites. In this study, the three monitored bridges constitute only about 0.16 percent of MassDOT-owned bridges over water in Massachusetts. Similarly, the 15 bridge decks

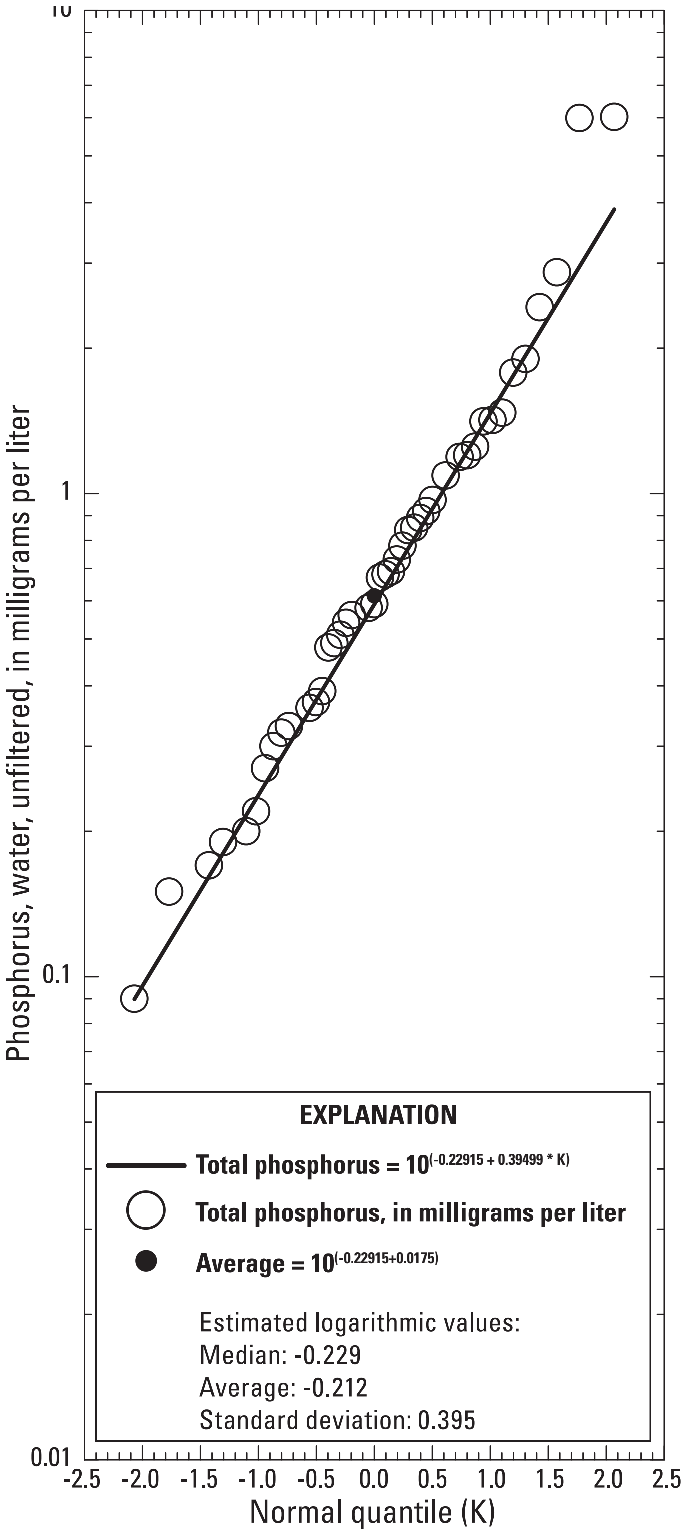


Figure 13. An example of the estimation of the average and standard deviation of total phosphorus concentrations in runoff composite samples collected from U.S. Geological Survey bridge-deck-monitoring station State Route 20 near Quinsigamond Village (421247071470201) by using the robust regression on order statistics method. Location of station is shown on figure 1.

in North Carolina in a larger study by Wagner and others (2011) constitute only about 0.1 percent of the 13,500 bridges maintained by North Carolina Department of Transportation (2017). Granato and Jones (2015) examined use of statistics from the same 15 bridge-runoff monitoring sites to estimate the risks for adverse effects of total phosphorus in receiving streams from bridge-deck runoff in North Carolina. They determined that correlations of concentrations to AADT counts (using both Pearson's R and Spearman's rho) were small and not statistically significant at the 95-percent confidence limits. Granato and Jones (2015) also determined a lack of significant correlation among statistics indicating that the average, SD, and skew of the common logarithms of concentration do not covary. They concluded that statistics may vary randomly from site to site, and the median of each concentration statistic may be representative for simulating runoff quality at unmonitored sites. Similarly, Risley and Granato (2014) examined potential effects of runoff-quality statistics on simulated concentrations and the potential for simulated water-quality excursions in receiving waters in Oregon. They concluded that using the median of statistics from hydrologically similar sites provided robust concentration estimates. Therefore, the median of statistics from the three bridge sites were used to simulate planning-level yield estimates for all bridges in eastern Massachusetts.

Simulating Runoff Treatment

Runoff treatment was analyzed to examine the potential effects of flow reductions and concentration reductions by stormwater BMPs on concentrations and annual yields from bridges. The BMP effluent concentrations and discharge volumes were simulated by using the BMP-treatment module in SELDM (Granato, 2013, 2014). The SELDM BMP-treatment module has provisions for stochastic modeling of three stormwater treatments: volume reduction, hydrograph extension, and water-quality treatment. Hydrograph extension is an important variable for dilution analyses, but the durations of BMP discharges do not substantially affect the total-annual yield from the highway. The SELDM BMP module uses the trapezoidal distribution and the rank correlation with the associated highway-runoff variable to provide a stochastic transfer function to approximate the quantity and quality of BMP effluent given the associated inflow values in a simulation. SELDM uses rank correlation to preserve the structure of inflow and outflow data commonly present in BMP studies. Correlations between the ratio of outflow to inflow volumes and the magnitude of inflows commonly are positive because it would be difficult for BMPs built with commonly used designs to retain or infiltrate a large proportion of flow from a large runoff event. The small positive correlation between highway inflow volumes and the outflow ratios reduces the average effectiveness of flow reduction by the BMP. Correlations between the concentration ratio and inflow concentrations are negative because BMP-monitoring datasets indicate that BMPs are more effective for substantially reducing large inflow concentrations than small inflow concentrations. The negative correlation between highway inflow concentrations and the outflow ratios increases the average effectiveness of concentration reduction by the BMP. In many studies, BMP outflow concentrations can exceed low inflow concentrations (Granato, 2014; Taylor and others, 2014). To represent this phenomenon, SELDM simulates the effect of the minimum irreducible concentration (MIC), which is the lowest expected BMP effluent concentration (Granato, 2013, 2014). SELDM substitutes the MIC for BMP effluent concentrations that are less than the MIC.

For these analyses, a generic BMP was simulated by using the median of treatment statistics for flow reductions, concentration reductions, and MICs from nine BMP categories with data from the 2012 International BMP database (Granato, 2014). The BMP categories and associated performance statistics for flow and concentration treatment from which the median values were derived and used for simulations in these analyses are shown in table 10. The categories bioretention, composite BMPs, detention basin, biofilter (swale), media filter, retention pond, wetland basin, and wetland channel were selected because flow statistics, concentration statistics, and MIC statistics were available from multiple BMP monitoring sites for these categories (Granato, 2014). The MIC values that were chosen for these simulations were based on the 25th percentile of MIC estimates from available sites for each category.

Quality of Bridge-Deck Runoff

Concentrations of SS, sediment particle size, nutrients, LOI, and PC were measured in more than 160 flow-proportional composite samples (about 50 or more per monitoring station) of bridge-deck runoff collected from the three bridge-deck-monitoring stations between 2014 and 2016 (U.S. Geological Survey, 2016). In addition to NWIS, the data also are available in the HRDB (version 1.0.0b) (Granato, 2017) that was developed by USGS in cooperation with the Federal Highway Administration (Granato and Cazenas, 2009). Summary statistics and statistical tests are presented to characterize and contrast the datasets for each bridge (table 11). The concentrations of constituents in composite samples of bridge-deck runoff varied considerably from storm to storm; however, concentration statistics for many constituents were similar for each bridge.

Suspended Sediment

Suspended sediment, especially the fine sediment fraction, is an important transport mechanism for many constituents in stormwater runoff. Several recent studies in Massachusetts have documented the affiliation of phosphorus and metals with sediment and the corresponding effect of concentration with specific particle sizes from samples of sediment collected from oil-grit separators (Smith, 2002), streambeds (Smith, 2005), street sweepings (Breault and others, 2005; Sorenson, 2013), and highway runoff (Smith and Granato, 2010). Metal concentrations associated with sediment tend to increase with a decrease in sediment particle size because as sediment particle size decreases the sediment surface area increases, allowing metals to bond to the sediment surface. Understanding the relation between sediment quality and particle size is important for the selection and implementation of structural and nonstructural BMPs to improve the quality of water discharged from bridge decks.

Concentrations of SS in composite samples of bridge-deck runoff ranged from 44 to 142,000 mg/L; however, most concentrations were less than 23,000 mg/L (maximum value for the 90th percentile for the three stations; table 11). Median concentrations of SS were nearly identical in samples collected from State Route 2A and Interstate 90 bridge-deck-monitoring stations (2,010 and 2,020 mg/L, respectively); the median concentration of SS in samples from State Route 20 bridge-deck-monitoring station was lower at 1,490 mg/L. The particle-size distribution of SS at each monitoring station was highly skewed towards the coarse size fraction (size fraction greater than 0.25 mm in diameter) (fig. 14). At each bridge-deck-monitoring station, the median concentration for the coarse size fraction was about an order of magnitude greater than the finer two size fractions (0.0625 to 0.25 mm and less than 0.0625 mm in diameter). The median distribution of particles in the fine size fraction (less than 0.0625 mm in diameter) ranged from 4 to 8 percent at each monitoring station (table 11). The median distribution of particles less than 0.25 mm in diameter was less than or equal to 26 percent for each bridge. The percentage of finer particles tended to increase with a decrease in concentration of SS (fig. 15), which is likely attributed to dissimilar buildup rates or roadway surface load capacity for the different particle sizes; that is, silt and clay size particles are easily dispersed by wind or vehicular turbulence, whereas coarse sand deposits tend to not disperse easily (less mobile) and increase in place between runoff events.

Loss on Ignition of Suspended Solids and Particulate Carbon

Concentrations of SS include organic particles in addition to mineral sediments. The organic fraction of the SS concentration is represented by LOI (or volatile suspended solids) and PC concentration data. Concentrations of LOI are generally considered a crude estimate of PC because other constituents, such as volatile salts, organic compounds, sulfide oxidation, inorganic carbon, and hydroxide compounds, also may be volatilized or otherwise diminished during the analytical method (Brown and Dykstra, 1995; Veres, 2002) and result in concentrations that are greater than those determined by methods for PC. Concentrations of LOI in composite samples of bridge-deck runoff generally were about 2.5 times greater than concentrations of PC in the same samples (fig. 16).

Table 10. Stormwater control measure best-management practice performance statistics for flow and concentration treatment used in the Stochastic Empirical Loading and Dilution Model.

[The concentration-reduction and flow-reduction statistics are for the trapezoidal distribution of the ratio of outflow to inflow concentration or flow volume. The Spearman's rho correlation coefficients are calculated by using the ranks of the inflow concentrations or flows and the associated ratios of outflow to inflow concentrations or flows. The minimum irreducible concentration (MIC) estimates for the suspended sediment concentrations were developed with total suspended solids concentrations but are considered applicable for estimating the MIC of suspended sediment concentrations because differences in the results of these analytical methods are small once the large grain-size fractions are removed within the best-management practice. LBMPV, lower bound of the most probable value; UBMPV, upper bound of the most probable value; Spearman's rho, Spearman's correlation coefficient; N, nitrogen; P, phosphorus; --, insufficient data; NA, not applicable]

Best-management practice type	Minimum	LBMPV	UBMPV	Maximum	Spearman's rho	MIC, in milligrams per liter
Flow reduction						
Bioretention	0	0.019	0.152	0.947	0.61	NA
Composite	--	--	--	--	--	NA
Detention basin	0.147	0.147	0.657	1.232	0.07	NA
Biofilter (swale)	0.06	0.306	0.495	1.085	0.29	NA
Infiltration basin	--	--	--	--	--	NA
Media filter	0.113	0.742	0.742	1.262	0	NA
Retention pond	0.208	0.665	0.903	1.832	0	NA
Wetland basin	0.136	0.934	0.934	1.233	0.21	NA
Wetland channel	0.116	0.548	0.548	1.849	0.27	NA
Median	0.116	0.548	0.657	1.233	0.21	NA
Total nitrogen as N						
Bioretention	0.148	0.4	0.593	2.01	-0.636	0.09
Composite	0.222	0.372	0.372	1.088	-0.081	0.06
Detention basin	0.141	0.417	1.998	3.121	-0.548	0.1
Biofilter (swale)	0.174	0.642	0.642	2.27	-0.552	0.17
Infiltration basin	0.052	0.052	0.158	2.598	-0.6	0.38
Media filter	0.126	0.391	0.536	1.703	-0.318	0.05
Retention pond	0.332	0.693	0.693	1.522	-0.508	0.14
Wetland basin	0.272	0.394	0.394	2.181	-0.437	0.04
Wetland channel	0.346	0.367	0.539	1.705	-0.595	0.11
Median	0.174	0.394	0.539	2.01	-0.548	0.1
Total phosphorus as P						
Bioretention	0.013	0.176	0.325	2.339	-0.42	0.01
Composite	0	0.126	0.17	1.562	-0.571	0.005
Detention basin	0.24	0.415	0.561	1.55	-0.498	0.03
Biofilter (swale)	0.105	0.669	0.827	3.556	-0.669	0.01
Infiltration basin	0.002	0.002	0.031	3.649	-0.292	0.002
Media filter	0.161	0.21	0.228	1.597	-0.555	0.005
Retention pond	0.053	0.199	0.38	1.653	-0.606	0.006
Wetland basin	0.056	0.512	0.88	2.158	-0.517	0.008
Wetland channel	0.171	0.226	0.623	2.203	-0.401	0.007
Median	0.056	0.21	0.38	2.158	-0.517	0.007
Suspended sediment concentration						
Bioretention	0	0	0	0.885	-0.635	0.06
Composite	0	0	0	0.791	-0.626	0.2
Detention basin	0	0	0	1.158	-0.631	0.89
Biofilter (swale)	0	0	0	1.545	-0.569	1
Infiltration basin	0	0	0	0.902	-0.738	1.9
Media filter	0	0	0	0.652	-0.604	0.43
Retention pond	0	0	0	0.822	-0.721	0.74
Wetland basin	0	0	0	1.681	-0.759	0.28
Wetland channel	0	0	0	2.21	-0.446	0.2
Median	0	0	0	0.902	-0.631	0.43

Table 11. Summary statistics for concentrations of constituents in composite samples of bridge-deck runoff collected from State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. mg/L, milligram per liter; N, nitrogen; P, phosphorus; <, less than]

Statistic	Suspended sediment, in mg/L (p80154)	Suspended sediment, percent smaller than 0.25 millimeter (p70333)	Suspended sediment, percent smaller than 0.0625 millimeter (p70331)	Loss on ignition of suspended solids, in mg/L (p00535)	Particulate carbon [inorganic plus organic], in mg/L (p00694)	Particulate organic carbon, in mg/L (p00689)	Particulate inorganic carbon, in mg/L (p00688)	Particulate nitrogen, in mg/L as N (p49570)	Total phosphorus, in mg/L as P (p00655)	Total dissolved nitrogen, in mg/L as N (p62854)	Total nitrogen (particulate nitrogen plus dissolved nitrogen), in mg/L as N (p00600)
State Route 2A in Boston, Massachusetts											
Count	54	54	54	54	53	51	51	53	53	52	52
Minimum	253	3	0	16.0	6.78	6.78	<0.03	0.179	0.200	0.18	0.360
10th	589	6	1	31.3	11.3	10.2	<0.03	0.298	0.292	0.31	0.678
25th	996	10	2	47.5	18.0	17.6	<0.03	0.449	0.480	0.41	1.08
Median	2,010	14	4	83.0	38.5	38.1	0.63	0.772	0.690	0.64	1.45
Mean	6,800	19	8	148	71.0	66.0	6.24	2.00	1.10	0.83	2.84
75th	5,020	23	9	141	69.6	69.5	1.28	1.64	1.10	0.95	2.45
90th	13,100	38	20	295	108	102	3.27	2.76	2.24	1.54	3.99
Maximun	142,000	68	45	1,740	1,360	1,100	255	26.7	7.02	3.37	29
Interstate 90 near Weston, Massachusetts											
Count	54	54	54	54	46	44	44	46	46	46	46
Minimum	78	7	1	19.0	7.31	7.11	<0.03	0.204	0.110	0.220	0.520
10th	589	12	2	43.4	13.9	13.0	0.20	0.420	0.270	0.345	0.925
25th	1,020	17	4	67.3	27.5	26.4	0.26	0.743	0.373	0.47	1.33
Median	2,020	26	8	94.5	38.4	35.4	0.77	1.11	0.505	0.74	1.8
Mean	5,250	28	9	187	60.6	57.4	3.68	1.72	0.660	1.06	2.78
75th	4,970	38	13	191	67.1	61.1	3.25	2.27	0.670	1.22	2.98
90th	11,400	45	18	476	119	116	8.86	3.49	1.09	1.45	5.25
Maximun	38,700	58	34	1,060	392	377	51.6	13.5	3.16	5.63	17
State Route 20 near Quinsigamond Village, Massachusetts											
Count	55	55	55	55	51	48	48	51	51	51	51
Minimum	44	6	1	15.0	6.68	6.57	<0.03	0.212	0.090	0.28	0.580
10th	132	8	2	29.8	12.6	11.6	0.03	0.448	0.200	0.51	1.200
25th	352	11	3	67.0	25.1	24.4	0.14	0.770	0.360	0.72	1.75
Median	1,490	21	7	139	54.4	51.5	0.57	1.89	0.590	0.90	2.8
Mean	6,390	31	18	218	88.2	80.6	8.81	2.81	0.974	1.20	4.01
75th	6,250	42	24	232	107	98.6	3.37	3.74	1.14	1.32	5.2
90th	22,900	75	59	622	213	199	12.1	6.21	1.78	1.92	7.9
Maximun	60,000	96	89	1,140	490	378	174	15.9	6.02	4.69	18

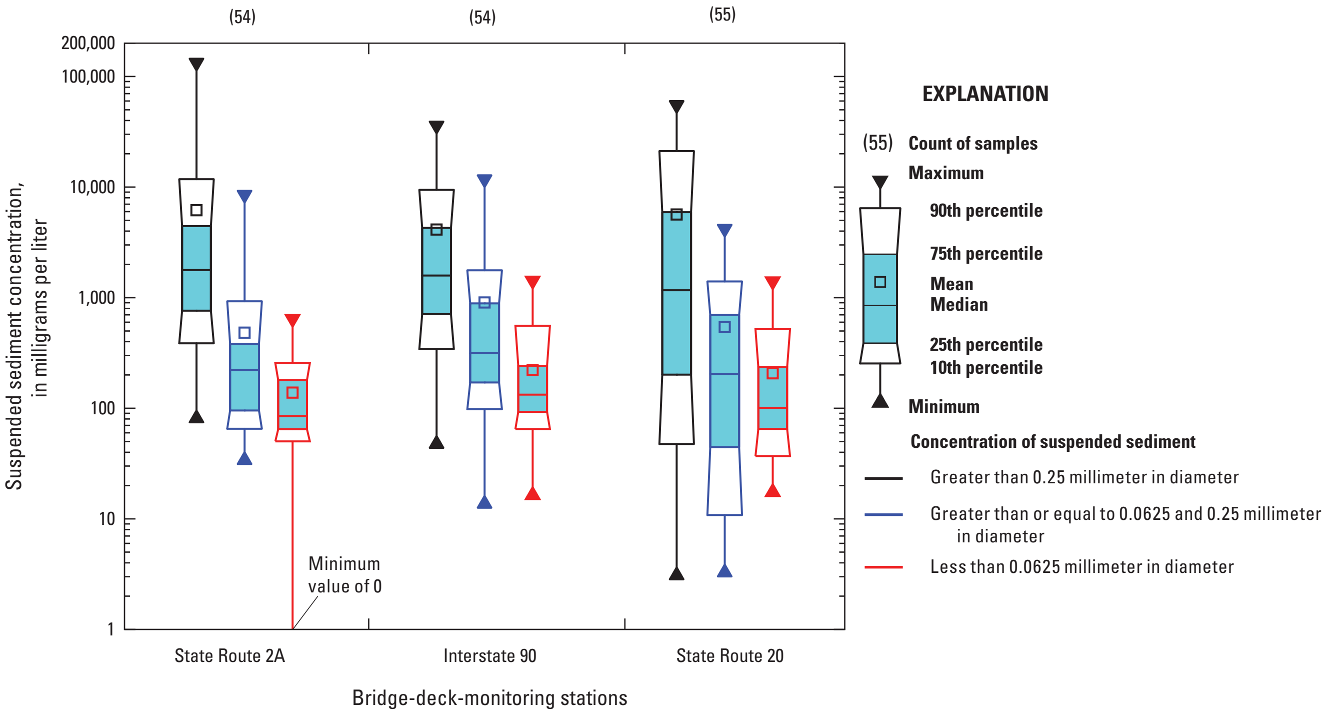


Figure 14. Distribution of three particle-size classes for suspended sediment in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

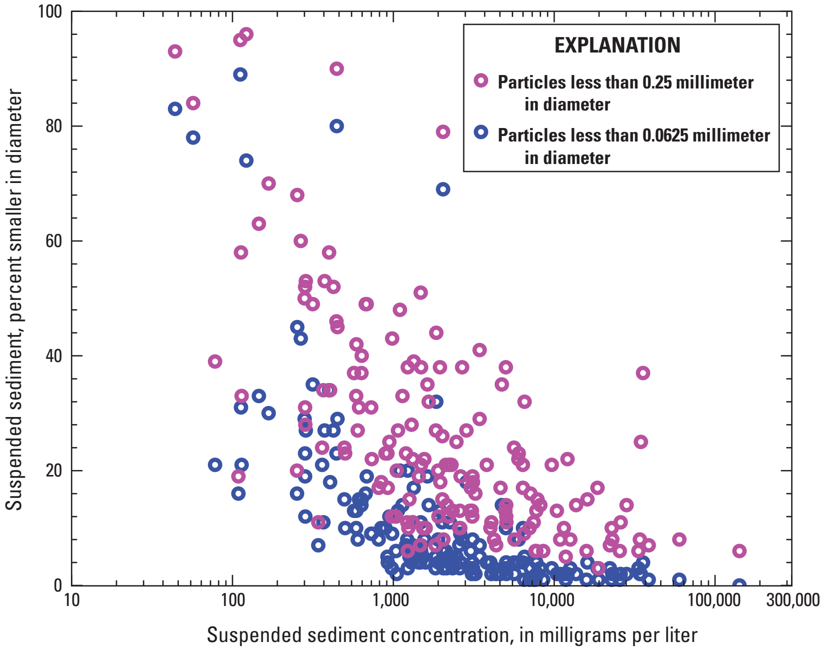


Figure 15. The relation between particles size less than 0.0625 millimeter in diameter and particles size less than 0.25 millimeter in diameter to concentrations of suspended sediment in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

