U.S. Department of the Interior
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Prepared in cooperation with the
FEDERAL HIGHWAY ADMINISTRATION

A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff

Open-File Report 00-497

A Contribution to the
NATIONAL HIGHWAY RUNOFF DATA AND METHODOLOGY SYNTHESIS

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A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff

By GARDNER C. BENT, JOHN R. GRAY, KIRK P. SMITH, and
G. DOUGLAS GLYSSON

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PREFACE

Knowledge of the characteristics of highway runoff (concentrations and loads of constituents and the physical and chemical processes which produce this runoff) is important for decision makers, planners, and highway engineers to assess and mitigate possible adverse impacts of highway runoff on the Nation’s receiving waters. In October 1996, the Federal Highway Administration and the U.S. Geological Survey began the National Highway Runoff Data and Methodology Synthesis to provide a catalog of the pertinent information available; to define the necessary documentation to determine if data are valid (useful for intended purposes), current, and technically supportable; and to evaluate available sources in terms of current and foreseeable information needs. This paper is one contribution to the National Highway Runoff Data and Methodology Synthesis and is being made available as a U.S. Geological Survey Open-File Report pending its inclusion in a volume or series to be published by the Federal Highway Administration. More information about this project is available on the World Wide Web at http://ma.water.usgs.gov/fhwa/runwater.htm

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

A Synopsis of Technical Issues for Monitoring Sediment in Highway and Urban Runoff

By Gardner C. Bent, John R. Gray, Kirk P. Smith, *and* G. Douglas Glysson

Abstract

Accurate and representative sediment data are critical for assessing the potential effects of highway and urban runoff on receiving waters. The U.S. Environmental Protection Agency identified sediment as the most widespread pollutant in the Nation's rivers and streams, affecting aquatic habitat, drinking water treatment processes, and recreational uses of rivers, lakes, and estuaries. Representative sediment data are also necessary for quantifying and interpreting concentrations, loads, and effects of trace elements and organic constituents associated with highway and urban runoff. Many technical issues associated with the collecting, processing, and analyzing of samples must be addressed to produce valid (useful for intended purposes), current, complete, and technically defensible data for local, regional, and national information needs. All aspects of sediment data-collection programs need to be evaluated, and adequate quality-control data must be collected and documented so that the comparability and representativeness of data obtained for highway- and urban-runoff studies may be assessed.

Collection of representative samples for the measurement of sediment in highway and urban runoff involves a number of interrelated issues. Temporal and spatial variability in runoff result from a combination of factors, including volume and intensity of precipitation, rate of snowmelt, and features of the drainage basin such as area, slope, infiltration capacity, channel roughness, and storage characteristics. In small drainage basins such as those found in many highway and urban settings, automatic samplers are often the most suitable method for collecting samples of runoff for a variety of reasons. Indirect sediment-measurement methods are also useful as supplementary and (or) surrogate means for monitoring sediment in runoff. All of these methods have limitations in addition to benefits, which must be identified and quantified to produce representative data. Methods for processing raw sediment samples (including homogenization and subsampling) for subsequent analysis for total suspended solids or suspended-sediment concentration often increase variance and may introduce bias. Processing artifacts can be substantial if the methods used are not appropriate for the concentrations and particle-size distributions present in the samples collected.

Analytical methods for determining sediment concentrations include the suspended-sediment concentration and the total suspended solids methods. Although the terms suspended-sediment concentration and total suspended solids are often used interchangeably to describe the total concentration of suspended solid-phase material, the analytical methods differ and can produce substantially different results. The total suspended solids method, which commonly is used to produce highway- and urban-runoff sediment data, may not be valid for studies of runoff water quality. Studies of fluvial and highway-runoff sediment data indicate that analyses of samples by the total suspended solids method tends to underrepresent the true sediment concentration, and that relations between total suspended solids and suspended-sediment concentration are not transferable from

site to site even when grain-size distribution information is available. Total suspended solids data used to calculate suspended-sediment loads in highways and urban runoff may be fundamentally unreliable. Consequently, use of total suspended solids data may have adverse consequences for the assessment, design, and maintenance of sediment-removal best management practices. Therefore, it may be necessary to analyze water samples using the suspended-sediment concentration method.