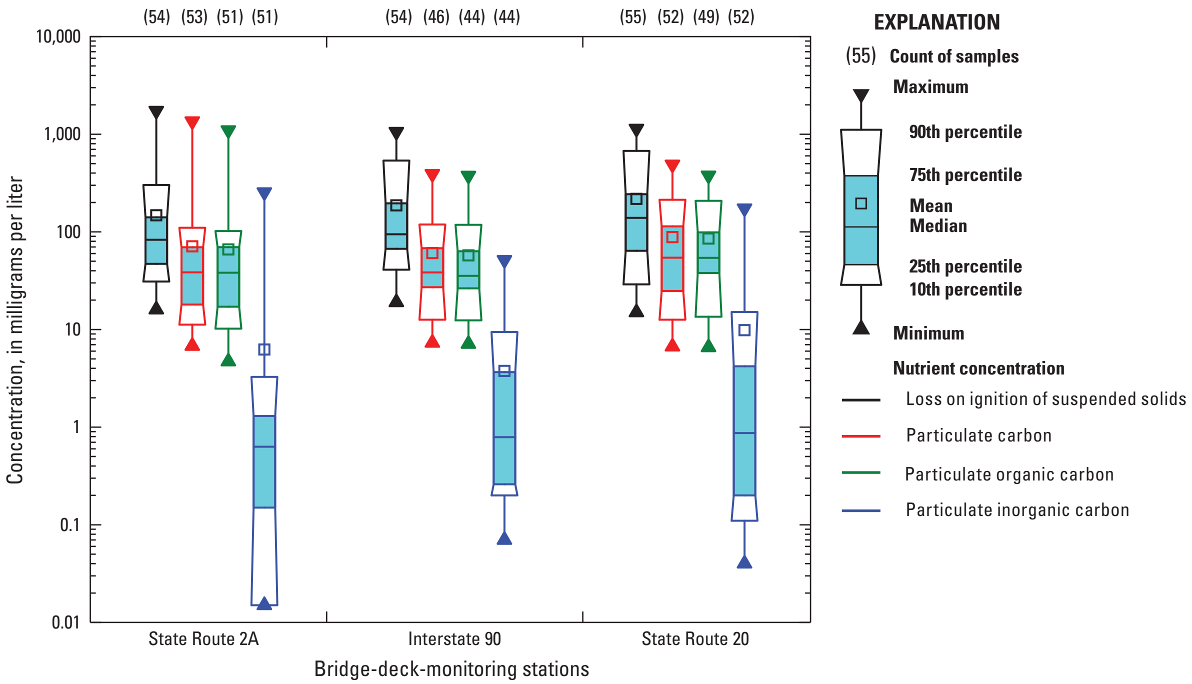


Figure 16. Distribution of concentrations of loss on ignition of suspended solids, particulate carbon, particulate organic carbon, and particulate inorganic carbon in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

Concentrations of LOI and PC in composite samples ranged from 15.0 to 1,740 mg/L and 6.68 to 1,360 mg/L, respectively (table 11). Median values representing the proportion of LOI and PC to SS were less than 10 and 3 percent in composite samples collected at the three bridge-deck-monitoring stations, respectively. Concentrations of PC were primarily organic in content (table 11; fig. 16). Less than about 12 percent of the total PC was inorganic in 90 percent of the samples collected at each bridge-deck-monitoring station.

Nutrients

Many studies have shown that stormwater runoff can be a source of nutrients (Davenport, 1990; Breault and Granato, 2000; Smith, 2002; Kayhanian and others, 2003; Smith and Granato, 2010). Phosphorus is somewhat insoluble and tends to be associated with sediment, including local soils and even maintenance sand used to increase traction on roads during winter storms (Smith and Granato, 2010). As previously noted in the “Site Selection” section, maintenance sand was not applied to any of the bridges in this study but may have been used on roadways in the vicinity of the monitoring stations and tracked onto the bridge decks. Natural organic material also is a source of TP and PN in stormwater runoff (Breault and others, 2005; Smith, 2005; Smith and Granato, 2010; Sorenson, 2013). Although each bridge is elevated and contains little or no adjacent vegetation, leaves and other natural organic matter were frequently observed in water samples. Concentrations of TP and TN in composite samples of bridge-deck runoff ranged from 0.09 to 7.02 mg/L and 0.36 to 29.0 mg/L, respectively (table 11). The distribution of TP concentrations was similar at each bridge-deck-monitoring station, whereas median concentrations ranged from 0.505 to 0.690 mg/L (fig. 17). Highest observed median concentrations of TP were in composite samples of bridge-deck runoff collected on State Route 2A in Boston (table 11). The distribution of PN and DN concentrations also was somewhat similar at each bridge; however, the concentrations of DN and PN were highest at the State Route 20 monitoring station. Approximately 40 percent of the TN concentration at each monitoring station consisted of DN. Annual precipitation-weighted mean concentrations of DN (inorganic forms of ammonia plus nitrate) during 2015 and 2016 were 0.625 and 0.859 mg/L in Boston, respectively (National Atmospheric Deposition Program, 2017a), and were 0.735 and 0.773 mg/L in central Massachusetts, respectively (National Atmospheric Deposition Program, 2017b), which are near the median DN concentrations in composite samples of bridge-deck runoff at each monitoring station (0.64 to

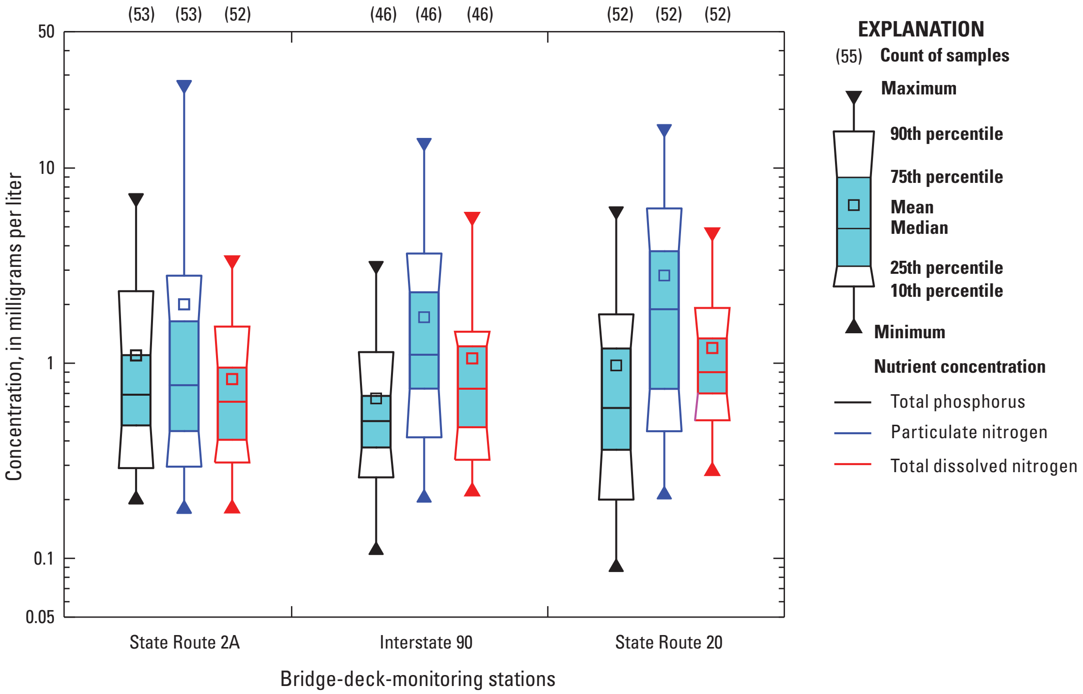


Figure 17. Distribution of concentrations of total phosphorus, particulate nitrogen, and total dissolved nitrogen in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

0.90 mg/L) (table 11). Traffic volume (table 1) and available land-use data (table 2) showed no consistent trend that might indicate why nitrogen concentrations in samples collected from the State Route 20 and Interstate 90 bridge locations seemed to differ from nitrogen concentrations in samples collected from the State Route 2A bridge location in Boston.

Correlation Between Constituents

Results for all Anderson-Darling tests were significant (*p*-value less than 0.05) (table 12) for sample sets at each bridge, indicating that concentration data for composite samples of bridge-deck runoff were not normally distributed. Right-skewed distributions for highway and urban runoff data are not unusual because concentration data are highly variable and often include high-concentration outliers (Driscoll and others, 1990; Smith, 2002; Smith and Granato, 2010). Because the bridge-deck runoff concentration data were not normally distributed, nonparametric statistical methods were used for analysis of all data.

Results for Spearman rho tests on the datasets indicated that the concentration data were positively correlated with each other (table 13). The relation between concentrations of SS and other particulate constituents (LOI, PC, POC, PIC, and PN) were significant and in many cases, the relations were moderately strong (Spearman rho coefficient greater than 0.7). Spearman rho test results indicated that the relations between concentrations of PN and LOI (coefficients ranging from 0.772 to 0.908) and PC (coefficients ranging from 0.906 to 0.942) were stronger than the relation between PN and SS (coefficients ranging from 0.595 to 0.640). Conversely, relations between concentrations of TP and LOI, PC, and SS were similar at each bridge, although the relations were consistently weaker at Interstate 90 (table 13). These data indicated that concentrations of organic constituents (LOI and PC) were better correlated with concentrations of TN compared to concentrations of SS, and these organic constituents seem to have relations of similar strength with TP compared to concentrations of SS, implying that natural organic materials are likely an important source for total nutrients.

Interbridge Comparison of Constituent Concentrations

Concentration data collected from each bridge were compared to the respective concentration data collected from each of the other bridges to determine if the datasets were significantly different. Results for the ANOVA and

Table 12. Results and attained significance levels for Anderson-Darling tests for concentrations of selected constituents in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. The alpha-numeric identifiers starting with "p" are the U.S. Geological Survey parameter codes. *p*-value, significance level; P, phosphorus; N, nitrogen; <, less than.]

Constituent	Anderson-Darling test results				
	Count	Average	Standard deviation	Anderson-Darling statistic	*p*-value
State Route 2A in Boston, Massachusetts					
Total phosphorus as P (p00655)	53	1.096	1.304	6.812	<0.005
Total nitrogen as N (p00600)	52	2.839	4.72	10.020	<0.005
Total dissolved nitrogen as N (p62854)	52	0.829	0.643	3.694	<0.005
Particulate nitrogen as N (p49570)	53	2.003	4.418	11.782	<0.005
Suspended sediment (p80154)	54	6,795	19,486	12.299	<0.005
Particulate carbon (p00694)	53	71.03	184.6	12.616	<0.005
Loss on ignition of suspended solids (p00535)	54	147.4	246.1	8.312	<0.005
Interstate 90 near Weston, Massachusetts					
Total phosphorus as P (p00655)	46	0.660	0.571	4.622	<0.005
Total nitrogen as N (p00600)	46	2.785	2.848	4.990	<0.005
Total dissolved nitrogen as N (p62854)	46	1.059	1.088	5.561	<0.005
Particulate nitrogen as N (p49570)	46	1.72	2.097	4.919	<0.005
Suspended sediment (p80154)	54	5,251	8,700	8.777	<0.005
Particulate carbon (p00694)	46	60.62	68.16	4.956	<0.005
Loss on ignition of suspended solids (p00535)	54	186.6	214	6.247	<0.005
State Route 20 near Quinsigamond Village, Massachusetts					
Total phosphorus as P (p00655)	51	0.974	1.179	5.809	<0.005
Total nitrogen as N (p00600)	51	4.013	3.395	2.734	<0.005
Total dissolved nitrogen as N (p62854)	51	1.197	0.937	4.719	<0.005
Particulate nitrogen as N (p49570)	51	2.815	3.048	3.873	<0.005
Suspended sediment (p80154)	55	6,393	11,368	8.062	<0.005
Particulate carbon (p00694)	51	88.24	95.84	3.973	<0.005
Loss on ignition of suspended solids (p00535)	55	217.6	237	4.723	<0.005

accompanying Tukey pairwise comparison tests performed on the rank-transformed data are reported in table 14. Results for the ANOVA test indicate if the differences among the datasets are significant. The subsequent Tukey pairwise comparison tests are necessary to determine which datasets differ from one another; datasets that share the same letter are not significantly different (*p*-value 0.05).

Results of the ANOVA tests indicated that concentrations of SS, LOI, PC, and TP in datasets for each bridge pair were not significantly different (table 14). Test results for the fine sediment-size fraction (less than 0.0625 mm in diameter), intermediate sediment-size fraction (greater than or equal to 0.0625 to 0.25 mm in diameter), TN, PN, and DN were significant, indicating that the dataset from at least one bridge may be different compared to the datasets from the other bridges. Results for the post hoc Tukey pairwise comparison test, however, did not indicate that there was a significant difference between the fine sediment-size fraction in composite samples collected at the three bridges. Test results for the Tukey pairwise comparison test did indicate that datasets for the intermediate sediment-size fraction, TN, PN, and DN were significantly different at one or more bridges. Grouping information indicated that the mean of the rank-transformed data for the intermediate sediment-size fraction collected on Interstate 90 was significantly higher than the means of the rank-transformed data for the other bridges (table 14). The higher

Table 13. Results and attained significance levels for Spearman rho tests for concentrations of selected constituents in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village(421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. Shaded areas indicate values that are significant at a 95-percent confidence interval. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. P, phosphorus; N, nitrogen; *p*-value, significance level; <, less than]

Constituent	Statistic	Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate organic carbon (p00689)	Particulate inorganic carbon (p00688)	Total dissolved nitrogen (p62854)	Particulate nitrogen (p49570)	Total phosphorus as P (p00655)	Total nitrogen as N (p00600)
State Route 2A in Boston, Massachusetts									
Particulate carbon [inorganic plus organic] (p00694)	Spearman rho	0.897							
	p-value	<0.001							
Particulate organic carbon (p00689)	Spearman rho	0.884	0.998						
	p-value	<0.001	<0.001						
Particulate inorganic carbon (p00688)	Spearman rho	0.676	0.511	0.483					
	p-value	<0.001	<0.001	0.001					
Total dissolved nitrogen as N (p62854)	Spearman rho	0.298	0.283	0.375	0.252				
	p-value	0.032	0.042	0.01	0.098				
Particulate nitrogen as N (p49570)	Spearman rho	0.908	0.942	0.938	0.546	0.398			
	p-value	<0.001	<0.001	<0.001	<0.001	0.003			
Total phosphorus as P (p00655)	Spearman rho	0.780	0.665	0.602	0.563	0.119	0.682		
	p-value	<0.001	<0.001	<0.001	<0.001	0.400	<0.001		
Total nitrogen as N (p00600)	Spearman rho	0.739	0.748	0.800	0.522	0.737	0.859	0.502	
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Suspended sediment (p80154)	Spearman rho	0.769	0.658	0.627	0.735	0.045	0.640	0.799	0.417
	p-value	<0.001	<0.001	<0.001	<0.001	0.752	<0.001	<0.001	0.002
Interstate 90 near Weston, Massachusetts									
Particulate carbon [inorganic plus organic] (p00694)	Spearman rho	0.845							
	p-value	<0.001							
Particulate organic carbon (p00689)	Spearman rho	0.852	0.995						
	p-value	<0.001	<0.001						
Particulate inorganic carbon (p00688)	Spearman rho	0.680	0.660	0.614					
	p-value	<0.001	<0.001	<0.001					
Total dissolved nitrogen as N (p62854)	Spearman rho	0.434	0.427	0.404	0.203				
	p-value	0.003	0.003	0.007	0.192				
Particulate nitrogen as N (p49570)	Spearman rho	0.772	0.906	0.905	0.618	0.507			
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001			
Total phosphorus as P (p00655)	Spearman rho	0.579	0.497	0.485	0.423	0.251	0.543		
	p-value	<0.001	<0.001	0.001	0.005	0.093	<0.001		
Total nitrogen as N (p00600)	Spearman rho	0.750	0.818	0.808	0.529	0.748	0.927	0.512	
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	
Suspended sediment (p80154)	Spearman rho	0.840	0.739	0.733	0.739	0.250	0.595	0.413	0.557
	p-value	<0.001	<0.001	<0.001	<0.001	0.094	<0.001	0.004	0.001

Table 13. Results and attained significance levels for Spearman rho tests for concentrations of selected constituents in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village(421247071470201) in eastern Massachusetts, 2014–16.—Continued

[Locations of stations are shown in figure 1. Shaded areas indicate values that are significant at a 95-percent confidence interval. The alpha-numeric identifiers starting with "p" are the U.S. Geological Survey parameter codes. P, phosphorus; N, nitrogen; *p*-value, significance level; <, less than]

Constituent	Statistic	Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate organic carbon (p00689)	Particulate inorganic carbon (p00688)	Total dissolved nitrogen (p62854)	Particulate nitrogen (p49570)	Total phosphorus as P (p00655)	Total nitrogen as N (p00600)
State Route 20 near Quinsigamond Village, Massachusetts									
Particulate carbon [inorganic plus organic] (p00694)	Spearman rho	0.874							
	p-value	<0.001							
Particulate organic carbon (p00689)	Spearman rho	0.830	0.993						
	p-value	<0.001	<0.001						
Particulate inorganic carbon (p00688)	Spearman rho	0.677	0.659	0.624					
	p-value	<0.001	<0.001	<0.001					
Total dissolved nitrogen as N (p62854)	Spearman rho	0.343	0.450	0.524	0.152				
	p-value	0.015	0.001	<0.001	0.330				
Particulate nitrogen as N (p49570)	Spearman rho	0.834	0.937	0.931	0.558	0.548			
	p-value	<0.001	<0.001	<0.001	<0.001	<0.001			
Total phosphorus as P (p00655)	Spearman rho	0.762	0.733	0.678	0.725	0.214	0.658		
	p-value	<0.001	<0.001	<0.001	<0.001	0.131	<0.001		
Total nitrogen as N (p00600)	Spearman rho	0.729	0.843	0.888	0.497	0.750	0.925	0.572	
	p-value	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	
Suspended sediment (p80154)	Spearman rho	0.783	0.735	0.661	0.827	0.082	0.621	0.831	0.484
	p-value	<0.001	<0.001	<0.001	<0.001	0.572	<0.001	<0.001	<0.001

proportion of sediment in this size fraction on the Interstate 90 may be related to the effect of concrete particles transported in runoff from the degradation of the bridge surface and median barriers that were not present at the other bridges (fig. 18). The mean of the rank-transformed data for TN collected on State Route 20 was significantly higher than the means of the rank-transformed data for the other bridges. Median concentrations of TN were about 93 and 55 percent lower at State Route 2A in Boston and at Interstate 90 near Weston, respectively, compared to the median concentrations of TN at State Route 20 near Quinsigamond Village (table 11). The means of the rank-transformed data for DN and PN for bridge pairs State Route 2A and Interstate 90, and Interstate 90 and State Route 20 were not statistically different; however, test results for the bridge pair State Route 2A and State Route 20 were significant and indicated that the fractional portions of TN were significantly higher at the State Route 20 bridge compared to State Route 2A.

Spatial Distribution of Bridge-Deck Sediment

Differences in wind current across the bridge, the slope of the bridge, sediment source, and depositional decay of vehicle tracking all can affect the distribution of sediment and associated constituents across each bridge. Samples of sediment were collected from the deck surface of each bridge to determine if sediment transported to the instrumented scupper inlets were representative of sediment mass across the entire bridge-deck surface. Samples of bridge-deck sediment were collected at five evenly distributed locations the entire length of each bridge deck three times between April 2015 and September 2016. These data represent a semiquantitative assessment of the distribution of bridge surface sediment on each bridge at the time of sampling.

Yields of bridge-deck sediment for each of the five sampling locations (table 6) ranged from 26 to 25,000 pounds per curb-mile (lbs/curb-mi). Yields were greatest in April 2015 at the bridge on State Route 2A and State Route 20. The bridge

Table 14. Attained F statistics, significance levels, predicted R-squared value, and relevant statistics from one-way analysis of variance tests and Tukey pairwise comparisons performed on the ranks of selected concentration and physical parameter values in composite samples of bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. Shaded areas indicate values that are significant at a 95-percent confidence interval. Constituents or parameters that do not share a letter (A, B) are significantly different for Tukey pairwise comparisons. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. Suspended sediment percentage representing particle size class greater than or equal to 0.0625 to 0.25 millimeter (mm) in diameter is the difference between U.S. Geological Survey parameter codes p70333 and p70331. ANOVA, one-way analysis of variance; mg/L, milligram per liter; <, less than; ≤, less than or equal to; >, greater than value shown; P, phosphorus; N, nitrogen; --, test not performed]

Constituent or physical parameter	ANOVA test results for rank-transfomed data								Tukey pairwise comparisons—grouping information from Tukey method at 95-percent confidence level
	F statistic	Attained significance level	Predicted R^2 of ANOVA test on ranks (percent)	Bridge	Sample count	Average	Standard deviation	95-percent confidence interval	
Suspended sediment (mg/L) (p80154)	0.98	0.379	0.00	State Route 2A	54	86.19	42.3	73.50 to 98.87	--
				Interstate 90	54	85.17	42.57	72.48 to 97.85	--
				State Route 20	55	74.78	55.39	62.21 to 87.35	--
Suspended sediment <0.0625 mm in diameter (percent) (p70331)	3.34	0.038	0.38	State Route 2A	54	68.71	46.02	56.24 to 81.18	A
				Interstate 90	54	87.59	39.41	75.12 to 100.06	A
				State Route 20	55	89.55	52.68	77.20 to 101.91	A
Suspended sediment 0.0625≤0.25 mm in diameter (percent)	13.2	<0.001	10.92	State Route 2A	54	65	42.27	53.19 to 76.81	B
				Interstate 90	54	106.5	42.14	94.69 to 118.31	A
				State Route 20	55	74.64	47.2	62.93 to 86.34	B
Loss on ignition of suspended solids (p00535)	2.85	0.061	0	State Route 2A	54	70.12	45.53	57.58 to 82.66	--
				Interstate 90	54	84.82	43.86	72.28 to 97.37	--
				State Route 20	55	90.89	50.3	78.46 to 103.32	--
Particulate carbon [inorganic plus organic] (p00694)	2.2	0.115	2.96	State Route 2A	53	65.89	41.92	54.42 to 77.35	--
				Interstate 90	46	73.43	38.58	61.13 to 85.74	--
				State Route 20	48	83.5	45.78	71.45 to 95.55	--
Total phosphorus as P (p00655)	3.42	0.078	3.42	State Route 2A	53	84.03	42.5	72.36 to 95.70	--
				Interstate 90	46	64.38	38.24	51.86 to 76.90	--
				State Route 20	51	76.67	47.29	64.77 to 88.56	--
Total nitrogen as N (p00600)	8.22	<0.001	6.39	State Route 2A	52	59.98	42.36	48.70 to 71.27	B
				Interstate 90	46	72.45	39.81	60.45 to 84.44	B
				State Route 20	51	92.62	41.15	81.22 to 104.01	A
Particulate nitrogen as N (p49570)	5.21	0.007	4.94	State Route 2A	52	62.57	44.6	51.06 to 74.07	B
				Interstate 90	46	73.37	43.98	61.14 to 85.60	A, B
				State Route 20	51	89.15	37.08	77.53 to 100.76	A
Total dissolved nitrogen as N (p62854)	6.99	<0.001	2.78	State Route 2A	53	60.79	42.83	49.45 to 72.14	B
				Interstate 90	46	74.78	39.09	62.60 to 86.96	A, B
				State Route 20	51	91.43	43.05	79.87 to 103.00	A

Figure 18. Sediment sources from deterioration of the *A*, bridge-deck surface; *B*, median barrier; and *C*, shoulder area that contributed to the sediment yield on the Interstate 90 bridge near Weston, Massachusetts, 2015–16. Location of bridge is shown on figure 1.

on Interstate 90 was not sampled at this time, but the greatest yields were measured in December 2015. High fluctuations in the sediment mass and yields on the bridge decks were similar to those seen on other types of streets and highway surfaces in the region (Smith, 2002; Breault and others, 2005; Smith and Granato, 2010; Sorenson, 2013).