Data quality, comparability, and utility are important considerations in collection, processing, and analysis of sediment samples and interpretation of sediment data for highway- and urban-runoff studies. Results from sediment studies must be comparable and readily transferable to be useful to resource managers and regulators. To meet these objectives, supporting ancillary information must be available to document the methods and procedures that are used and to describe quality-assurance and quality-control procedures that are used in the studies. Valid, current, and technically defensible protocols for collecting, processing, and analyzing sediment data for the determination of water quality in highway and urban runoff therefore need to be documented with study results.

INTRODUCTION

Recognition of the importance of sediment as a water-quality constituent has increased dramatically in recent years. The U.S. Environmental Protection Agency (2000) identified sediment as the most widespread pollutant in the Nation's rivers and streams, in that sediment affects aquatic habitat, drinking-water treatment processes, and recreational uses of rivers, lakes, and estuaries. To address the combined, cumulative impacts of both point and nonpoint sources of sediment, the U.S. Environmental Protection Agency (USEPA) has adopted a watershed approach, of which total maximum daily loads (TMDLs) are a part (U.S. Environmental Protection Agency, 1998 and 1999).

In addition to sediment itself being a major pollutant, many trace elements, such as copper, zinc, cadmium, chromium, lead, and nickel—constituents often detected in highway runoff—are associated with sediments (Gupta and others, 1981; Horowitz, 1995). Some organic constituents associated with highway runoff are also associated with sediments (Lopes and Dionne, 1998). Sediment in highway runoff is a potential problem as a physical contaminant and as a source of potentially toxic substances to the local ecosystem (Schueler, 1997; Buckler and Granato, 1999). Hence, sediment in highway runoff can be a dominant factor in water quality, particularly when selected trace elements or organic constituents are associated with the sediment.

Highways affect sediment transport in runoff through several processes. Reduced infiltration from impervious surfaces, rapid concentration of flow with minimal flow resistance, and relatively high slopes of roadside drainage structures combine to increase velocities, volumes, and peaks of storm runoff, thus increasing the potential for erosion and increased entrainment of sediment. Materials entrained in highway runoff from road-surface and vehicle degradation can be discharged to receiving streams, as can materials such as sand or cinders that may be applied for traction on snow or ice. Particles from atmospheric deposition that include combustion and other by-products from vehicles also can be entrained in highway runoff.

This report addresses technical issues pertinent to the methods for the collection, processing, and analysis of sediment samples to determine the concentration and physical characteristics of sediment in highway and urban runoff, best management practice (BMP) structures, and receiving waters. Data-quality issues and appropriate quality-assurance techniques for sediment data collection and laboratory-analysis methods are also discussed. Although this report focuses on sediment-transport issues related to highway use, information presented in this report also is applicable to many issues related to sediment in urban runoff. Sediment-transport issues related to highway construction are presented within the Nonpoint Pollution Discharge Elimination System (NPDES) (U.S. Environmental Protection Agency, 1992; 1995) and are not included herein. Many of the techniques discussed herein may be used to monitor receiving waters, although those discussed by Edwards and Glysson (1999) may be more appropriate in fluvial systems. Hence, this paper focuses on valid, current, and technically defensible protocols for collecting, processing, and analyzing sediment data for the determination of water quality in highway and urban runoff.

SEDIMENT CONCEPTS RELATED TO HIGHWAY RUNOFF

Sediment comprises particles derived from rocks, biological materials, or chemical precipitates that are transported by, suspended in, or deposited in flowing water (American Society for Testing and Materials, 1997b). Highway sediments can be a mix of materials including pavement dust and particles; atmospheric dust, natural soils, traction sand and cinders; vehicle rust particles; tire dust and particles; trash; and plant and leaf material. The mode of transport can be described by the origin of the material as bed-material load and wash load; or operationally (as measured by sediment samplers) as suspended load and bedload (International Standards Organization, written commun., 2000). Wash load is material atypical of the bottom-material size distribution that tends to flow through a reach without significant interaction with the bed. Suspended-sediment load is material carried in suspension by turbulence. Suspended particles less than about 0.04 mm are typically well mixed within the water column profile (Butler and others, 1996a). As particle-size distribution (PSD) increases to include sand-size material (larger than 0.062 mm median diameter), a vertical gradient may form, with largest particles concentrating near the bed. For example, the theoretical vertical distribution of sediments in the water column calculated using the Rouse equation (Graf, 1996) for highway sediments of different grain sizes are presented in figure 1. The concentration distribution (relative to a normalized sampling point that is at 0.1 of the water level above the bed) is uniform for finer particles (diameters less than 0.062 mm). As grain size increases from very fine sand to coarse sand (0.062 to 1.0 mm), however, the relative concentration increases with depth as a function of increasing grain size under standard conditions (fig. 1). These theoretical concentration distributions compare favorably with patterns in data that have been collected in fluvial systems (Guy, 1970) and in the results of an experiment designed to assess the vertical distribution of sediments in a small highway drainage pipe (Smith, 2000).

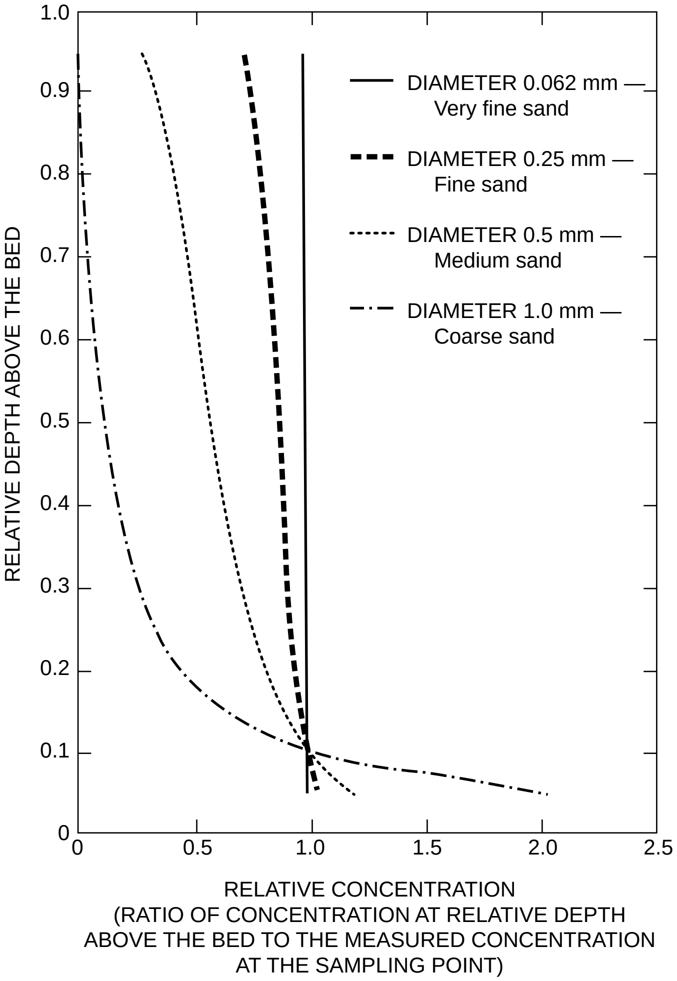


Figure 1. Theoretical vertical distribution of sediments (specific gravity 2.65) in a runoff drainage pipe with a 5-percent slope in open channel flow under standard conditions based on the Rouse equation (Graf, 1996).

Bedload is material that moves by rolling, sliding, or saltating along the channel bottom. Butler and others (1996a) indicate that bedload particle sizes are typically larger than about 0.3 mm in storm sewers. This distinction, however, is not quantitative because it depends on several hydraulic variables including channel slope, specific gravity of solids, particle shape, and flow energy. Material composing the bed at a low flow may move as bedload at a higher flow, and as suspended load at still higher flows. In comparison, bedload in fluvial systems rarely includes sediment that is finer than 0.1–0.2 mm in diameter, because once disturbed, the finer particle sizes go directly into suspension (Gomez and others, 1991). Because storm flows can vary from zero to peak flow in minutes, the dominant phase of transport can change rapidly. For example, 0.25 mm material might be transported predominately as bedload at flows of 1 ft^3/s, but at flows of 10 ft^3/s the dominant phase of transport might be suspended sediment.