The mean yields of bridge-deck sediment were 1,500, 250, and 5,700 lbs/curb-mi for State Route 2A, Interstate 90, and State Route 20, respectively (table 6). The mean yields were only calculated from three events and were heavily affected by the April and December values. Nevertheless, the yields of bridge-deck sediment in this study were similar to those reported in other studies. Mean yields of material on streets in Cambridge, Mass., ranged from 522 to 740 lbs/curb-mi, and end-of-winter yields ranged from 2,609 to 4,788 lbs/curb-mi (Sorenson, 2013). Selbig and Bannerman (2007) reported residential street-dirt yields of 614 and 569 lbs/curb-mi; Law and others (2008) reported mean street-solid yields of 645 lbs/curb-mi within an area routinely swept and 1,100 lbs/curb-mi for a control area within their study; and the Seattle Public Utilities and Herrera Environmental Consultants (2009) reported median yields of street solids that ranged from 69 to 2,200 lbs/curb-mi on streets swept twice per month. Yields of bridge-deck sediment (table 6) at each sampling location were normalized to the yield of bridge-deck sediment measured proximate to the monitoring station at each bridge (fig. 19) for greater comparison of the sediment distribution across each bridge.

The State Route 2A bridge is the only convex bridge in this study where the center of the bridge is higher in elevation than either side of approach. Although the bridge-deck yields were often variable, normalized bridge-deck sediment yields indicated that the sediment mass often was lower at the fixed sampling location proximate to the monitoring station compared to the other fixed sampling locations (fig. 19*A*). The mean yield of bridge-deck sediment measured proximate to the monitoring station (680 lbs/curb-mi) on the eastern end (Boston) of the bridge (fig. 1) was 55 percent lower than the mean yield of bridge-deck sediment represented by the sampling locations (1,500 lbs/curb-mi) (table 6). The lower

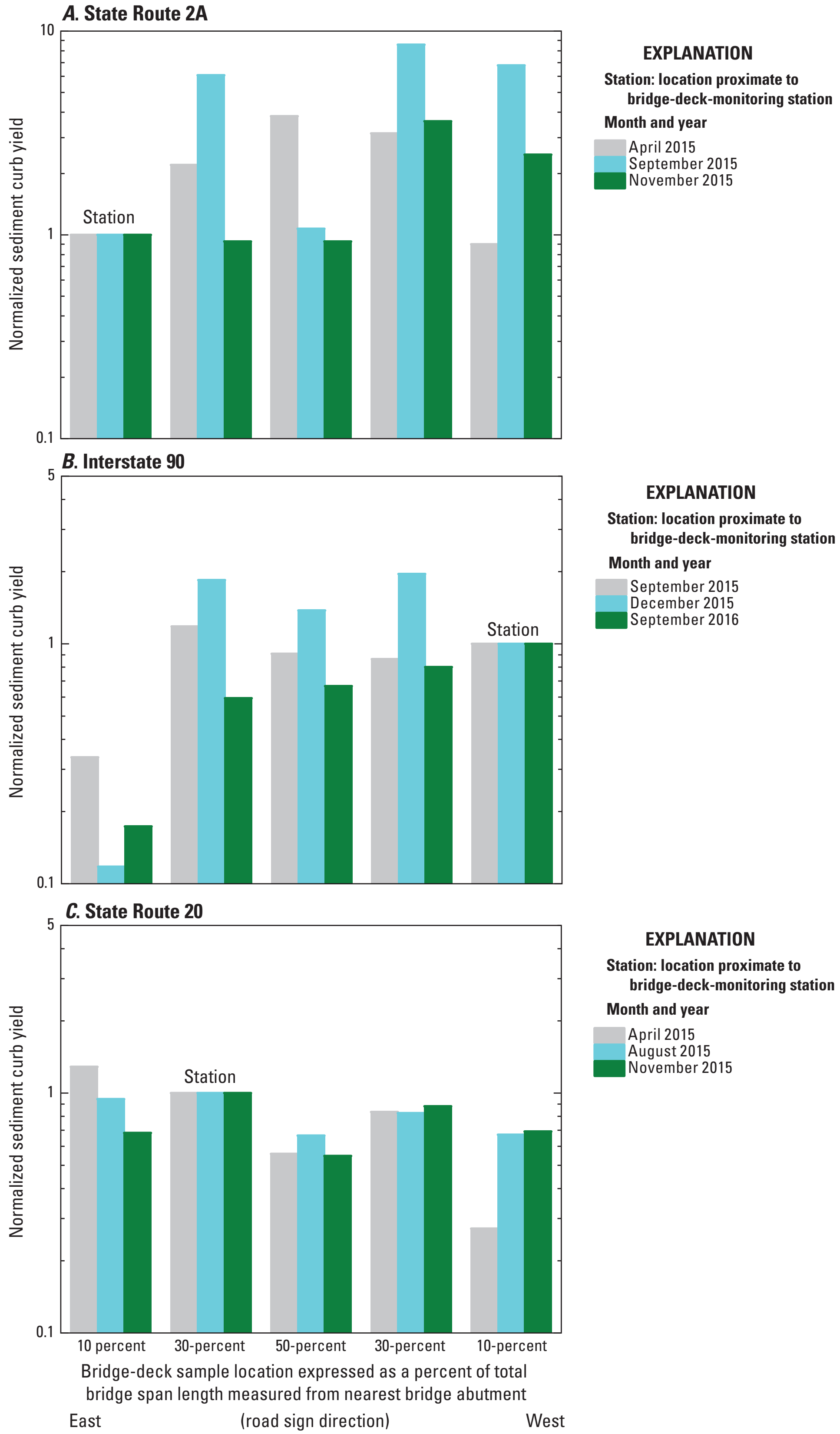


Figure 19. Normalized bridge-deck sediment yields at five fixed locations on three bridges monitored by the U.S. Geological Survey on *A*, State Route 2A in Boston (422108071052501); *B*, Interstate 90 near Weston (422025071154501); and *C*, State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2015–16. Locations of stations are shown on figure 1.

bridge-deck sediment yields measured near the monitoring station might be related to depositional decay of vehicle tracking because the traffic flow at the fixed sampling locations is from west to east (city of Cambridge to the city of Boston).

Normalized bridge-deck sediment yields for Interstate 90 were similar for much of the bridge, except for the easternmost location, which was lower in comparison to the four other sampling locations (fig. 19*B*).The mean yield of bridge-deck sediment measured proximate to the monitoring station on Interstate 90 (240 lbs/curb-mi), located on the most western section of the bridge (fig. 1), was similar to the mean yield of bridge-deck sediment represented by the sampling locations (250 lbs/curb-mi). The distribution of the sediment mass across this bridge was largely related to the contribution of solids from the deterioration of the bridge-deck surface, median barrier, and shoulder area (fig. 18). The elevation of the Interstate 90 bridge decreased from east to west causing the mass of bridge sediments to migrate westward with traffic and runoff and resulting in higher deposits in the western sampling locations. Scupper inlets were often blocked (fig. 18*C*) on the bridge, which can contribute to the migration of sediments westward.

Normalized bridge-deck sediment yields for State Route 20 near Quinsigamond Village seemed to indicate that the sediment mass decreased from east to west, especially for the April and August 2015 sampling events (fig. 19*C*). The monitoring station was about one-third of the way across the bridge from the eastern side (fig. 1). The mean yield of bridge-deck sediment proximate to the monitoring station on State Route 20 (7,200 lbs/curb-mi) was about 26 percent higher than the mean yield of bridge-deck sediment representing the sampling locations (5,700 lbs/curb-mi) (table 6). This bridge was constructed in 2005 (Massachusetts Department of Transportation, 2017b) and showed no signs of deterioration that might contribute to the sediment mass on the bridge deck. The roadway approach and the bridge both decreased in elevation from east to west. The distribution of the sediment mass across this bridge likely was the result of wash-on from the roadway upgradient of the bridge (fig. 20). Unlike the Interstate 90 bridge, the materials from the State Route 20 bridge did not seem to substantially contribute to the sediment mass, but sediment yields did diminish westward as the sediment was captured in the scuppers. Similar to Interstate 90, the scupper inlets often were blocked on State Route 20, which caused the sediment mass to propagate farther onto the bridge than it might otherwise if the scupper inlets were always open.

The results from this study and from studies in other areas of the United States discussed previously in this section indicate that street-surface sediment masses and yields can vary widely. The distribution of sediment measured three times at each bridge during this study does not represent a quantitative assessment; however, plausible explanations are described above for the likely causes of the general distribution of the sediment yields measured and observed during this study on each bridge.

Figure 20. Sediment buildup propagating westward onto the State Route 20 bridge from the upgradient roadway, near Quinsigamond Village, Massachusetts, 2016. Location of bridge is shown on figure 1.

Chemical Analysis of Sediment

Many trace metals are associated with roadway sediments (Gupta and others, 1981; Smith, 2002; Breault and others, 2005; Smith and Granato, 2010; Sorenson, 2013). An analysis of the particulate fraction of SS in samples of bridge-deck runoff indicated that PC represents about 3 percent of the SS and about 60 percent of TN is associated with the sediment fraction (U.S. Geological Survey, 2016). Natural plant matter, which is directly associated with the PC, also is a source of TP and TN and may contain a greater amount of these nutrients per unit mass compared to mineral sediment alone (Smith and Granato, 2010).

Results of laboratory analysis of sieved sediment samples indicated that bridge-deck sediment contained high concentrations of TP and various metals and that in many cases, the two fractions of sediment less than 0.25 mm in diameter were more enriched compared to the coarse sediment fraction (table 15). Concentrations of TP in the fine sediment fraction (less than 0.0625 mm in diameter) were about 6 times greater than in the coarse sediment fraction (greater than or equal to 0.25 mm in diameter), but concentrations of TP in the intermediate sediment fraction (greater than or equal to 0.0625 to less than 0.25 mm in diameter) were similar to concentrations in the coarse sediment fraction. Total-recoverable Cu was not detected at the reporting limit concentration, 7.5 milligrams

Table 15. Mean proportion of suspended sediment in three particle-size classes in composite samples of bridge-deck and highway runoff and dry weight total-recoverable concentrations by sediment-size class for selected elements in three composite samples of bridge-deck sediments collected from bridges on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2016, and from highways in eastern Massachusetts, 2005–7.

[Locations of stations are shown in figure 1. The alpha-numeric identifiers starting with "p" are the U.S. Geological Survey parameter codes. <, less than; ≤, less than or equal to; ≥, greater than or equal to]

U.S. Geological Survey station number	Highway	Sediment particle-size class (millimeter in diameter)	Mean proportion of suspended sediment in composite samples of runoff (percent)	Constituents measured in composite samples of sediment collected from bridges or highways, in milligrams per kilogram										
				Phosphorus (p65196)	Aluminum (p65196)	Arsenic (p67876)	Barium (p67877)	Cadmium (p67880)	Chromium (p67882)	Copper (p67884)	Lead (p64181)	Manganese (p67888)	Nickel (p67890)	Zinc (p64180)
421247071470201		<0.0625	18	280	17,000	17	350	1.5	97	140	110	510	54	770
421247071470201	State Route 20	0.0625≤0.25	13	35	5,500	5.6	63	0.4	120	10	31	340	41	240
421247071470201		≥0.25	69	44	7,400	2.0	37	0.1	22	<4.5	8.8	220	23	73
422025071154501		<0.0625	9	180	18,000	32	540	1.4	140	240	230	530	53	1,200
422025071154501	Interstate 90	0.0625≤0.25	18	35	6,200	6.8	100	0.4	56	5.0	120	290	34	300
422025071154501		≥0.25	73	27	8,500	1.7	50	0.2	21	<4.1	3.5	480	19	67
422108071052501		<0.0625	8	280	22,000	32	190	1.5	120	140	100	560	57	1,100
422108071052501	State Route 2A	0.0625≤0.25	11	48	5,800	5.3	47	0.4	59	7.0	30	330	31	240
422108071052501		≥0.25	81	51	8,900	3.1	58	0.3	25	<7.5	11	510	21	350
			Mean values											
Bridges in this study		<0.0625	12	250	19,000	27	360	1.5	120	170	150	530	55	1,000
		0.0625≤0.25	14	39	5,800	5.9	70	0.37	78	7	60	320	35	260
		≥0.25	74	41	8,300	2.3	48	0.20	23	<7.5	7.8	400	21	160
Highways in eastern Massachusetts (Smith and Granato, 2010) Average		<0.0625	60	1,100	23,000	23	270	1.3	380	250	160	760	56	1,500
		0.0625≤0.25	23	470	9,900	9.7	110	<1.0	130	160	103	300	30	270
		≥0.25	17	270	6,000	7.3	58	<1.0	510	46	24	290	27	102

per kilogram or less, in the coarse sediment fraction of samples of bridge-deck sediment collected from any of the bridges. Concentrations of Cu in the fine sediment fraction were 13 to 47 times more concentrated than concentrations in the intermediate sediment fraction. Total-recoverable concentrations of aluminum (Al), manganese (Mn), and nickel (Ni) were only slightly higher in the fine sediment fraction (less than 2 times higher) than concentrations in the coarse sediment fraction, which were similar or slightly higher than concentrations in the intermediate sediment fraction. Total-recoverable concentrations for arsenic (As), barium (Ba), cadmium (Cd), Cr, and zinc (Zn) were about 2 to 17 times greater in the fine sediment fraction than concentrations in the coarse sediment fraction. Total-recoverable concentrations of As, Ba, Cd, Cr, and Zn were generally higher (about 1 to 4 times) in the intermediate sediment fraction than in the coarse sediment fraction. Similar to total-recoverable concentrations of Cu, concentrations of lead (Pb) also were highly associated with the finer sediment fractions where the concentration of Pb in the fine sediment fraction and the intermediate sediment fraction were about 8 to 65 times greater and about 2 to 33 times greater than the concentration in the coarse sediment fraction, respectively.

These data demonstrate that the proportion of sediment in each particle-size class and sediment chemistry associated with each of these particle-size classes can have a substantial effect on the overall concentration of the various constituents, including TP, in aggregate samples of bridge-deck sediment and in composite samples of bridge-deck runoff containing SS. The overall concentration for a given sample can be estimated from the sum of the product of each sediment particle-size class and associated chemistry (eq. 2). On the basis of the mean proportion of SS in each particle-size class for all three bridges and the mean chemical concentration of each particle-size fraction for the three bridges (table 15), about 54 percent of the estimated sediment-associated TP was associated with the two larger sediment fractions (fig. 21). The cumulative proportion of the concentration of 6 of 10 metals (As, Ba, Cd, Cu, Pb, and Zn) in the intermediate and coarse sediment fractions was less than 56 percent. About 66 to 84 percent of the concentration of the other 4 of 10 metals (Al, Cr, Mn, and Ni) was associated with the intermediate and coarse sediment fractions. Only about 5 percent of the Cu concentration was associated with the intermediate and coarse sediment fraction.

$$C = \sum_{i=1}^{n} \left(c_i * p_i \right) \tag{2}$$

where

C is the concentration of the selected constituent, in milligrams per kilogram;
n is the total number of particle-size classes (three in the present study);
i is an index to each particle-size class;
c is the mean concentration of the selected constituent associated with the particle-size class, in milligrams per kilogram; and
p is the mean proportion of sediment in each particle-size class.

Although the fine sediment fraction generally contains higher concentrations of TP and metals, the proportion of the fine sediment in composite samples of runoff was relatively small in comparison to the two larger sediment fractions (fig. 14). As a result, more than 50 percent of the estimated sediment-associated TP and various metals (8 of the 10) may be directly related to the larger mass of the intermediate and coarse sediment fractions (fig. 21) and can potentially be remediated by nonstructural BMPs (such as street sweeping) and by various structural BMPs that operate through settling (Waschbusch, 1999; Smith, 2002). Removal of the finer sediment fraction, though often more difficult, also may be achieved with other structural BMPs (Shoemaker and others, 2000) and high-efficiency street sweepers (Breault and others, 2005; Sorenson, 2013). Unlike structural BMPs that operate during each event, assuming proper maintenance, street sweeping is only a periodic method for removing sediment from the roadway. The State Route 2A bridge in Boston was reported to be swept weekly (weather permitting); however, concentrations of SS were not significantly different compared to the other two bridges that were swept infrequently. This is not an indication that the sweeping practice on the State Route 2A bridge is ineffective, but perhaps the bridge-deck sediment buildup or recovery occurs quickly. Breault and others (2005) estimated a street-sediment accumulation rate of about 50 pounds per curb-mile per day and indicated that the coarser size fractions between 0.25 and 2.0 mm seemed to accumulate most rapidly in New Bedford, Mass., which is similar to the measured conditions at this bridge.

Comparisons of Highway and Bridge-Deck Constituent Concentrations

The USGS, in cooperation with Federal Highway Administration and the MassDOT, conducted a field study during 2005–7 to characterize the quality of highway runoff for a wide range of constituents throughout Massachusetts (Smith and Granato, 2010). These data included concentrations of SS, TP, and TN collected from catch-basin outlets on highway segments with 100-percent impervious drainage areas. Sample concentrations from highway-monitoring stations on State Route 2 (USGS stations 423027071291301, 423027071291302), Interstate 190 (USGS station 423016071431501), Interstate 495 (USGS stations 422821071332001, 422716071343901), Interstate 95 (USGS stations 422420071153302, 422620071153301), and Interstate 93 (USGS station 421647071024703) (fig. 1), which are in eastern Massachusetts and have similar AADT volumes, were compared to constituent concentrations collected in

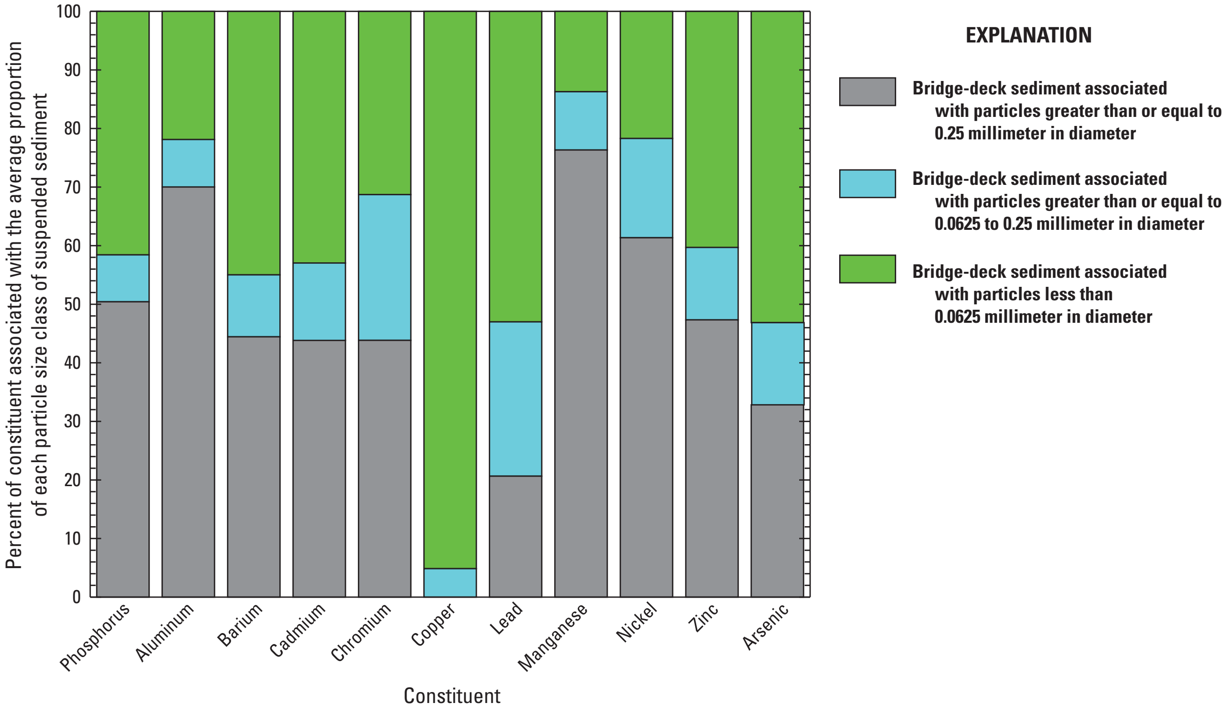


Figure 21. Showing the percentage of the concentration estimated for selected constituents associated with the mean particle size of suspended sediment collected from three bridges monitored by the U.S. Geological Survey on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

the present study. Concentrations of total-recoverable metals in samples of sediment collected from highways in Massachusetts and the bridges in this study also were compared to determine if the 2005–7 total-recoverable metals data are transferable and can be used to expand the number of constituents measured in bridge-deck runoff in Massachusetts.

Suspended Sediment

Concentrations of SS in samples of bridge-deck runoff were significantly higher (Mann-Whitney test results *p*-values <0.001) than those collected from the selected highway-monitoring stations in eastern Massachusetts (table 16). Much of this difference was likely the result of the collection of runoff downstream from catch basins on highways where some portion of the SS was reduced in the runoff, particularly coarse sediments (Smith, 2002), whereas the bridge scuppers provided no SS reduction within the stormwater flow train. Other factors such as high bridge walls adjacent to the roadway (figs. 9*A* and 20) and median barriers (fig. 18*B*) may more effectively trap sediment on the bridges compared to highways with low curbing; deterioration of bridge components (fig. 18) and bridge wash-on (fig. 20) also may have contributed to higher concentrations of SS in samples of bridge-deck runoff. The proportion of fine and coarse particle-size fractions also was significantly different (*p*-values <0.001) in samples collected from the bridge-deck-monitoring stations compared to the highway-monitoring stations (table 16; fig. 22); however, the proportion of the intermediate sediment-size fraction in bridge-deck runoff was not statistically different than in highway-runoff composite samples. Although the percentage of the fine particle-size fraction of SS in composite samples of bridge-deck runoff (median of 6 percent) was statistically different than in composite samples of highway runoff (median of 60 percent), the range in the concentrations of the fine fraction of SS was not substantially higher than that in the highway dataset compared to the range in concentrations for the two larger sediment-size fractions where the median values were separated by an order of magnitude or more (fig. 22).

Concentrations of SS varied widely in the highway-runoff dataset, but sample sets generally were statistically similar from highway to highway (Smith and Granato, 2010). Data collected from the bridges in this study indicated that concentrations of SS in all particle-size fractions in untreated bridge-deck runoff were generally higher, particularly in the two larger sediment-size fractions, than concentrations of SS for the respective particle-size fractions in samples collected from highways with catch-basin treatment. Although treatment on par with catch-basin performance may reduce the bridge-runoff SS concentration substantially, such treatment may have little effect on the reduction of fine-grained SS.

Table 16. Results and attained significance levels (*p*-values) from Mann-Whitney tests for paired sample sets of constituent concentrations in bridge-deck runoff collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) during 2014–16 and in highway runoff collected from U.S. Geological Survey monitoring stations on State Route 2 (USGS stations 423027071291301, 423027071291302), Interstate 190 (USGS station 423016071431501), Interstate 495 (USGS stations 422821071332001, 422716071343901), Interstate 95 (USGS stations 422420071153302, 422620071153301), and Interstate 93 (USGS station 421647071024703) in eastern Massachusetts, 2005–7.

[Locations of stations are shown in figure 1. Shaded areas indicate values that are significant at a 95-percent confidence interval. The alpha-numeric identifiers starting with "p" are the U.S. Geological Survey parameter codes. Suspended sediment percentage representing particle size class greater than or equal to 0.0625 to 0.25 millimeter (mm) in diameter is the difference between U.S. Geological Survey parameter codes p70333 and p70331. Suspended sediment percentage representing particle size class greater than or equal to 0.25 mm in diameter is the difference greater than U.S. Geological Survey parameter code p70333. mg/L, milligram per liter; <, less than; ≤, less than or equal to; ≥, greater than or equal to; P, phosphorus; N, nitrogen]

Constituent	Highway		Bridge		Point estimate	95-percent confidence interval	W statistic	*p*-value
	Count	Median	Count	Median				
Suspended sediment (mg/L) (p80154)	94	87	163	1,960	-1,810	-2,230 to -1,320	5,442	<0.001
Suspended sediment <0.0625 mm in diameter (percent) (p70331)	94	60	163	6	51.0	46.0 to 57.0	18,945	<0.001
Suspended sediment 0.0625≤0.25 mm in diameter (percent)	94	13.5	163	12.0	1.00	-1.00 to 3.99	12,700	0.318
Suspended sediment ≥0.25 mm in diameter (percent)	94	17	163	79	-56.0	-60.9 to -51.0	5,465	<0.001
Total phosphorus (mg/L as P) (p00655)	96	0.130	150	0.575	0.450	-0.530 to -0.380	5,642	<0.001
Total nitrogen (mg/L as N)[1] (p00600)	96	1.24	103	2.10	-0.720	-1.10 to 0.380	7,777	<0.001
Total nitrogen (mg/L as N)[2] (p00600)	96	1.24	46	1.80	-0.560	-0.910 to -0.250	6,041	<0.001

[1] Bridge data inclusive of State Route 2A and Interstate 90.

[2] Bridge data inclusive of State Route 20.

Nutrients

Concentrations of TP and TN in samples of bridge-deck runoff also were higher compared to the concentrations in samples collected from the selected highway-monitoring stations in eastern Massachusetts (fig. 23). Concentrations of TP in sample sets collected at each of the bridges were significantly higher (*p*-values <0.001) than those collected from the highway-monitoring stations (table 16). High concentrations of TP in bridge-deck runoff samples were not unexpected given the high concentrations of SS in the samples. Chemical analysis of bridge-deck sediment indicated that TP was closely associated with the sediments, particularly the fine sediment fraction (table 15).

Concentrations of TN in sample sets collected at each bridge were significantly higher (*p*-values <0.001) than those collected from the highway-monitoring stations (table 16). The difference in TN concentrations between the highway and bridge datasets may, in part, be somewhat overstated and affected by analytical method bias. Whole-water concentrations of TN in highway-runoff samples were analyzed by alkaline persulfate digestion (Patton and Kryskalla, 2003). Experimental evidence has since indicated that a negative bias in concentrations of TN is present across a range of sediment concentrations and increases as SS concentration increases (Rus and others, 2012). As a result, concentrations of TN in the prior highway dataset (Smith and Granato, 2010), particularly samples with high SS concentrations, were likely underestimated. Concentrations of TN in this study were calculated as the sum of DN and PN (table 3), and therefore the negative bias was eliminated. The alkaline persulfate digestion method, when used for samples absent of SS (filtered samples), has a reported precision of 2.3 percent (Rus and others, 2012). The RPDs between concentrations of DN in environment and replicate samples in this study (fig. 12) generally were within this reported precision, indicating that the performance of the method also was acceptable for the sample matrix in this study.

Concentrations of TN in the highway dataset may exhibit a negative bias as a result of method performance during the earlier study (Smith and Granato, 2010); however, this bias may not fully explain the difference in TN concentrations for each study. The substantial difference between concentrations of SS in samples of bridge-deck runoff and highway runoff (fig. 22) also may explain part of the difference in TN concentrations. In this study, most of the TN concentration in samples of bridge-deck runoff consisted of PN, and thus it is likely that the particulate concentration of nitrogen in the highway

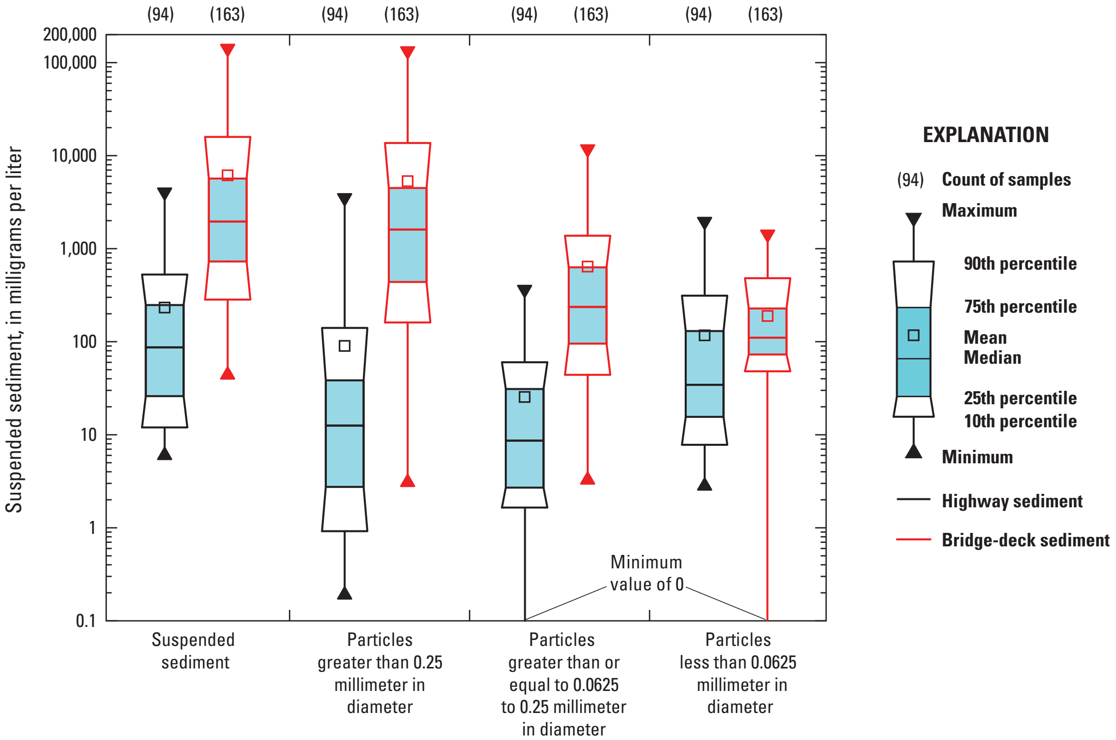


Figure 22. Distribution of concentrations of suspended sediment and the distribution of concentrations of three particle-size classes for suspended sediment in composite samples of highway runoff collected at USGS stations 423027071291301, 423027071291302, 423016071431501, 422821071332001, 422716071343901, 422420071153302, 422620071153301, and 421647071024703 in eastern Massachusetts, 2005–7 (Smith and Granato, 2010), and from three bridge-deck-monitoring stations (422108071052501, 422025071154501, and 421247071470201) in this study, eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

samples, which have significantly lower concentrations of SS, also was proportionally lower than the concentrations of PN in the bridge-runoff samples. Therefore, much of the difference between concentrations of TN in the highway and bridge datasets may in fact be realistic.

Sediment Quality

The quality of bridge-deck sediment from State Route 2A in Boston, Interstate 90 near Weston, and State Route 20 near Quinsigamond Village was compared to the sediment quality measured in three composite samples of highway sediment collected from monitoring stations on State Route 2 in Littleton (USGS stations 423027071291301, 423027071291302), Interstate 495 in Boxborough (USGS stations 422821071332001, 422716071343901), and Interstate 495 in Waltham, Mass. (USGS stations 422420071153302, 422620071153301) (Smith and Granato, 2010) (fig. 1). For each of the three particle-size fractions, concentrations of TP in bridge sediment were lower than concentrations measured in highway sediment (fig. 24). Concentrations of TP in highway sediment were 3 to 5 times greater in the fine fraction and 6 to 40 times greater in the intermediate and coarse fractions compared to concentrations in the same size fractions of bridge-deck sediment. Except for concentrations of Cr, concentrations of total-recoverable metals in the fine fraction of bridge-deck sediment were similar (within 50 percent) to the concentration in the same size fraction of highway sediment (fig. 24*A*). Concentrations of Cr were 5 to 17 times greater in the intermediate and coarse fraction of highway sediment in comparison to concentrations in the same respective size fractions in bridge sediment samples (figs. 24*B*–*C*). Concentrations of Cu were as much as 49 times greater in the intermediate fraction of highway sediment in comparison to concentrations in the bridge sediment samples (fig. 24*B*); Cu was not detected in samples containing the coarse size fraction of bridge sediment.

Although the quality of sediment for each size fraction is important, it is necessary to consider the proportion of sediment in each particle-size fraction within the sample. As was previously discussed in the “Suspended Sediment” section, the concentration of SS, as well as the particle-size distribution, in samples of bridge-deck runoff was significantly different compared to the SS concentration and particle-size distribution in composite samples of highway runoff. To better illustrate the relation, a 1-kilogram synthetic sample was estimated on the basis of the mean SS particle-size distribution and mean

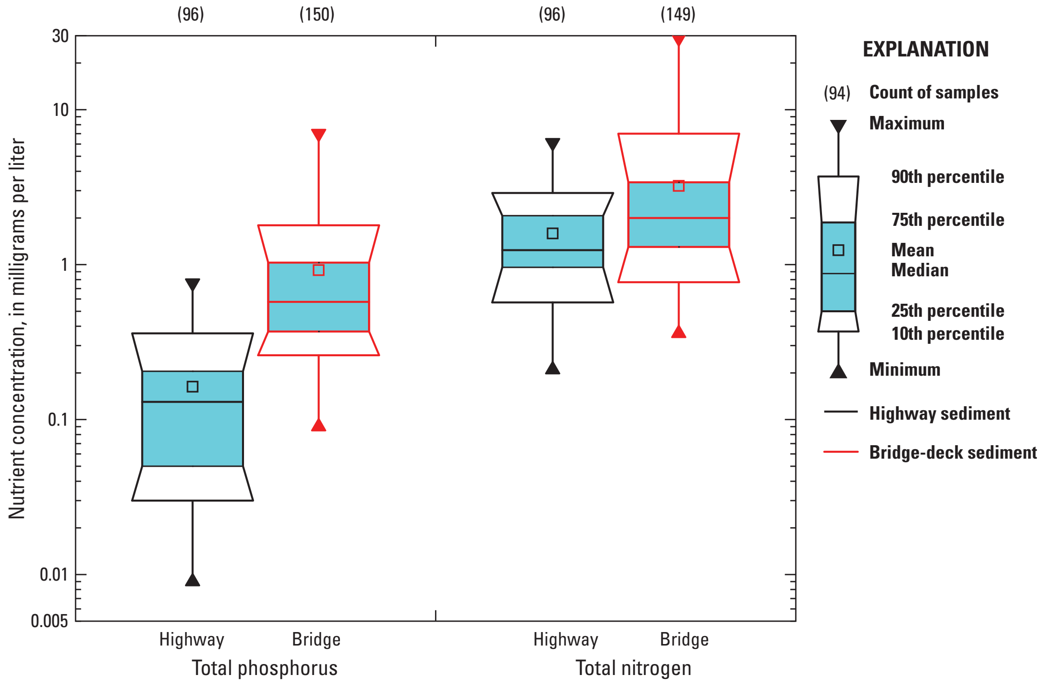


Figure 23. Distribution of total phosphorus and total nitrogen in composite samples of highway runoff collected at USGS stations 423027071291301, 423027071291302, 423016071431501, 422821071332001, 422716071343901, 422420071153302, 422620071153301, and 421647071024703 in eastern Massachusetts, 2005–7 (Smith and Granato, 2010), and from three bridge-deck-monitoring stations (422108071052501, 422025071154501, and 421247071470201) in this study, eastern Massachusetts, 2014–16. Locations of stations are shown on figure 1.

associated constituent concentration for each size fraction (eq. 2; table 15) for bridge deck and highway SS (fig. 25). This simulated sample indicated that the concentrations of TP and trace metals associated with SS in highway runoff were higher than concentrations in the same mass of bridge-deck sediment. The higher concentrations of TP and trace metals (except for Al) associated with the highway sediment were the result of a higher proportion of fine to coarse sediment compared to that in bridge-deck sediment and the greater affinity for phosphorus and trace metals to associate with the fine size fraction (fig. 24).

These data demonstrated that the distribution of sediment particle size and associated chemical concentrations in bridge-deck sediment was different compared to highway sediment quality, and that Massachusetts highway-runoff data cannot reliably be used to estimate constituent concentrations and yields of nutrients and trace metals from bridge decks. Where bridge-deck runoff is treated by catch basins or other BMPs that provide similar sediment removal characteristics as present in the highway setting, some trace metal yields for both highway and bridge decks may be similar. As discussed earlier, concentrations associated with specific particle-size classes for many constituents, except for TP, Cd, Cr, and Cu, were similar in highway and bridge sediments. Therefore, reasonable planning-level concentrations for many trace metals in bridge-deck runoff can be derived from known concentrations of specific trace metals associated with sediments from both studies (Smith and Granato, 2010) and from the average gradated concentrations of SS in the composite samples of runoff collected from the bridges in this study in the absence of site-specific data.

Example Bridge-Deck Runoff Simulations

SELDM was developed to indicate the risk for stormwater concentrations, flows, and loads to be larger than user-selected water-quality goals, the potential need for mitigation measures, and the potential effectiveness of such measures for reducing these risks (Granato, 2013). SELDM is a stochastic model because it uses Monte Carlo methods to produce the random combinations of input variable values needed to generate the stochastic population of values for each component variable. Results are ranked and plotting positions are calculated to indicate the level of risk as a probability of occurrence. SELDM is designed to provide long-term planning-level estimates, which are defined as the results of analyses used to evaluate alternative management measures.

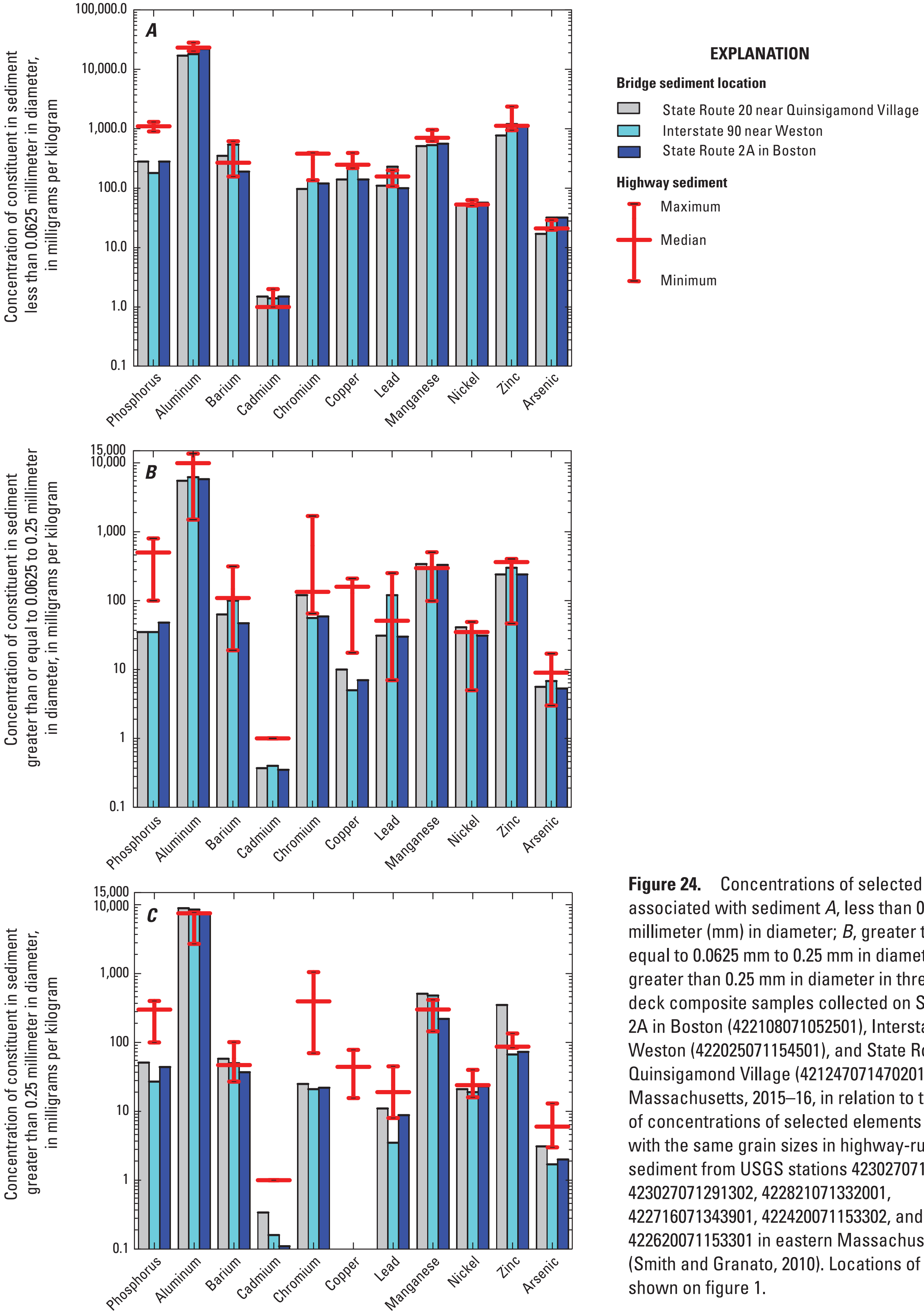


Figure 24. Concentrations of selected elements associated with sediment *A*, less than 0.0625 millimeter (mm) in diameter; *B*, greater than or equal to 0.0625 mm to 0.25 mm in diameter; and *C*, greater than 0.25 mm in diameter in three bridge-deck composite samples collected on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2015–16, in relation to the range of concentrations of selected elements associated with the same grain sizes in highway-runoff sediment from USGS stations 423027071291301, 423027071291302, 422821071332001, 422716071343901, 422420071153302, and 422620071153301 in eastern Massachusetts, 2005–7 (Smith and Granato, 2010). Locations of stations are shown on figure 1.

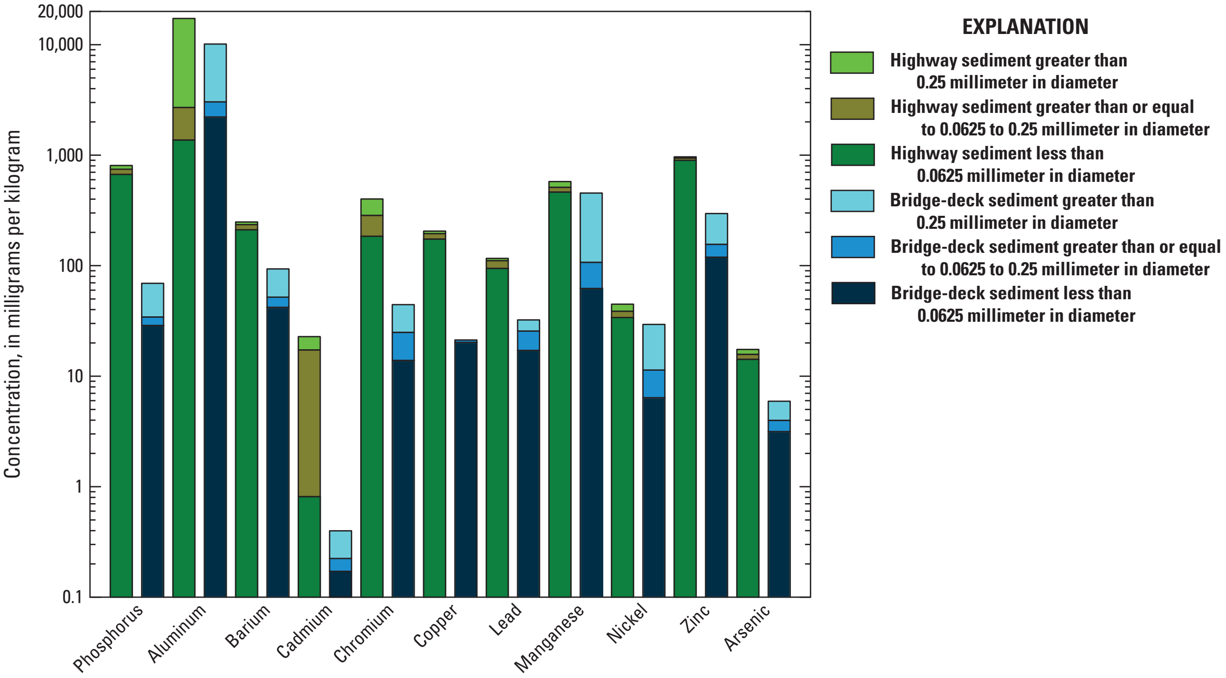


Figure 25. The distribution of concentrations of selected constituents in 1 kilogram of sediment estimated on the basis of the mean concentration of each constituent associated with three particle-size ranges in highway sediment collected from USGS stations 423027071291301, 423027071291302, 422821071332001, 422716071343901, 422420071153302, and 422620071153301 in eastern Massachusetts in 2005–7 (Smith and Granato, 2010) and from bridges on State Route 2A (422108071052501) in Boston, Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2015–16, and from the mean particle-size distribution of suspended sediment in composite samples of runoff collected at each location. Locations of stations are shown on figure 1.

Planning-level estimates are recognized to include substantial uncertainties, commonly of orders of magnitude (Barnwell and Krenkel, 1982; Marsalek, 1991; Granato, 2013). These uncertainties are especially applicable to stormwater issues because measured flows and concentrations commonly vary by several orders of magnitude, even within monitoring studies with few samples. The SELDM analyses for this study documents the results of simulations that can be used to assess the potential effects of various input concentration statistics on simulated concentrations, provide an example concentration risk analysis, and produce estimates of long-term yields of SS, TP, and TN.

Representativeness of Selected Statistics

Runoff-concentration statistics are used by SELDM to perform the long-term simulations. The dataset collected for this study has more event-mean composites than most other datasets (Granato and Cazenas, 2009; Smith and Granato, 2010), but generating the long-term simulated record dataset required extrapolation beyond the percentiles of the original data. Concentrations of TP, TN, and SS in bridge-deck samples collected in this study ranged by about 2 orders of magnitude for TP and TN (ranged from 0.09 to 7.02 mg/L and 0.36 to 29 mg/L, respectively) and almost 4 orders of magnitude for SS (ranged from 44 to 142,000 mg/L) (table 11). Examples of maximum or typical concentrations of phosphorus, nitrogen, and sediment species in environmental samples recorded in the literature also are shown in table 17.

Concentrations of various species of nitrogen and sediment are shown in table 17 because these other species are more commonly measured in highway- and urban-runoff studies. For example, the National Stormwater Quality Database (Pitt and others, 2015) contains 6,156 total Kjeldahl nitrogen (TKN) measurements but only 694 TN concentrations. Similarly, the International BMP Database contains 21,964 total suspended solids measurements but only 1,384 SS concentrations. The maximum TN and TP concentrations measured in this study were comparable to maximum nitrogen and phosphorus concentrations in other highway and urban runoff studies and to weak (low-level) human wastewater concentrations (table 17). The maximum SS concentrations, however, were 2 to 17 times the maximum concentrations measured in other highway and urban runoff studies.

In SELDM, concentrations are simulated by using the frequency-factor method (eq. 3). The frequency factor is calculated using the following equation:

Table 17. Examples of maximum or typical concentrations of phosphorus, nitrogen, and sediment species in environmental samples recorded in the literature.

[The count in the dataset is provided to compare availability of different water-quality parameters. Precise constituent name parameter codes are not provided because several of the sources provide commonly used constituent names but do not specify the exact definitions. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. mg/L, milligram per liter; N, nitrogen; total nitrogen (p00600), nitrate plus nitrite (p00631); total Kjeldahl nitrogen (p00625); P, phosphorus; total phosphorus (p00665); SSC, suspended sediment concentration (p80154); TSS, total suspended solids (p00530); EPA, U.S. Environmental Protection Agency; NA, not applicable; HRDB, Highway-Runoff Database, version 1.0.0a; BMPDB, International Stormwater Best Management Practices Database, version 2016-11-17; NSQD, National Stormwater Quality Database, version 4.02; SWQDM, Surface-Water Quality Data Miner; EPA, U.S. Environmental Protection Agency]

Constituent	Water-quality matrix	Value type	Concentration, in mg/L	Count in Dataset	Source of information
		Nitrogen as N			
Total nitrogen	Highway runoff	Maximum (State Route 2A)	29	52	This study
Total nitrogen	Highway runoff	Maximum (Interstate 90)	17	46	This study
Total nitrogen	Highway runoff	Maximum (State Route 20)	18	51	This study
Total nitrogen	Highway runoff	Maximum	6.1	164	HRDB, Smith and Granato, 2010
Nitrite plus nitrate	Highway runoff	Maximum	9	412	HRDB, Smith and Granato, 2010
Total Kjeldahl nitrogen	Highway runoff	Maximum	36	1,410	HRDB, Smith and Granato, 2010
Total nitrate	Highway runoff	Maximum	48	1,055	HRDB, Smith and Granato, 2010
Total nitrogen	Urban runoff	Maximum	53	12,001	BMPDB, http://www.bmpdatabase.org/
Total nitrogen	Urban runoff	Maximum	90.1	694	NSQD, Pitt and others, 2015
Total Kjeldahl nitrogen	Urban runoff	Maximum	200	16,195	BMPDB, http://www.bmpdatabase.org/
Total Kjeldahl nitrogen	Urban runoff	Maximum	940	6,156	NSQD, Pitt and others, 2015
Total nitrogen	Human wastewater	Typical (weak)	20	NA	Peavy and others, 1985
Total nitrogen	Human wastewater	Typical (medium)	40	NA	Peavy and others, 1985
Total nitrogen	Human wastewater	Typical (strong)	85	NA	Peavy and others, 1985
Total nitrogen	Human wastewater	Typical (weak)	26	NA	Gross, 2005
Total nitrogen	Human wastewater	Typical (medium)	60	NA	Gross, 2005
Total nitrogen	Human wastewater	Typical (strong)	75	NA	Gross, 2005
Total nitrogen	Livestock waste slurry	Typical cattle	3,000	NA	Hooda and others, 2000
Total nitrogen	Livestock waste slurry	Typical pig	5,000	NA	Hooda and others, 2000
Total nitrogen	Livestock liquid manure	Typical hog	2,645	NA	Brown, 2013
Total nitrogen	Livestock liquid manure	Typical dairy	1,601	NA	Brown, 2013
Total nitrogen	Livestock liquid manure	Typical beef	1,543	NA	Brown, 2013
Total nitrogen	Livestock liquid manure	Typical poultry	5,567	NA	Brown, 2013
Total nitrogen	Receiving water	Maximum	1,500	50,160	SWQDM, Granato and others, 2009
Total nitrogen	Receiving water	Maximum (EPA Ecoregion 59)	45	3,932	SWQDM, Granato and others, 2009

Table 17. Examples of maximum or typical concentrations of phosphorus, nitrogen, and sediment species in environmental samples recorded in the literature.—Continued

[The count in the dataset is provided to compare availability of different water-quality parameters. Precise constituent name parameter codes are not provided because several of the sources provide commonly used constituent names but do not specify the exact definitions. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. mg/L, milligram per liter; N, nitrogen; total nitrogen (p00600), nitrate plus nitrite (p00631); total Kjeldahl nitrogen (p00625); P, phosphorus; total phosphorus (p00665); SSC, suspended sediment concentration (p80154); TSS, total suspended solids (p00530); EPA, U.S. Environmental Protection Agency; NA, not applicable; HRDB, Highway-Runoff Database, version 1.0.0a; BMPDB, International Stormwater Best Management Practices Database, version 2016-11-17; NSQD, National Stormwater Quality Database, version 4.02; SWQDM, Surface-Water Quality Data Miner; EPA, U.S. Environmental Protection Agency]

Constituent	Water-quality matrix	Value type	Concentration, in mg/L	Count in Dataset	Source of information
Phosphorus as P					
Total phosphorus	Bridge-deck runoff	Maximum (State Route 2A)	7.02	53	This study
Total phosphorus	Bridge-deck runoff	Maximum (Interstate 90)	3.16	46	This study
Total phosphorus	Bridge-deck runoff	Maximum (State Route 20)	6.02	51	This study
Total phosphorus	Highway runoff	Maximum	17	1,439	HRDB, Smith and Granato, 2010
Total phosphorus	Urban runoff	Maximum	80.2	7,232	NSQD, Pitt and others, 2015
Total phosphorus	Urban runoff	Maximum	80.2	20,258	BMPDB, http://www.bmpdatabase.org/
Total phosphorus	Human wastewater	Typical (weak)	4	NA	Peavy and others, 1985
Total phosphorus	Human wastewater	Typical (medium)	8	NA	Peavy and others, 1985
Total phosphorus	Human wastewater	Typical (strong)	15	NA	Peavy and others, 1985
Total phosphorus	Human wastewater	Typical (weak)	6	NA	Gross, 2005
Total phosphorus	Human wastewater	Typical (medium)	10	NA	Gross, 2005
Total phosphorus	Human wastewater	Typical (strong)	12	NA	Gross, 2005
Total phosphorus	Livestock waste slurry	Typical cattle	520	NA	Hooda and others, 2000
Total phosphorus	Livestock waste slurry	Typical pig	1,310	NA	Hooda and others, 2000
Total phosphorus	Livestock liquid manure	Typical hog	814	NA	Brown, 2013
Total phosphorus	Livestock liquid manure	Typical dairy	369	NA	Brown, 2013
Total phosphorus	Livestock liquid manure	Typical beef	317	NA	Brown, 2013
Total phosphorus	Livestock liquid manure	Typical poultry	1,924	NA	Brown, 2013
Total phosphorus	Receiving water	Maximum	640	246,403	SWQDM, Granato and others, 2009
Total phosphorus	Receiving water	Maximum (EPA Ecoregion 59)	9	10,644	SWQDM, Granato and others, 2009

Table 17. Examples of maximum or typical concentrations of phosphorus, nitrogen, and sediment species in environmental samples recorded in the literature.—Continued

[The count in the dataset is provided to compare availability of different water-quality parameters. Precise constituent name parameter codes are not provided because several of the sources provide commonly used constituent names but do not specify the exact definitions. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. mg/L, milligram per liter; N, nitrogen; total nitrogen (p00600), nitrate plus nitrite (p00631); total Kjeldahl nitrogen (p00625); P, phosphorus; total phosphorus (p00665); SSC, suspended sediment concentration (p80154); TSS, total suspended solids (p00530); EPA, U.S. Environmental Protection Agency; NA, not applicable; HRDB, Highway-Runoff Database, version 1.0.0a; BMPDB, International Stormwater Best Management Practices Database, version 2016-11-17; NSQD, National Stormwater Quality Database, version 4.02; SWQDM, Surface-Water Quality Data Miner; EPA, U.S. Environmental Protection Agency]

Constituent	Water-quality matrix	Value type	Concentration, in mg/L	Count in Dataset	Source of information
		Suspended sediment and solids			
SSC	Highway runoff	Maximum (State Route 2A)	60,000	55	This study
SSC	Highway runoff	Maximum (Interstate 90)	142,000	54	This study
SSC	Highway runoff	Maximum (State Route 20)	38,700	54	This study
SSC	Highway runoff	Maximum	8,580	431	HRDB, Smith and Granato, 2010
TSS	Highway runoff	Maximum	5,100	2,253	HRDB, Smith and Granato, 2010
SSC	Urban runoff	Maximum	8,580	1,384	BMPDB, http://www.bmpdatabase.org/
TSS	Urban runoff	Maximum	10,505	21,964	BMPDB, http://www.bmpdatabase.org/
TSS	Urban runoff	Maximum	10,700	6,695	NSQD, Pitt and others, 2015
TSS	Human wastewater	Typical (weak)	100	NA	Peavy and others, 1985
TSS	Human wastewater	Typical (medium)	200	NA	Peavy and others, 1985
TSS	Human wastewater	Typical (strong)	350	NA	Peavy and others, 1985
TSS	Human wastewater	Typical (weak)	155	NA	Gross, 2005
TSS	Human wastewater	Typical (medium)	250	NA	Gross, 2005
TSS	Human wastewater	Typical (strong)	330	NA	Gross, 2005
SSC	Receiving water	Maximum (post volcanic eruption)	1,770,000	2,904	SWQDM, Granato and others, 2009
SSC	Receiving water	Maximum (nonvolcanic)	966,000	273,046	SWQDM, Granato and others, 2009
SSC	Receiving water	Maximum (EPA Ecoregion 59)	640	3,546	SWQDM, Granato and others, 2009

$$\mathrm{Log}(C_i) = Avg + SD \times K_i \qquad (3)$$

where

i is the individual simulated value, which ranges from one to the number of simulated storm events;

C_i is the ith simulated concentration;

Avg is the average of the logarithms of concentration;

SD is the standard deviation of the logarithms of concentration; and

K_i is the Pearson type III random variate.

The calculated average value (Avg) sets the magnitude of the center of the simulated sample. The magnitude of the SD controls the variation of concentrations above and below the average; larger SD values will result in a larger range in simulated values. The Pearson type III random variate (K_i), which is a function of the skew (Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988; Granato, 2013), is the value generated by SELDM. If the skew is equal to zero, then K_i is a normal random variate. The SELDM simulations that use precipitation statistics from ecoregion 59 (the Northeastern Coastal Zone) result in about 1,680 events. In theory, the associated range of normal K_i values would be about plus or minus 3.24 for this number of events. SELDM, however, generates K_i values randomly, and more extreme K_i values may be generated in any simulation. If the skew is nonzero then the K_i values will be skewed (Interagency Advisory Committee on Water Data, 1982; Chow and others, 1988), which increases the probability that extreme K_i values may be generated (Granato, 2013).

To understand why very extreme outliers may not have very extreme percentiles, it is important to understand that the plotting positions written to the output files by SELDM are the sample statistics, calculated from the ranks of the output values rather than the population statistics, which are the percentiles based on the random number that is generated. However, it is the magnitude of SD values that controls the effect of K_i values on simulated concentrations. Therefore, statistics used for simulation data must be carefully selected because these high concentrations, measured within a 2-year study, will be used to simulate a 29 to 30 year period. If conditions during the study period resulted in uncharacteristically high or low concentrations, then the probability of occurrence based on sample statistics may be inflated in comparison to the actual population statistics. For example, if a streamgage is established and operated for 5 years and the 100-year flood (a flood magnitude with an actual exceedance risk of about 1 percent) occurs, the sample statistics would indicate that that measured flood-flow magnitude would have an exceedance risk of about 17 percent based on the 5 available annual-flood values.

The average, SD, and skew of the common (base 10) logarithms of event-mean concentrations in composite samples of bridge-deck runoff calculated by using the traditional statistics and the robust statistics are shown in table 18. The medians of each statistic, which in theory may be the best estimates of runoff quality from any randomly selected unmonitored bridge in the State, are also shown in table 18. The median of the statistics may include the average from one site, the SD from another, and the skew from the third site; therefore, concentrations simulated by using these statistics may not represent the data from any particular site. Statistics for the lumped data, which may better represent the exceedance risk of the highest and lowest concentrations if the individual site datasets come from the same population of bridge-runoff quality (the samples from different bridges are not statistically different), also are documented in table 18. Concentrations of SS and TP in sample sets for the bridge in this study were not significantly different. Concentrations of nitrogen in samples of bridge-deck runoff were lowest at State Route 2A in Boston and highest at State Route 20 near Quinsigamond Village; concentrations of TN were significantly higher for State Route 20 than for the other two bridges (table 14). As with the median statistics, simulations made by using the lumped statistics may not represent values from a particular site, but if lumping the data represents the probability of exceedance for the highest and lowest concentrations, results may be more realistic than statistics from the individual datasets.

Information about the uncertainty in the sample statistics is also included in table 18. The standard error of the estimate and the 95-percent confidence interval of the average, SD, and skew of the traditional statistics were calculated by using methods specified by the Interagency Advisory Committee on Water Data (1982). The 95-percent confidence intervals for each statistic indicate if the statistics calculated by using the different methods and by using the lumped data are significantly different from the values calculated by using traditional methods. The values of the average and SD calculated by using the robust alternative methods were within the 95-percent confidence intervals of the associated statistics calculated by using traditional methods. The values of Pearson's second skew calculated by using the robust statistics also were within the 95-percent confidence intervals of skews calculated by using traditional methods, except for the second skew of TN and TP for the State Route 2A monitoring station and TN for the lumped data (table 18). Statistics for the median values were within the 95-percent confidence intervals of the other statistics calculated with data from individual sites (table 18). Although the statistics were not significantly different, there were substantial differences among the values that affected the outcomes of long-term simulations.

The effects of selected statistics (table 18) on simulated TN concentrations are shown in figure 26. The effects of the large positive skew of the traditional TN statistics for data from the monitoring stations on State Routes 20 and 2A are evident in the fact that the distribution of simulated concentrations was concave up, which contributed to the high outlier values of 130 and 245 mg/L (fig. 26*A*). These values were higher than maximum values of TN in published highway and urban runoff datasets (table 17). The simulated values were comparable to typical values of "strong" human wastewater but were within the maximum values for urban runoff (table

Table 18. Average, standard deviation, and skew of the common logarithms of event-mean concentrations in composite samples of bridge-deck runoff collected from State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16, as calculated by using traditional and robust methods.

[Locations of stations are shown in figure 1. The standard error of the estimate (SEE) and 95-percent confidence interval (CI) were calculated by using equations in the Interagency Advisory Committee on Water Data (1982) Bulletin 17B. The calculated statistic is not significantly different from zero if the 95-percent CI crosses zero. Numbers have been rounded to three significant figures. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. N, nitrogen; P, phosphorus]

Bridge-monitoring station	Count	Median	Average			Average[1]	Standard deviation			Standard deviation[1]	Skew			Skew[2]	Skew[3]
			Value	SEE	95-percent CI		Value	SEE	95-percent CI		Value	SEE	95-percent CI		
Total nitrogen as N (p00600) (milligrams per liter)															
State Route 2A	52	0.161	0.236	0.051	0.134–0.338	0.191	0.370	0.052	0.266–0.474	0.307	1.17	0.330	0.507–1.833	0.608	0.293
Interstate 90	46	0.255	0.317	0.046	0.224–0.410	0.305	0.311	0.038	0.234–0.388	0.305	0.697	0.350	-0.008–1.402	0.598	0.492
State Route 20	51	0.447	0.474	0.048	0.378–0.570	0.472	0.340	0.034	0.272–0.408	0.362	0.064	0.333	-0.605–0.733	0.238	0.207
Median of sites	51	0.255	0.317	0.048	0.221–0.413	0.305	0.340	0.039	0.262–0.418	0.307	0.697	0.333	0.028–1.366	0.547	0.293
Lumped data	149	0.301	0.342	0.029	0.285–0.399	0.311	0.354	0.023	0.309–0.399	0.338	0.569	0.199	0.176–0.962	0.347	0.089
Total phosphorus as P (p00665) (milligrams per liter)															
State Route 2A	53	-0.161	-0.123	0.047	-0.217– -0.029	-0.155	0.345	0.041	0.263–0.427	0.322	0.805	0.327	0.149–1.461	0.330	0.056
Interstate 90	46	-0.297	-0.280	0.041	-0.363– -0.197	-0.279	0.280	0.031	0.218–0.342	0.256	0.464	0.350	-0.241–1.169	0.182	0.211
State Route 20	51	-0.229	-0.196	0.054	-0.304– -0.088	-0.212	0.388	0.040	0.308–0.468	0.395	0.299	0.333	-0.370–0.968	0.255	0.129
Median of sites	51	-0.229	-0.196	0.048	-0.292– -0.100	-0.212	0.345	0.037	0.271–0.419	0.322	0.464	0.333	-0.205–1.133	0.287	0.129
Lumped data	150	-0.240	-0.196	0.028	-0.251– -0.141	-0.214	0.346	0.022	0.303–0.389	0.323	0.557	0.198	0.166–0.948	0.382	0.241
Suspended sediment concentration (p80154) (milligrams per liter)															
State Route 2A	54	3.30	3.38	0.076	3.228–3.532	3.36	0.555	0.06	0.435–0.675	0.553	0.602	0.325	-0.050–1.254	0.432	0.325
Interstate 90	54	3.31	3.35	0.078	3.194–3.506	3.34	0.571	0.055	0.461–0.681	0.559	0.085	0.325	-0.567–0.737	0.210	0.161
State Route 20	55	3.17	3.19	0.109	2.971–3.409	3.20	0.806	0.077	0.652–0.960	0.871	0.076	0.322	-0.570–0.722	0.074	0.103
Median of sites	54	3.30	3.35	0.078	3.194–3.506	3.34	0.571	0.055	0.461–0.681	0.559	0.085	0.325	-0.567–0.737	0.263	0.161
Lumped data	163	3.29	3.30	0.051	3.199–3.401	3.30	0.656	0.036	0.585–0.727	0.665	0.038	0.091	-0.142–0.218	0.046	0.045

[1] Estimated by using robust regression on order statistics (Helsel and Hirsch, 2002; Granato, 2006).

[2] Estimated by using the robust Pearson’s second coefficient of skewness (Haan, 1977) with the commonly used average and standard deviation.

[3] Estimated by using the robust Pearson’s second coefficient of skewness (Haan, 1977) with the robust regression on order statistics for the average and standard deviation.

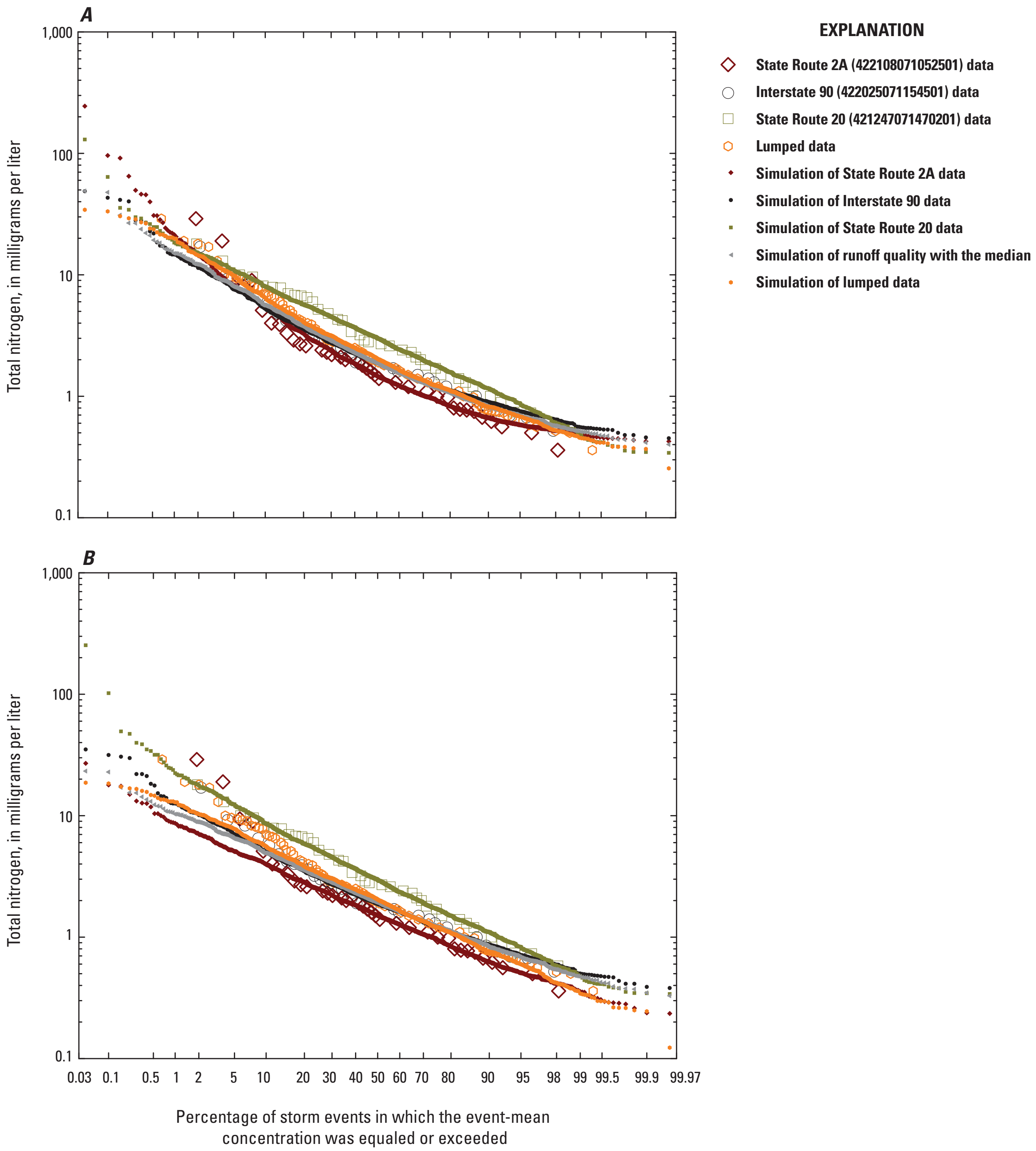


Figure 26. Measured total nitrogen concentrations and concentrations simulated by using *A*, traditional statistics and *B*, statistics calculated by using robust alternative methods. The selected statistics are shown in table 18.

17). These values were, however, well within TKN concentrations measured in urban runoff. In theory TN concentrations should be greater than or equal to TKN concentrations; the higher TKN values reflect the fact that there are many more TKN than TN values in the highway and urban-runoff databases (table 17). The high urban-runoff concentrations may represent the effects of fertilizer application in urban areas that were not typical of conditions within the highway right-of-way. The simulations performed using the lumped data and simulated statistics shown in table 18 indicated that the two largest measured values (19 and 29 mg/L) from the current study may be outliers with actual exceedance probabilities that were smaller than would be assumed by the sample size. In comparison, the robust skew statistic for data from the monitoring station on State Route 20 was higher than the skew calculated by using traditional methods, which resulted in a high outlier for the robust alternative simulation for the bridge on State Route 20 (fig. 26*B*). In this case, the maximum simulated value for bridge-deck runoff from State Route 20 was 253 mg/L. With the exception of the two outliers (130 and 245 mg/L) in the State Route 20 monitoring station dataset, the robust alternatives produced simulated populations that were representative of the data and that were more consistent with highway-runoff maxima from other studies in the HRDB than the simulations done with the classic statistics. Unlike urban areas, which may be fertilized, bridge decks may have a limited source of nitrogen controlling the upper bounds of possible values. However, as data from urban runoff, human wastewater, agricultural wastewater, precipitation, and receiving waters indicated, the simulated values were well within concentrations expected from dissolved and suspended matter in flowing water (table 17).

The effects of selected statistics (table 18) on simulated TP concentrations are shown in figure 27. TP skew values were small and, with the exception of State Route 2A monitoring station dataset and the lumped dataset, were not significantly different from zero. Therefore, unlike TN, neither the data nor the simulation populations were strongly concave up on figure 27 and extreme values were not generated. Maximum values simulated with traditional and robust statistics were well below the maximum for urban runoff (table 17), which probably included runoff from fertilized areas. Maximum values simulated with traditional statistics, however, were between 10 and 20 mg/L and so were comparable to typical values for strong human wastewater. Concentrations simulated by using the robust alternative statistics were well within the existing highway maximum in table 17. The simulations performed using the lumped data and simulated statistics shown in table 18 indicated that the two largest measured values measured at the State Route 2A and State Route 20 monitoring stations may have been outliers with actual exceedance probabilities that were smaller than would be assumed by the sample size. As with TN, comparison with data from urban runoff, human wastewater, agricultural wastewater, and receiving waters indicated the simulated TP values were well within concentrations expected from dissolved and suspended matter in flowing water (table 17).

The effects of selected statistics (table 18) on simulated SS concentrations are shown in figure 28. In this case, the maximum simulated values of SS were for the State Route 20 dataset (more than 1,000,000 mg/L). With the exception of the State Route 2A data, the skews of the SS samples were very small and none of the skew values were significantly different from zero. In this case, the relatively large SD for the State Route 20 dataset (table 18) was the statistic that was driving these extreme values. The SDs for the traditional and robust alternative statistics were large. A few high outliers did not cause these relatively large SDs. The large range and the relatively high percentage of SS concentrations below 300 mg/L at State Route 20 caused the large SDs calculated by using both methods and therefore the large simulated values. Although concentrations approaching or exceeding 1,000,000 mg/L may seem unrealistic, receiving-water monitoring data indicated that such hyperconcentrated flows did occur in environments with high-energy flows and a large supply of erodible sediments (table 17). Although the bridge deck may become sediment limited in a long or large storm, figures 18 and 20 and tables 5 and 6 indicate that a large amount of sediment may be available for wash off. The available sediment could produce large concentration in a small but intense storm. The statistics from this dataset indicated that the maximum measured value of 140,000 mg/L had a smaller percent exceedance than would be calculated from the sample size (fig. 28), but statistics indicated that this large value may have an exceedance risk representing a 1-in-10- or a 1-in-20-year event.

Because the traditional and robust alternative statistics produced extreme concentrations in these simulations, additional simulations were made by using L-moment statistics, which are not as influenced by extreme values in the data as other calculation methods (Hosking, 1990; Stedinger and others, 1993). The average, SD, and skew of the common (base 10) logarithms of event-mean concentrations in composite samples of bridge-deck runoff calculated by using L-moment statistics are documented in table 19. The medians of each L-moment statistic and the L-moment statistics for the lumped data are also shown in table 19. The L-moment averages were equal to the averages calculated by using traditional methods (table 18) because they were calculated with the same equations. The L-moment SDs and skew statistics in table 19, however, were substantially lower than the analogous statistical values shown in table 18 because L-moments are linear combinations of probability-weighted moments. Examination of simulation results, however, indicated that the L-moment statistics are not suitable for simulating runoff concentrations with the frequency-factor method (fig. 29). No extreme values were generated, but the simulated values did not represent measured values because the SDs and skews did not result in simulated values that were comparable to measured values.

Analysis of the calculated statistics and simulated values indicated that if the median of statistics from the monitored sites were used, neither the traditional nor the robust

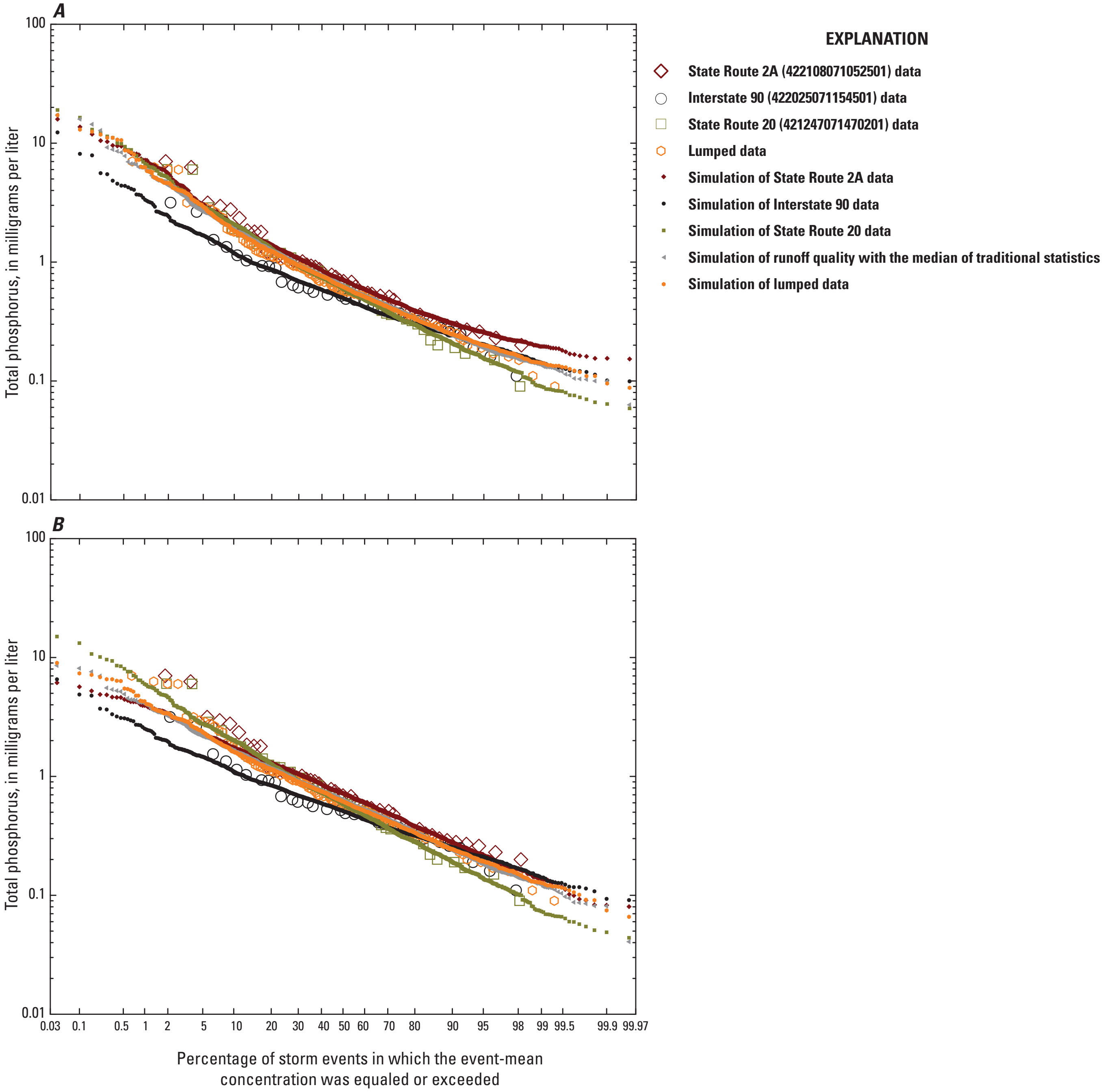


Figure 27. Measured total phosphorus concentrations and concentrations simulated by using *A*, traditional statistics and *B*, statistics calculated by using robust alternative methods. The selected statistics are shown in table 18.

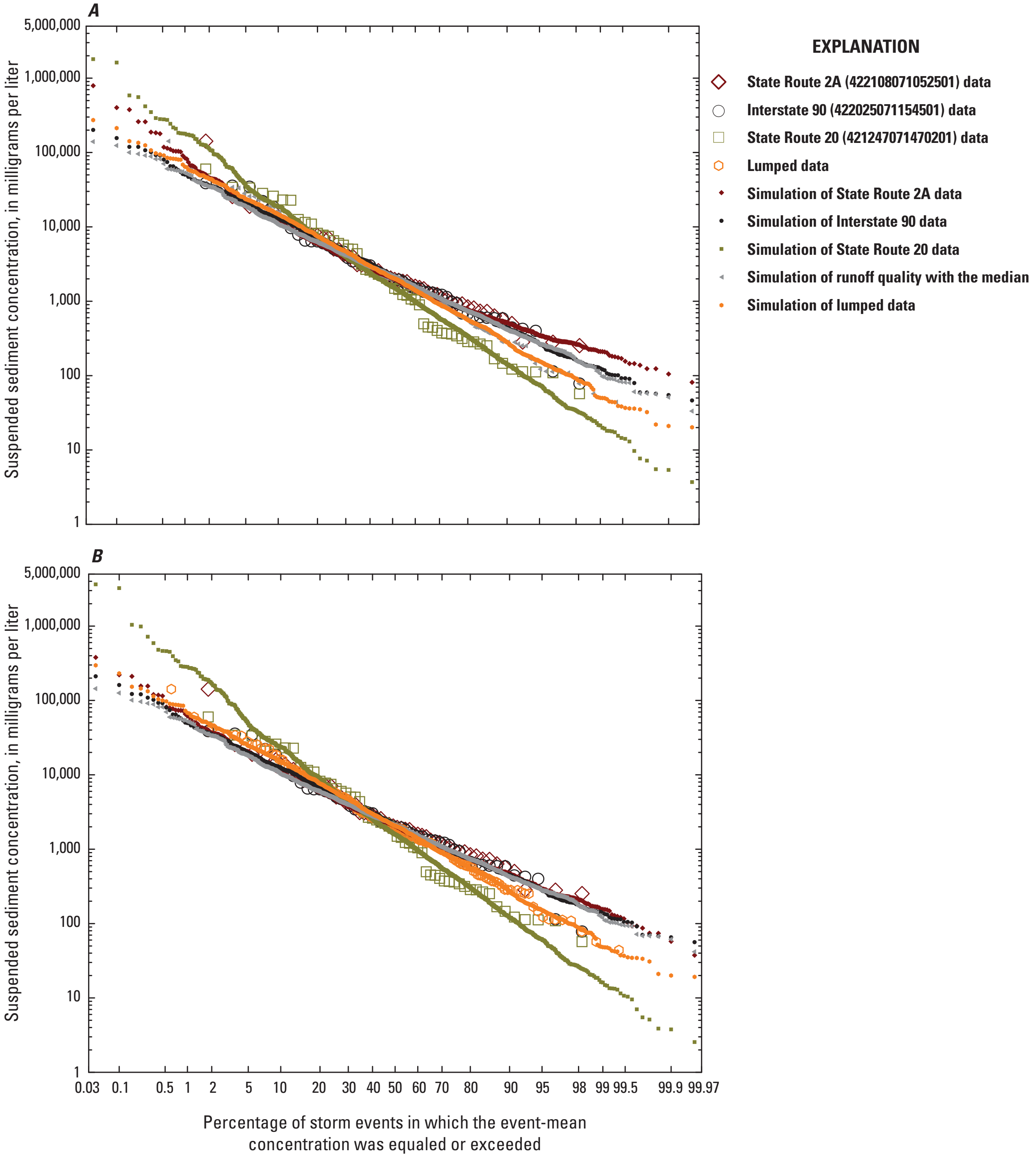


Figure 28. Measured suspended sediment concentrations and concentrations simulated by using *A*, traditional statistics and *B*, statistics calculated by using robust alternative methods. The selected statistics are shown in table 18.

Table 19. Average, standard deviation, and skew of the common logarithms of event-mean concentrations in composite samples of bridge-deck runoff collected from State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16, as calculated by using L-moment methods.

[Locations of stations are shown in figure 1. The alpha-numeric identifiers starting with "p" are the U.S. Geological Survey parameter codes. Numbers have been rounded to three significant figures. L-moments are linear combinations of probability-weighted moments used for estimating sample statistics (Hosking, 1990; Stedinger and others, 1993). N, nitrogen; P, phosphorus]

Bridge-monitoring site	Count	Average	Standard deviation	Skew
Total nitrogen as N (p00600) (milligrams per liter)				
State Route 2A	52	0.236	0.198	0.167
Interstate 90	46	0.317	0.172	0.134
State Route 20	51	0.474	0.195	0.014
Median of sites	51	0.317	0.195	0.134
Lumped data	149	0.342	0.198	0.107
Total phosphorus as P (p00665) (milligrams per liter)				
State Route 2A	53	-0.123	0.192	0.140
Interstate 90	46	-0.280	0.153	0.079
State Route 20	51	-0.196	0.219	0.035
Median of sites	51	-0.196	0.192	0.079
Lumped data	150	-0.196	0.191	0.091
Suspended sediment concentration (p80154) (milligrams per liter)				
State Route 2A	54	3.38	0.311	0.097
Interstate 90	54	3.35	0.320	0.042
State Route 20	55	3.19	0.466	0.022
Median of sites	54	3.35	0.32	0.042
Lumped data	163	3.30	0.372	0.009

alternative statistics produced extreme simulated values (table 18). Analysis by robust alternatives provides information about the effect of outliers on sample statistics and the probable exceedance risks of such outliers. In this study, the robust alternative statistics were within the 95-percent confidence intervals of the traditional statistics. If the medians of site statistics are used to simulate runoff quality for risk analyses or to estimate annual loads, then the traditional statistics will be suitable for such analyses.

Runoff-Quality Risk Analysis

In Massachusetts, the National Pollutant Discharge Elimination System permits for stormwater runoff currently (2017) specify required management measures rather than numeric discharge limits (Massachusetts Department of Environmental Protection, 2013). This approach reflects the fact that relatively small isolated BMPs cannot meet discharge standards developed for actively managed municipal wastewater treatment systems; however, stringent numerical discharge-quality standards have been proposed in other States (Granato and Jones, 2015). SELDM can be used to assess the risk of exceeding any proposed discharge-concentration standard with and without use of BMPs. In this example, numeric effluent criteria of 8 mg/L for TN and 1 mg/L for TP were selected as examples because these are published standards for discharges from wastewater treatment plants (WWTPs) using the best available technology (Massachusetts Department of Environmental Protection, 2013).

It should be noted that bridge-deck flows also are orders of magnitude smaller than WWTP flows. Many of the WWTPs subject to numerical standards commonly discharge more than 1 million gallons per day (Mgal/d). In this example bridge-runoff simulation, the average-annual discharge per acre of bridge deck was 115,497 cubic feet per year, which is equivalent to 0.0024 million gallons per day per acre during an entire year or about 0.037 million gallons per day per acre during the periods of runoff that only occur about 6.5 percent of the year on the basis of the input statistics used for this study. In comparison, about 2.6 acres of the State Route 2A bridge, the largest bridge in this study, is over water.

The risks for exceeding the example TN discharge criteria of 8 mg/L were substantial for the measured data and simulated long-term concentrations. The percentage of measured storm-event samples that exceeded 8 mg/L ranged from about 6.7 (Interstate 90 bridge) to 11 percent (State Route 20 bridge) with an average exceedance of about 8.4 percent of events (fig. 30*A*). Bridge-deck runoff event-mean concentrations simulated by using the median of the robust statistics exceeded the criteria in about 5 percent of events. The differences in exceedances for the data in comparison to the values simulated by using the robust median statistics may indicate that the simulated values were conservative or that the extreme values occurred in the sampled events. Event-mean concentrations in BMP discharges simulated by using the generic (median) BMP statistics (table 10) exceeded the criteria in about 1.6 percent of events. Therefore, neither the simulated runoff nor the simulated BMP discharge quality would meet a water-quality criterion of 8 mg/L if the commonly used recurrence interval of one event in 3 years is applied because the exceedance risk for one event in 3 years was about 0.58 percent in these simulations.

The risks for exceeding the example TP discharge criteria of 1 mg/L were even more substantial for the measured data and simulated long-term concentrations than for the TN values. The percentage of measured storm-event samples that exceeded 1 mg/L ranged from about 14 (Interstate 90 bridge) to 30 percent (State Route 20 bridge) with an average exceedance of about 25 percent of events (fig. 30*B*). Bridge-deck runoff event-mean concentrations simulated by using the median of traditional statistics exceeded the 1-mg/L criterion in about 28 percent of events. Event-mean concentrations

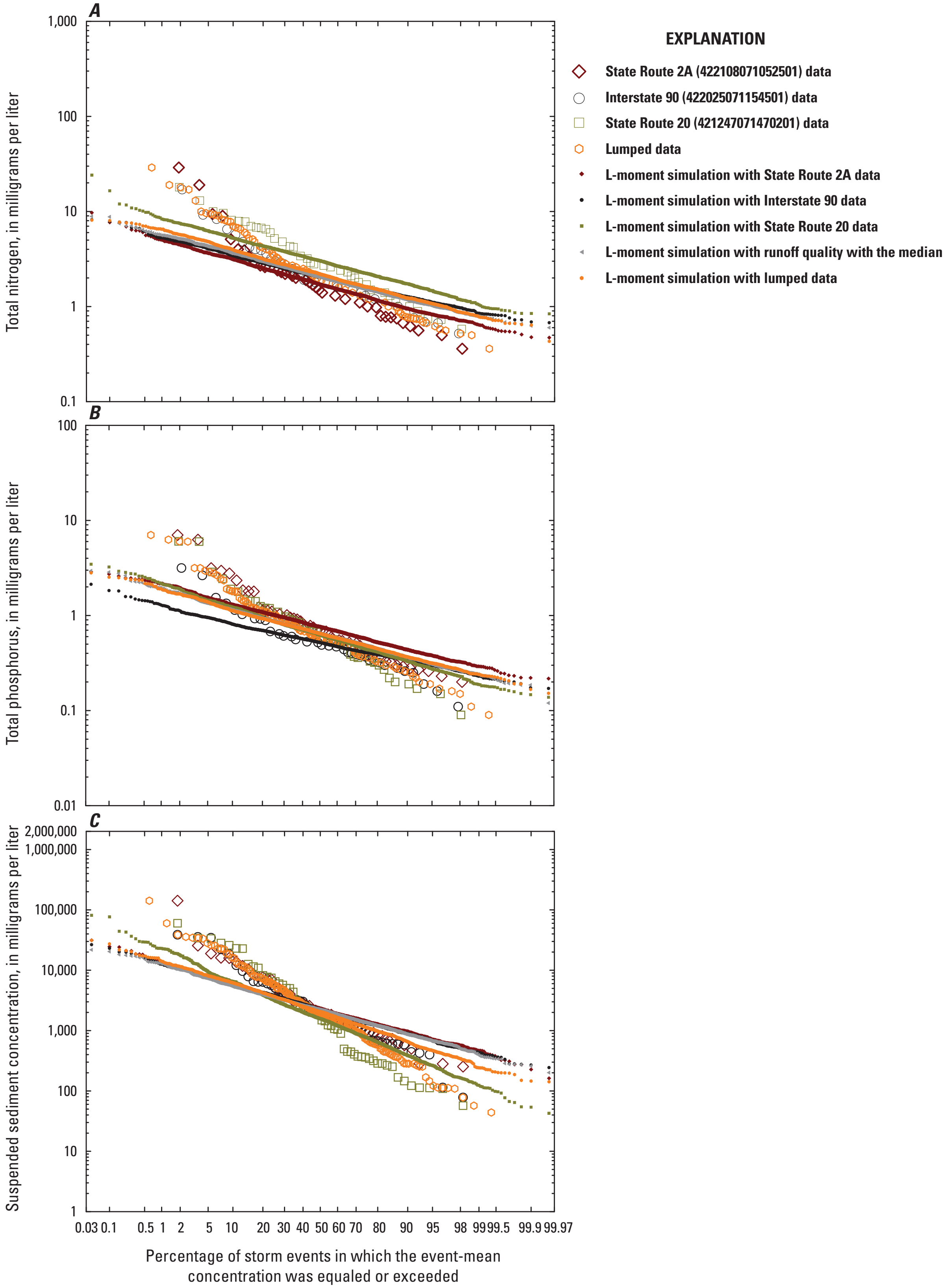


Figure 29. Concentrations simulated by using L-moments and measured *A*, total nitrogen; *B*, total phosphorus; and *C*, suspended sediment concentrations. The selected statistics are shown in table 19.

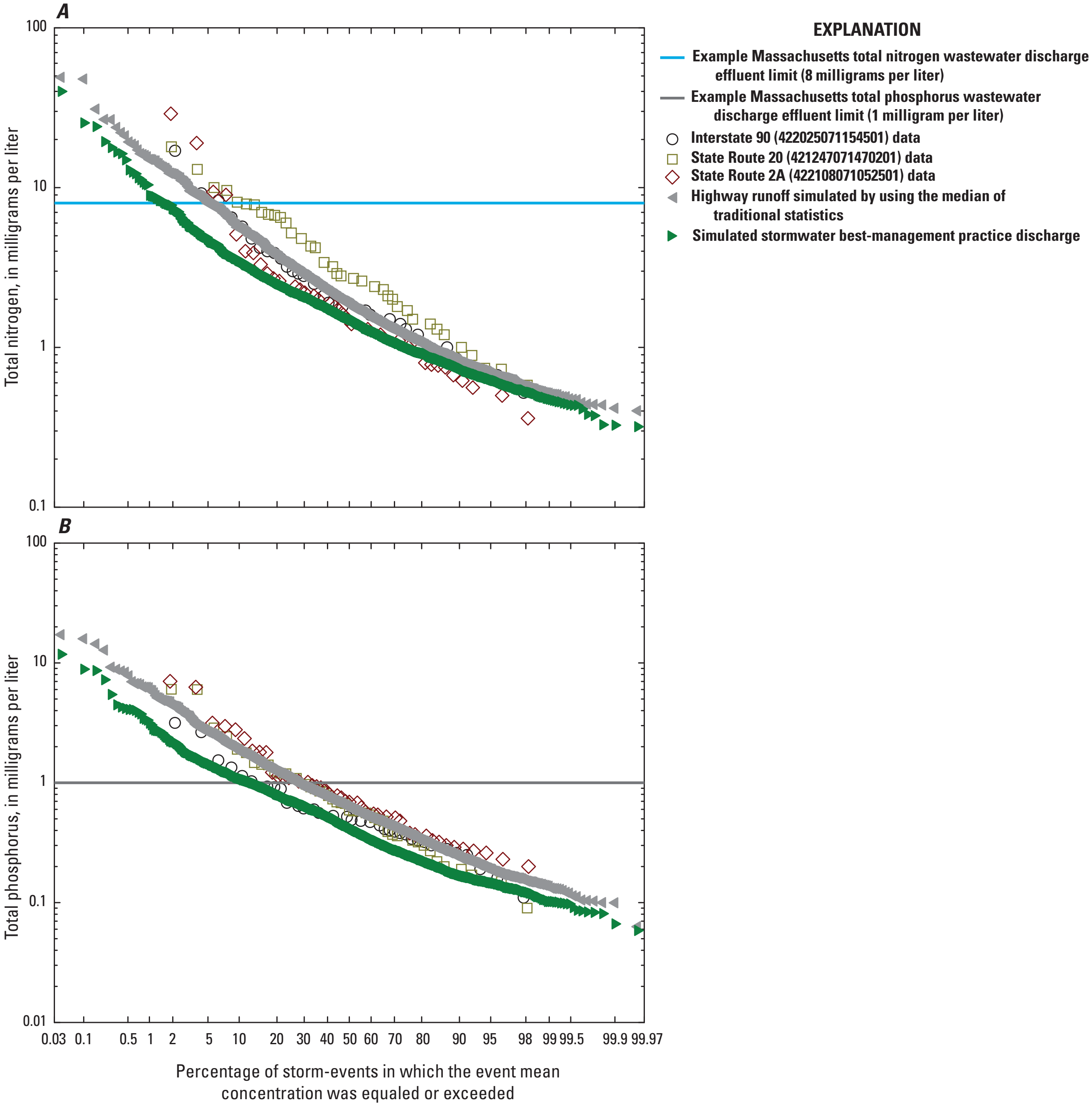


Figure 30. Probability plots of *A*, total nitrogen and *B*, total phosphorus, including measured concentrations, concentrations simulated with the median of robust statistics (table 18), and concentrations simulated by modifying the simulated highway runoff by using the generic best-management practice statistics (table 10).

in BMP discharges simulated by using the generic (median) BMP statistics (table 10) exceeded the 1-mg/L criterion in about 13 percent of events. These exceedances, therefore, did not meet the exceedance risk for one event in 3 years (about 0.58 percent).

In these simulations, the BMP reduced the percentage of concentration exceedances of both TN and TP by more than one-half. Better reductions in the concentration exceedances may be achieved if a specific BMP, designed for nutrient reduction, is used instead of the median of category medians as used in this example. However, this simulation indicates that the numeric WWTP standards for these nutrients may be unattainable, with or without a BMP, unless greater criterion concentrations or a larger exceedance risk is acceptable.

Runoff-Quality Annual Yield Analyses

Eleven simulations of 29–30 years were performed with the same hydrologic and concentration statistics and different random seeds to estimate yields of TN, TP, and SS. In these simulations, SELDM calculated an annual yield in pound per acre per year of pavement for each annual-load accounting year. Yields were simulated for runoff from 1 acre of pavement by using precipitation statistics for ecoregion 59 (the Northeastern Coastal Zone) and standard highway-runoff coefficient statistics (Granato, 2013). The medians of traditional statistics from the three sites (table 18) were used to model long-term constituent yields. Doing multiple simulations with the same hydrologic statistics accounts for stochastic variability in the combinations of concentrations, flows, and loads that could occur during a long period (Granato, 2013; Granato and Jones, 2014, 2017).

The populations of annual yields of TN, TP, and SS from the 11 simulations and the average and median of the values for each plotting position are shown in figure 31. To construct this graph, plotting-position results for the 30-year simulations were adjusted by using linear interpolation with the normal variate of each plotting position percentile to calculate yields that were equivalent to the 29-year simulation results. The results of individual simulations show a tight cluster around the median and mean except for the highest and lowest yields (fig. 31). The values of large concentration outliers do not matter for discharge exceedance analysis once they are already over the criterion concentration, but an extreme concentration outlier may have a substantial effect on the maximum annual

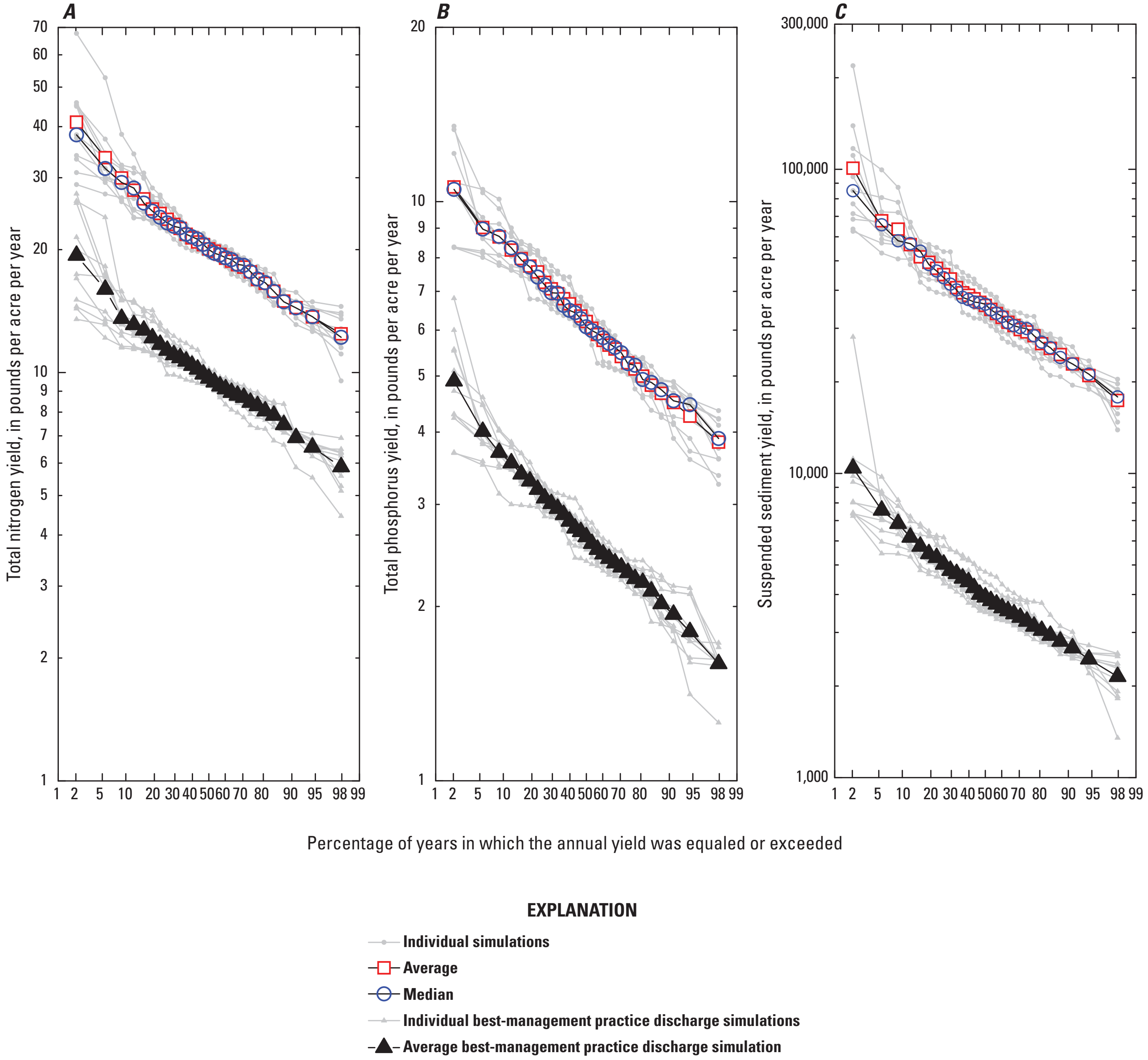


Figure 31. Yields of *A*, total nitrogen; *B*, total phosphorus; and *C*, suspended sediment in pounds per acre per year for each simulated year by percentile. The graph shows the individual, average, and median yields from 11 individual simulations.

yield. An extreme flow event (such as the rainfall volume that may be associated with an intense storm) also may contribute to a high annual yield.

The results of the analyses are shown as long-term average-annual runoff yields for each of the simulations (table 20). The long-term average-annual yield is the sum of the loads, per unit area, for the entire simulation period divided by the number of years in the simulation. The medians of the average-annual yields in the different simulations are presented in table 20 as the best estimator to account for stochastic variability from simulation to simulation. Results of simulations indicated that long-term average yields of TN, TP, and SS may be about 21.4, 6.44, and 40,600 pounds per acre per year, respectively. Granato and Jones (2017) did a similar annual yield analysis for different road classes by using concentration statistics from sites in Massachusetts from version 1.0.0a of the HRDB (Smith and Granato, 2010). They used the average of precipitation statistics from 11 National Weather Service stations in eastern Massachusetts and Rhode Island. The percent differences between the runoff-event precipitation statistics used by Granato and Jones (2017) and the precipitation statistics used in this study were about 0.85 for event volume, 5.2 for event duration, and 1.3 for the number of hours between event midpoints. The comparable yields of TN, TP, and SS in this current bridge-runoff study (table 20) were about 1.3, 3.4, and 16 times the ultra-urban highway yields simulated by Granato and Jones (2017), respectively. This comparison indicates that bridge-deck yields are not representative of yields from the entire road network in Massachusetts; however, bridge-deck yields may be a substantial portion of annual yields from highways in a watershed because the bridge-deck yields were much higher than yields for all the road classes simulated by Granato and Jones (2017). Furthermore, many bridges are over and discharge to receiving waters, whereas State roadways typically discharge to the local land surface.

Runoff Treatment Analyses

Runoff treatment was analyzed to examine the potential effects of flow reductions and concentration reductions by stormwater BMPs on annual yields from bridge-deck runoff. The SELDM BMP-treatment module has provisions for stochastic modeling of three stormwater treatments: volume reduction, hydrograph extension, and water-quality treatment (Granato, 2013, 2014). Hydrograph extension is an important variable for dilution analyses, but the duration of BMP discharges does not substantially affect the total-annual yields. For this analysis, a generic BMP was simulated by using the median of treatment statistics for flow reductions, concentration reductions, and MICs from seven BMP categories with data from the 2012 International BMP database (Geosyntec

Table 20. Simulated long-term average-annual bridge-deck runoff and stormwater control measure best-management practice discharge yields, in pounds per acre per year for total nitrogen, total phosphorus, and suspended sediment.

[The alpha-numeric identifiers starting with "p" are the U.S. Geological Survey parameter codes. run, stochastic empirical loading and dilution model run number and median of values from the eleven runs; seed, Monte Carlo random seed; years, annual-load accounting years; N, nitrogen; lb/ac/yr, pound per acre per year; runoff, bridge-deck runoff; BMP discharge, stormwater control measure best-management practice discharge; P, phosphorus; NA, not applicable]

Run	Seed	Years	Total nitrogen as N (p00600), in lb/ac/yr		Total phosphorus (p00665) as P, in lb/ac/yr		Suspended sediment (p80154), in lb/ac/yr	
			Runoff	BMP discharge	Runoff	BMP discharge	Runoff	BMP discharge
1	11,093	30	21.4	10.6	6.44	2.88	36,900	3,980
2	856	29	22.4	10.9	6.29	2.77	41,400	4,470
3	2,519	29	21.5	10.3	6.46	2.89	38,000	4,270
4	3,366	29	20.4	9.72	6.30	2.70	40,700	5,100
5	3,418	29	23.7	11.1	6.77	2.76	40,600	4,790
6	6,996	30	21.7	10.7	6.04	2.63	41,100	4,360
7	10,482	30	20.5	9.47	6.60	2.80	35,400	4,120
8	8,418	29	20.7	9.63	6.56	2.77	41,000	4,260
9	4,370	29	20.8	9.84	6.51	2.84	34,700	3,860
10	5,240	29	20.3	10.0	6.23	2.56	45,400	4,890
11	7,022	29	21.4	10.1	6.12	2.62	38,000	4,070
Median	NA	NA	21.4	10.1	6.44	2.77	40,600	4,270

Consultants and Wright Water Engineers, 2016) (table 10); BMP yields for TN, TP, and SS from bridge-deck runoff are shown in table 20.

The results of the yield analyses of TN, TP, and SS for bridge-deck runoff are shown in figure 31. The reduction in annual yields at each percentile represents the effects of flow and concentration reduction. Although average-annual yields with and without the BMP treatments are shown, these values represent results of stochastic simulations for each runoff event, not application of average performance statistics for the entire simulation period (Granato, 2013, 2014). Individually, flow reduction and concentration reduction have a substantial effect on the annual yields of TP in these simulations; however, the BMPs can produce excess flows and concentrations in some storms, which can reduce or eliminate the combined effectiveness for those storms. For example, if concentrations are reduced in a given storm but the discharge flow is larger than the runoff inflow, then the total BMP discharge load may be greater than or equal to the runoff load for a particular storm event. Increases in flow can be caused by carryover from previous storms and (or) groundwater discharge to the BMP (especially for wet BMPs). Resuspension of previously deposited constituents can cause increases in discharge concentrations. Results for this runoff-treatment analysis indicated that use of a BMP to treat bridge-deck runoff may reduce TN, TP, and SS discharge yields to about 10, 2.8, and 4,300 pounds per acre per year, respectively. In these simulations, the median BMP with performance statistics shown in table 10 attenuates long-term average-annual bridge-deck runoff yields by about 52 percent for TN, 57 percent for TP, and 89 percent for SS (table 20).

Summary

The U.S. Geological Survey (USGS) conducted a field study between 2014 through 2016 to document the quality of bridge-deck runoff from three bridges maintained by the Massachusetts Department of Transportation (MassDOT) in eastern Massachusetts. Bridge sites monitored in this study include State Route 2A (Massachusetts Avenue Bridge) in the city of Boston, Interstate 90 in the town of Weston, and State Route 20 near Quinsigamond Village in the city of Worcester. The annual average daily traffic volumes for these bridges ranged from 21,200 to 124,000 vehicles per day. The land use surrounding each bridge was primarily developed land (43 to 78.8 percent) with accompanying high impervious area (25 to 67 percent).

At each bridge, a monitoring system was installed to collect continuous measurements of water level and rainfall (rainfall measurements were not available at the State Route 2A bridge location, but estimated from data collected at a nearby USGS streamgage) and to collect composite samples of bridge-deck runoff. Bridge-deck runoff was diverted from a scupper outlet at each bridge to a shelter containing an H flume where flow was measured. Composite samples of bridge-deck runoff were collected on a flow-proportional basis by an automatic sampler for more than 50 runoff events at each bridge-deck-monitoring station and analyzed for concentrations of suspended sediment (SS), SS particle size, total phosphorus (TP), dissolved nitrogen (DN), particulate nitrogen (PN), loss on ignition of suspended solids (LOI), and particulate carbon (PC). Samples of runoff were collected year round and during events that were characteristic of the range of antecedent dry periods and event rain totals that existed throughout the study period (August 2014 through August 2016). Samples of bridge-deck sediment also were collected three times during the study period to characterize the distribution of sediment across each bridge deck. A composite sample of sediment from each bridge was analyzed for concentrations of TP and 10 total-recoverable metals in three particle-size ranges.

Quality-assurance data were collected at each monitoring station to ensure the accuracy of the flow and constituent data. Redundant measurements of water level were collected at each monitoring station, runoff coefficients were calculated to help identify sensor error and stormflow alterations, and the theoretical level-flow relation of each flume was tested at each bridge. Field blank and replicate-split samples were collected to identify potential bias in processing methods and contamination resulting from the sampling equipment and the sample-collection, processing, and analysis process. During the study period, 10 field blanks and 33 concurrent replicate-split samples of bridge-deck composite samples were collected and submitted for chemical and sediment analysis. Concentrations of SS in field blanks were slightly greater than the laboratory reporting limit in 7 of 10 field blank samples. Concentrations of LOI, PC, particulate organic carbon (POC), and DN were detected less often in field blanks than concentrations of SS, but in general, contamination bias was low for all constituents. The range of concentrations for each constituent in concurrent replicate-split samples was similar to the range of constituent concentrations measured in composite samples collected during the study. The median relative percent difference (RPD) for concentrations of SS and particle-associated constituents ranged from 10 to 25 percent, except for particulate inorganic carbon (PIC), which was 65 percent, and the median RPD for DN was less than 2 percent. The RPD for replicate-split samples of bridge-deck sediment for TP and total-recoverable metals generally was less than 12 percent in the fine-sediment fraction and ranged from 0 to 64 percent for most metals in the coarser sediment fractions. These differences in the replicate-split samples represent a measure of the variability associated with sample processing and analytical methods. The RPDs associated with the composite samples of runoff are relatively high but not unusual for water samples containing high concentrations of sand-size particles.

Concentrations of SS, SS particle size, nutrients, LOI, and PC were measured in more than 160 flow-weighted composite samples of runoff collected from the three bridge-deck-monitoring stations. Concentrations of SS in composite samples of bridge-deck runoff from the three bridge-deck-monitoring stations ranged from 44 to 142,000 milligrams per liter (mg/L); however, median concentrations of SS per site ranged from 1,490 to 2,020 mg/L. Concentrations of LOI and PC in composite samples of runoff ranged from 15 to 1,740 mg/L and 6.68 to 1,360 mg/L, respectively, and generally represented less than 10 and 3 percent of the median mass of SS, respectively. Concentrations of PC were primarily represented by the particulate organic carbon (POC) fraction. Concentrations of TP and total nitrogen (TN) (sum of DN and PN) in composite samples of runoff ranged from 0.09 to 7.02 mg/L and 0.36 to 29.0 mg/L, respectively. Median concentrations of TP ranged from 0.505 to 0.690 mg/L and were highest on the bridge on State Route 2A in Boston. Median DN concentrations ranged from 0.64 to 0.90 mg/L and generally represented about 40 percent of the TN concentration at each bridge. Median concentrations of DN were similar to annual precipitation-weighted mean concentrations of nitrogen (ammonia plus nitrate) reported in Massachusetts.

Results for one-way analysis of variance and post hoc Tukey pairwise comparison tests performed on the rank-transformed data for each bridge indicated that concentrations of SS, LOI, PC, and TP were not significantly different from bridge to bridge. The mean of the rank-transformed data for TN collected on State Route 20 was significantly higher than the means of the rank-transformed data for the other bridges. Test results for the fractional portion of TN for bridge pairs State Route 2A and Interstate 90, and Interstate 90 and State Route 20 were not statistically different; however, test results for the bridge pair State Route 2A and State Route 20 were significant and indicated that the fractional portions of TN were both significantly higher at the State Route 20 bridge compared to State Route 2A. Median concentrations of TN were about 93 percent lower at State Route 2A in Boston compared to the median concentrations of TN at State Route 20 near Quinsigamond Village.

Samples of sediment were collected from five fixed locations (equally spaced) on three occasions during dry weather on each bridge road surface between April 2015 and September 2016 to assess the distribution of sediment yields on the bridge surface in respect to the scupper inlet location where samples of runoff were collected. Samples of bridge-deck sediment were collected with portable vacuums in the travel lane of the instrument scupper on each bridge, the sediment was dried to a constant weight, and yields were estimated on the basis of the sediment mass and curb distance sampled. Yields of bridge-deck sediment for each of the five sampling locations ranged from 26 to 25,000 pounds per curb-mile (lbs/curb-mi) and were similar to yields reported elsewhere in Massachusetts and the United States.

Yields of bridge-deck sediment, normalized to the yield measured proximate to the monitoring station at each bridge, indicated that sediment on each bridge surface was not uniform. On State Route 2A, the mean yield of bridge-deck sediment measured proximate to the monitoring station (680 lbs/curb-mi) on the east end of the bridge near Boston was about 55 percent lower than the mean yield of sediment for the entire eastward bridge-deck span, which might be explained by depositional decay of vehicle tracking through the fixed sampling locations as the yield distribution decreased with flow of traffic. Normalized bridge-deck sediment yields for Interstate 90 near Weston indicated that the sediment mass increased from east to west. The mean yield of bridge-deck sediment for Interstate 90 measured proximate to the monitoring station (240 lbs/curb-mi) on the west end of the bridge was similar to the mean yield of sediment for the entire westward bridge-deck span. The distribution of the sediment mass across this bridge was likely related to the contribution of solids from the deterioration of the bridge-deck surface, median barrier, and shoulder area; these solids migrate westward with the bridge-deck slope and flow of traffic. Normalized bridge-deck sediment yields for Route 20 near Quinsigamond Village indicated that the sediment mass decreased from east to west. The mean yield of bridge-deck sediment proximate to the monitoring station on State Route 20 (7,200 lbs/curb-mi) was about 26 percent higher than the mean yield of sediment for the entire westward bridge-deck. The distribution of the sediment mass across this relatively new bridge likely resulted from sediments that washed onto the bridge from the eastern roadway uphill of the bridge. Although these data only represent a semiquantitative assessment of the sediment distribution, visual observations throughout the study period support the findings.

A composite sample of bridge-deck sediment from each bridge was sieved into fine, intermediate, and coarse size fractions (less than 0.0625 millimeter, greater than or equal to 0.0625 to 0.25 millimeter, and greater than or equal to 0.25 millimeter in diameter, respectively), and analyzed for concentrations of TP and 10 total-recoverable metals. These analyses indicated that bridge-deck sediment contained high concentrations of phosphorus and various metals. In particular, the two fine sediment fractions typically had higher concentrations than the coarse sediment fraction. Concentrations of TP in the fine fraction were about 6 times greater than in the coarse fraction. Total-recoverable concentrations of aluminum (Al), manganese (Mn), and nickel (Ni) were about two times greater in the fine fraction; total-recoverable concentrations for arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), and zinc (Zn) were about 2 to 17 times greater in the fine sediment fraction; and total-recoverable concentrations of lead (Pb) were about 8 to 65 times greater in the fine sediment fraction compared to the concentration in the coarse sediment fraction. The only total-recoverable metal not detected in the coarse fraction of any of the bridge-deck sediment samples was copper (Cu), but concentrations in the fine fraction were 13 to 47 times more concentrated than concentrations in the intermediate sediment fraction.

The distribution of the sediment in the three size fractions and the relation of TP and total-recoverable metals to each sediment-size fraction indicated that for a given mass of sediment, about 54 percent of the estimated TP is associated with the intermediate and coarse sediment mass. The cumulative proportion of the mass of As, Ba, Cd, Cu, Pb, and Zn in the intermediate and coarse sediment fraction was less than 56 percent for a given mass of sediment. Only about 5 percent of the sediment-associated Cu was associated with the intermediate sediment fraction. In contrast, as much as 66 to 84 percent of Al, Cr, Mn, and Ni was associated with the intermediate and coarse fractions of bridge-deck sediment.

Results for Mann-Whitney tests indicated that concentrations of SS in composite samples of bridge-deck runoff for this study were significantly larger (*p*-values less than 0.001) than in composite samples of highway runoff collected on State Route 2, Interstate 190, Interstate 495, Interstate 95, and Interstate 93 in eastern Massachusetts during a 2005–7 study using similar sampling methods. Highway-runoff samples were collected at the outlet of catch basins, whereby some pretreatment by the catch basin results in a reduction of SS concentrations; therefore, the difference between the two datasets, in part, is likely explained by the lack of any SS reduction by the bridge scuppers. Other factors such as the high bridge walls, concrete barriers in the bridge median, deterioration of bridge components, and bridge wash-on also may have contributed to higher concentrations of SS in samples of bridge-deck runoff. Concentrations of TP and TN in samples of bridge-deck runoff in this study were significantly higher than in samples collected from the selected highway-monitoring stations in eastern Massachusetts during 2005–7. Both of these nutrients were determined to be closely associated with bridge-deck sediment and SS; therefore, the higher concentrations of TP and TN in bridge-deck runoff may be explained by the significantly higher concentrations of SS measured in composite samples of bridge-deck runoff.

Comparisons between bridge-deck sediment quality in this study and highway sediment quality collected in 2005–7 indicated that bridge-deck sediment was less enriched in phosphorus. Concentrations of phosphorus in highway sediment were 3 to 5 times greater in the fine fraction and 6 to 40 times greater in the intermediate and coarse fractions compared to concentrations in the same fractions of bridge-deck sediment. Except for concentrations of Cr and Cu, concentrations of total-recoverable metals in the fine fraction of bridge-deck sediment were similar (within 50 percent) to the concentration in the same fraction of highway sediment. Concentrations of Cr were 5 to 17 times greater in the intermediate and coarse fraction of highway sediment and Cu was as much as 49 times greater in the intermediate fraction of highway sediment in comparison to concentrations in the same respective size fractions in bridge sediment samples.

The particle-size distribution and association of each constituent to each sediment-size fraction affects the overall constituent concentration associated with the mass of SS. Bridge-deck sediment as a whole was less enriched chemically compared to highway sediment because it was dominated by the chemically dilute coarse sediment fraction.

Version 1.0.2 of the Stochastic Empirical Loading and Dilution Model (SELDM) was used to simulate concentrations and annual yields of SS, TN, and TP in bridge-deck runoff and in discharges from a hypothetical stormwater treatment best-management practice (BMP) structure. Simulations were performed for a 1-acre portion of a bridge deck by using precipitation statistics for ecoregion 59 (the Northeastern Coastal Zone) and by using the standard SELDM runoff-coefficient statistics. The flow and concentration performance of the BMP was simulated by using the median of statistics from nine BMP categories in the 2012 version of the International BMP database.

High variability in measured concentrations during this study resulted in extreme simulated concentrations when the available data were used to simulate a long-term (29–30-year) record; therefore, three methods were used to calculate statistics for stochastic simulations. The first method was to use the average, standard deviation (SD), and skew calculated by using standard equations. The second method was to use the average and SD calculated by using robust regression on order statistics with the Kendall-Theil Robust Line. The robust skew was calculated by using Pearson's second skew with the robust average and SD values. The third method was to use the average, SD, and skew calculated by using the L-moments methods. These methods were used to calculate statistics for each of the three bridges and for a lumped dataset. The medians of these statistics also were calculated. These median statistics were selected for the interpretive simulations so that the simulations could be used to estimate concentrations and yields from other, unmonitored bridges in Massachusetts. Comparisons of the standard and robust statistics indicated that simulation results with either method would be similar, which indicated that the large variability in simulated results was not caused by a few outliers. Comparison to simulations performed using statistics calculated by the L-moments methods indicated that L-moments do not produce extreme concentrations, but they do not produce results that represent the bulk of concentration data.

Runoff-quality risk was analyzed to show how SELDM can be used to evaluate runoff-quality management alternatives. These simulations were done with concentration-criteria discharge standards commonly used for large, advanced wastewater treatment plants. Effluent criteria of 8 mg/L for TN and 1 mg/L for TP were selected as hypothetical criteria but not as suggested targets for small stormwater discharges. The risk analysis indicated that TN in bridge-deck runoff may exceed the selected TN criterion in about 5 percent of events. This simulated risk was similar to the exceedance risk estimated from measured data at the bridge sites. In comparison, simulated BMP discharge concentrations exceeded the selected TN criteria in about 1.6 percent of events. The risk analysis indicated that TP in bridge-deck runoff may exceed the selected TP criterion in about 28 percent of events, which was similar to the exceedance risk estimated from measured data at the bridge sites. In comparison, simulated BMP discharge concentrations exceeded the selected TN criteria in about 13 percent of events.

Eleven simulations of 29–30 years were performed with the same hydrologic and concentration statistics and different random seeds to estimate yields of TN, TP, and SS. Results of simulations indicated that long-term average yields of TN, TP, and SS may be about 21.4, 6.44, and 40,600 pounds per acre per year, respectively. The long-term average-annual yield is the sum of the loads, per unit area, for the entire simulation period divided by the number of years in the simulation. The TN, TP, and SS yields were about 1.3, 3.4, and 16 times the simulated ultra-urban highway yields in Massachusetts. This comparison indicated that bridge-deck yields were not representative of yields from the entire road network in Massachusetts; however, bridge-deck yields may be a substantial portion of annual loads from highways in a watershed. Furthermore, many bridges are over and discharge to receiving waters, whereas a high proportion of State roadway miles discharge to the local land surface.

Runoff treatment was analyzed to examine the potential effects of flow reductions and concentration reductions by stormwater BMPs on annual yields from bridge-deck runoff. For this analysis, a generic BMP was simulated by using the median of treatment statistics for flow reductions, concentration reductions, and minimum irreducible concentration from seven BMP categories with data from the 2012 International BMP database. This analysis indicated that use of a BMP to treat bridge-deck runoff may reduce TN, TP, and SS discharge yields to about 10, 2.8, and 4,300 pounds per acre per year, respectively. These changes represent long-term average reductions of about 52 percent for TN, 57 percent for TP, and 89 percent for SS. These results are based on the stochastic performance of a generic BMP, and better results may be possible with a better-performing BMP design.

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Table 7. Quality-control samples collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.

[Locations of stations are shown in figure 1. Time is hours and minutes in military time format with leading zeroes omitted. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. USGS, U.S. Geological Survey; yyyy, year; mm, month; dd, day; Composite, composite runoff sample; Replicate, concurrent replicate-split sample; <, less than laboratory reporting limit; NA, not available; RPD, absolute relative percent difference between environmental and replicate sample values]

USGS station number	Begin date (yyyymmdd)	Begin time	End date (yyyymmdd)	End time	Sample type	Concentration (milligrams per liter)							
						Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate inorganic carbon (p00688)	Particulate organic carbon (p00689)	Total phosphorus (p00665)	Particulate nitrogen (p49570)	Total dissolved nitrogen (p62854)	Suspended sediment concentration (p80154)
421247071470201	20140829	1400	NA	NA	Field blank	1	0.76	NA	NA	<0.01	<0.030	<0.05	1
422108071052501	20140903	1200	NA	NA	Field blank	<0.5	<0.05	NA	NA	<0.01	<0.030	0.07	1
422108071052501	20150317	1200	NA	NA	Field blank	<0.5	<0.05	<0.03	<0.05	<0.01	<0.030	<0.05	<0.5
421247071470201	20150327	1200	NA	NA	Field blank	1	0.11	<0.03	0.11	<0.01	<0.030	<0.05	1
421247071470201	20150611	1400	NA	NA	Field blank	1	0.06	<0.03	0.06	<0.01	<0.030	<0.05	1
421247071470201	20150903	1100	NA	NA	Field blank	NA	<0.05	<0.03	<0.05	<0.01	<0.030	<0.05	1
421247071470201	20151209	1330	NA	NA	Field blank	<0.5	<0.05	<0.03	<0.05	<0.01	<0.030	<0.05	1
422108071052501	20160303	1330	NA	NA	Field blank	NA	<0.05	<0.03	<0.05	<0.01	<0.030	<0.05	<0.5
422025071154501	20160614	1430	NA	NA	Field blank	NA	0.1	<0.03	<0.10	<0.01	<0.030	<0.05	<0.5
422025071154501	20160817	1430	NA	NA	Field blank	2	<0.05	<0.03	<0.05	<0.01	<0.030	<0.05	2
421247071470201	20141016	43	20141016	1400	Composite	99	58.7	0.37	58.4	0.55	2.9	0.94	977
421247071470201	20141016	42	20141016	1400	Replicate	144	41	0.55	40.4	0.56	1.89	0.94	1,040
RPD (percent)						37	35.5	39.1	36.4	1.8	42	0.00	6.2
421247071470201	20141101	1133	20141101	2126	Composite	25	17.5	0.25	17.3	0.18	0.448	0.52	308
421247071470201	20141101	1132	20141101	2126	Replicate	29	9.15	0.41	8.75	0.17	0.212	0.53	342
RPD (percent)						15	63	48	66	5.7	72	1.9	10

Table 7. Quality-control samples collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.—Continued

[Locations of stations are shown in figure 1. Time is hours and minutes in military time format with leading zeroes omitted. The alpha-numeric identifiers starting with “p” are the U.S. Geological Survey parameter codes. USGS, U.S. Geological Survey; yyyy, year; mm, month; dd, day; Composite, composite runoff sample; Replicate, concurrent replicate-split sample; <, less than laboratory reporting limit; NA, not available; RPD, absolute relative percent difference between environmental and replicate sample values]

USGS station number	Begin date (yyyymmdd)	Begin time	End date (yyyymmdd)	End time	Sample type	Concentration (milligrams per liter)							
						Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate inorganic carbon (p00688)	Particulate organic carbon (p00689)	Total phosphorus (p00665)	Particulate nitrogen (p49570)	Total dissolved nitrogen (p62854)	Suspended sediment concentration (p80154)
421247071470201	20141126	951	20141128	1854	Composite	147	69.2	0.94	68.2	0.52	2.35	0.73	3,480
421247071470201	20141126	950	20141128	1854	Replicate	144	57.9	0.27	57.6	0.58	2.14	0.74	2,610
RPD (percent)						2.1	18	111	17	10.9	9.4	1.4	29
421247071470201	20150403	2356	20150404	629	Composite	470	297	20.3	277	1.26	5.25	1.83	35,700
421247071470201	20150403	2355	20150404	629	Replicate	745	287	174	113	2.43	5.15	1.85	60,000
RPD (percent)						45	3.4	158	84	63	1.9	1.1	51
421247071470201	20150408	1601	20150409	624	Composite	34	30	0.1	29.9	0.19	0.956	0.86	122
421247071470201	20150408	1600	20150409	624	Replicate	31	16.1	<0.03	16.1	0.19	0.407	0.85	122
RPD (percent)						9.2	60	NA	60	0.00	81	1.2	0.00
421247071470201	20150609	1745	20150610	117	Composite	161	63.6	0.91	62.7	1.43	2.11	1.08	6,390
421247071470201	20150609	1744	20150610	117	Replicate	205	54.9	6.18	48.8	1.47	1.55	1.1	7,750
RPD (percent)						24	15	149	25	2.8	31	1.8	19
421247071470201	20150615	504	20150615	1638	Composite	163	64.7	1.79	63	1.73	2.18	0.74	6,720
421247071470201	20150615	503	20150615	1638	Replicate	170	53.7	3.21	50.5	1.41	1.92	0.74	6,510
RPD (percent)						4.2	19	57	22	20	13	0.00	3.2
421247071470201	20150621	10	20150621	1233	Composite	76	46.8	2.22	44.6	0.56	1.85	0.56	1,140
421247071470201	20150621	9	20150621	1233	Replicate	72	46.7	0.36	46.4	0.54	1.45	0.57	1,070
RPD (percent)						5.4	0.21	144	4.00	3.6	24	1.8	6.3
421247071470201	20150910	1540	20150911	626	Composite	409	209	14.2	194	1.7	4.41	0.73	10,700
421247071470201	20150910	1539	20150911	626	Replicate	376	237	27.3	209	2.87	12.1	0.74	10,900
RPD (percent)						8.4	13	63	7.4	51	93	1.4	1.9

Table 7. Quality-control samples collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.—Continued

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USGS station number	Begin date (yyyym-mdd)	Begin time	End date (yyyym-mdd)	End time	Sample type	Concentration (milligrams per liter)							
						Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate inorganic carbon (p00688)	Particulate organic carbon (p00689)	Total phosphorus (p00665)	Particulate nitrogen (p49570)	Total dissolved nitrogen (p62854)	Suspended sediment concentration (p80154)
422025071154501	20141126	953	20141126	2237	Composite	93	54.4	0.26	54.1	0.46	1.33	0.61	1,240
422025071154501	20141126	952	20141126	2237	Replicate	99	36	0.33	35.7	0.41	0.747	0.58	1,320
RPD (percent)						6.3	41	24	41	11	56	5.0	6.3
422025071154501	20150103	2123	20150104	2220	Composite	59	16.5	1.06	15.5	0.38	0.451	0.71	1,300
422025071154501	20150103	2122	20150104	2220	Replicate	67	44.9	0.07	44.9	0.34	0.522	0.69	1,220
RPD (percent)						13	93	175	97	11	15	2.9	6.3
422025071154501	20150404	536	20150404	623	Composite	190	80.5	37.3	43.2	3	1.6	0.79	5,240
422025071154501	20150404	535	20150404	623	Replicate	196	112	4.66	107	2.64	2.14	0.78	4,730
RPD (percent)						3.10	33	156	85	13	29	1.3	10
422025071154501	20150420	1245	20150421	523	Composite	175	54.2	1.94	52.3	1.55	1.16	0.52	6,660
422025071154501	20150420	1244	20150421	523	Replicate	170	80.5	5.47	75	0.92	3.65	0.52	6,020
RPD (percent)						2.9	39	95	36	51	104	0.00	10
422025071154501	20150531	407	20150602	809	Composite	113	50.1	2.43	47.7	0.27	1.21	0.72	4,020
422025071154501	20150531	406	20150602	809	Replicate	78	57.6	4.66	53	0.26	1.39	0.73	3,810
RPD (percent)						37	14	63	11	3.8	14	1.40	5.4
422025071154501	20150609	1911	20150609	1935	Composite	86	39.3	0.38	39	0.57	1.15	1.32	1,110
422025071154501	20150609	1910	20150609	1935	Replicate	107	42.1	12	30.1	0.61	1.19	1.34	1,340
RPD (percent)						22	6.9	188	26	6.8	3.4	1.5	19

Table 7. Quality-control samples collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.—Continued

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USGS station number	Begin date (yyyymmdd)	Begin time	End date (yyyymmdd)	End time	Sample type	Concentration (milligrams per liter)							
						Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate inorganic carbon (p00688)	Particulate organic carbon (p00689)	Total phosphorus (p00665)	Particulate nitrogen (p49570)	Total dissolved nitrogen (p62854)	Suspended sediment concentration (p80154)
422025071154501	20150621	51	20150621	1327	Composite	68	7.74	0.03	7.71	0.45	0.289	0.47	1,680
422025071154501	20150621	50	20150621	1327	Replicate	68	9.68	0.86	8.83	0.52	0.417	0.44	1,840
RPD (percent)						0.00	22	187	14	14	36	6.6	9.1
422025071154501	20150710	6	20150710	300	Composite	25	9.55	0.06	9.49	0.24	0.315	0.29	481
422025071154501	20150710	5	20150710	300	Replicate	37	10.1	<0.03	10.1	0.19	0.241	0.28	601
RPD (percent)						39	5.6	NA	6.2	23	27	3.5	22
422025071154501	20150804	1601	20150804	1623	Composite	65	25	0.22	24.8	0.4	0.761	0.82	615
422025071154501	20150804	1600	20150804	1623	Replicate	75	35.1	0.24	34.8	0.53	0.921	0.79	684
RPD (percent)						14	34	8.7	34	28	19	3.7	11
422025071154501	20150811	1013	20150811	1257	Composite	241	140	14.8	125	2.1	3.85	0.54	5,970
422025071154501	20150811	1012	20150811	1257	Replicate	334	119	9.43	110	1.34	2.42	0.56	7,870
RPD (percent)						32	16	44	13	44	46	3.6	27
422025071154501	20150930	200	20150930	1509	Composite	34	30.2	0.24	29.9	0.32	1.26	0.32	588
422025071154501	20150930	201	20150930	1509	Replicate	38	16	0.33	15.6	0.28	0.907	0.32	613
RPD (percent)						11	61	32	63	13	33	0.00	4.2
422108071052501	20141106	1117	20141106	2017	Composite	107	54.3	0.66	53.6	1.02	1.31	1.1	4,050
422108071052501	20141106	1116	20141106	2017	Replicate	131	44.3	0.98	43.3	2.96	1.05	1.11	4,230
RPD (percent)						20	20	39	21	97	22	0.90	4.3

Table 7. Quality-control samples collected at U.S. Geological Survey bridge-deck-monitoring stations on State Route 2A in Boston (422108071052501), Interstate 90 near Weston (422025071154501), and State Route 20 near Quinsigamond Village (421247071470201) in eastern Massachusetts, 2014–16.—Continued

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USGS station number	Begin date (yyyym-mdd)	Begin time	End date (yyyym-mdd)	End time	Sample type	Concentration (milligrams per liter)							
						Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate inorganic carbon (p00688)	Particulate organic carbon (p00689)	Total phosphorus (p00665)	Particulate nitrogen (p49570)	Total dissolved nitrogen (p62854)	Suspended sediment concentration (p80154)
422108071052501	20141117	409	20141117	1841	Composite	76	50.8	0.13	50.6	0.53	1.15	0.4	2,310
422108071052501	20141117	408	20141117	1841	Replicate	75	45.2	0.13	45.1	0.8	0.979	0.37	1,910
RPD (percent)						1.3	12	0.00	11	41	16	7.8	19
422108071052501	20141126	1051	20141126	1529	Composite	58	19.6	0.33	19.3	0.36	0.392	0.39	1,570
422108071052501	20141126	1050	20141126	1529	Replicate	54	13.4	0.14	13.2	0.37	0.337	0.41	1,470
RPD (percent)						7.1	38	81	38	2.7	15	5.0	6.6
422108071052501	20141224	1436	20141224	1838	Composite	172	66.1	1.49	64.7	0.62	1.39	0.5	1,650
422108071052501	20141224	1435	20141224	1838	Replicate	158	74.6	0.63	74	0.69	1.57	0.47	1,230
RPD (percent)						8.5	12	81	13	11	12	6.2	29
422108071052501	20150103	2356	20150104	327	Composite	86	34.8	4.33	30.5	1.67	0.68	0.35	6,790
422108071052501	20150103	2355	20150104	327	Replicate	93	28.3	1.26	27	1.12	0.826	0.35	7,750
RPD (percent)						7.8	21	110	12	39	19	0.00	13
422108071052501	20150326	1448	20150327	712	Composite	119	93	0.49	92.5	1.02	1.81	NA	1,010
422108071052501	20150326	1443	20150327	712	Replicate	141	71.4	0.86	70.5	1.01	1.64	NA	1,850
RPD (percent)						17	26	55	27	0.99	9.9	NA	59
422108071052501	20150408	1726	20150409	120	Composite	306	61.9	5.24	56.7	5.31	1.38	0.46	28,300
422108071052501	20150408	1725	20150409	120	Replicate	267	63.7	3.03	60.6	6.28	1.23	0.48	25,600
RPD (percent)						14	2.9	53	6.6	17	11	4.3	10

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USGS station number	Begin date (yyyym-mdd)	Begin time	End date (yyyym-mdd)	End time	Sample type	Concentration (milligrams per liter)							
						Loss on ignition of suspended solids (p00535)	Particulate carbon [inorganic plus organic] (p00694)	Particulate inorganic carbon (p00688)	Particulate organic carbon (p00689)	Total phosphorus (p00665)	Particulate nitrogen (p49570)	Total dissolved nitrogen (p62854)	Suspended sediment concentration (p80154)
422108071052501	20150531	1544	20150602	729	Composite	40	30.7	0.3	30.4	0.56	0.809	0.36	1,570
422108071052501	20150531	1543	20150602	729	Replicate	49	23	0.15	22.8	0.57	0.646	0.37	1,830
RPD (percent)						20	29	67	29	1.8	22	2.7	15
422108071052501	20150615	619	20150615	1542	Composite	1,110	1,490	87.6	1,410	0.21	39.2	2.23	89,500
422108071052501	20150615	618	20150615	1542	Replicate	1,740	1,360	255	1,100	0.62	26.7	2.19	142,000
RPD (percent)						44	9.1	98	25	99	38	1.8	45
422108071052501	20150621	107	20150621	1304	Composite	33	11.7	0.1	11.6	0.42	0.495	0.41	1,290
422108071052501	20150621	106	20150621	1304	Replicate	34	18	<0.03	18	0.48	0.266	0.4	1,260
RPD (percent)						3.0	42	NA	43	13	60	2.5	2.4
422108071052501	20150710	19	20150710	258	Composite	31	15.7	<0.03	15.7	0.3	0.375	0.34	967
422108071052501	20150710	18	20150710	258	Replicate	26	10.3	0.37	9.9	0.51	0.211	0.35	924
RPD (percent)						18	42	NA	45	52	56	2.9	4.5
422108071052501	20150811	1022	20150811	2010	Composite	330	102	5.53	96.6	2.99	2.09	0.96	17,200
422108071052501	20150811	1021	20150811	2010	Replicate	280	101	4.4	96.7	1.8	1.97	0.95	15,900
RPD (percent)						16	0.99	23	0.10	50	5.9	1.0	7.9
422108071052501	20160116	434	20160116	932	Composite	26	13.3	0.05	13.2	0.24	0.333	0.31	302
422108071052501	20160116	433	20160116	932	Replicate	26	9.74	<0.03	<9.74	0.2	0.251	0.31	283
RPD (percent)						0.00	31	NA	NA	18	28	0.00	6.5

Director, New England Water Science Center
U.S. Geological Survey
10 Bearfoot Road
Northborough, MA 01532
dc_nweng@usgs.gov
or visit our website at
https://newengland.water.usgs.gov

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