Sediment transport in highway and urban runoff is controlled by precipitation runoff and the availability of erodible and (or) transportable sediments. The amount and timing of runoff is largely dependent on rainfall intensity and depth. Rainfall intensity has a two-fold effect on entrainment and transport of sediment through (1) raindrop splash erosion and (2) through sheet flow. The kinetic energy imparted by rain, which causes splash erosion when incident on sediment, increases exponentially with rainfall intensity (Hudson, 1981). The volume and velocity of sheet flow tends to increase with rainfall volume and intensity, entraining sediment from paved surfaces. Large flows resulting from high-intensity rains can lead to suspension and transport of sediment on paved areas and in drainage structures. Therefore, a lone sample collected during the first 30 minutes of the runoff period, such as is required by the U.S. Environmental Protection Agency (Bailey, 1993; Stillwell and Bailey, 1993), is a somewhat arbitrary requirement and may not adequately describe sediment concentrations associated with the "first flush" of runoff sediment. Also, because of the effects of varying rainfall intensities on the timing and the magnitude of runoff, a maximum sampling duration of 3 hours, as recommended by the USEPA (Bailey, 1993; Stillwell and Bailey, 1993), may result in substantial underestimation of sediment discharges for extended runoff periods.

The erosive capacity of runoff from highways and urban areas can be substantial because runoff from paved areas, ditches, and storm drains can be hydraulically supercritical and turbulent. The area contributing to surface runoff is usually small, water-surface slope is commonly relatively steep, and surface roughness is usually low. Under these conditions, runoff quickly becomes concentrated. Although some coarser sediment can move as bedload, most highway drainage systems are designed to maintain sediments suspended in runoff so that the volumetric capacities of the highway conveyance structures are not diminished (Butler and others, 1996a).

Most highway runoff sediment-monitoring programs are implemented in areas ranging from a fraction of an acre to several square miles. These are small areas compared to the median drainage area of 296 mi^2 for the 1,593 U.S. Geological Survey (USGS) gaging stations listed in the USGS historical daily-value suspended-sediment and ancillary data base (U.S. Geological Survey, 1999b). Monitoring sediment and flow in small drainage systems in which runoff responds rapidly to rainfall usually requires a combination of manual and automatic methods for data collection (Robertson and Roerish, 1999). Water-discharge and sediment-concentration data are required to calculate suspended-sediment transport (Porterfield, 1972; Koltun and others, 1994). Samples for sediment-concentration analyses should be collected during the rising limb, peak, and falling limb of the runoff hydrograph to describe adequately variations in sediment concentrations for the runoff period. This data-collection scheme is important because the relation between the concentration of suspended material and runoff is generally not the same on the rising limb of the hydrograph as the falling limb of the hydrograph (fig. 2) (Porterfield, 1972; Mustard and others, 1987). In the case of highway runoff, consecutive samples may need to be collected only minutes apart, particularly on the rising limb of the hydrograph, due to large temporal variations in sediment concentrations, and a “first-flush” effect that may occur at highway and urban monitoring sites where sediments have accumulated between runoff periods. The “first-flush” effect with sediment in highway runoff results when a period of the rising limb of the runoff hydrograph is disproportionally enriched in sediment compared to the remaining period of the hydrograph (fig. 2), and has been quantified in highway-runoff studies by Patrick (1975), Ellis (1976), Ellis and others (1981), and Mustard and others (1987). The “first-flush” effect is likely due to an accumulation of fine sediments that are entrained in the initial runoff. These finer sediments available for transport could have been previously deposited in the drainage conveyance structures or could have accumulated on the road surface, usually near the curb or road edge, which is generally the flow path of runoff going to the

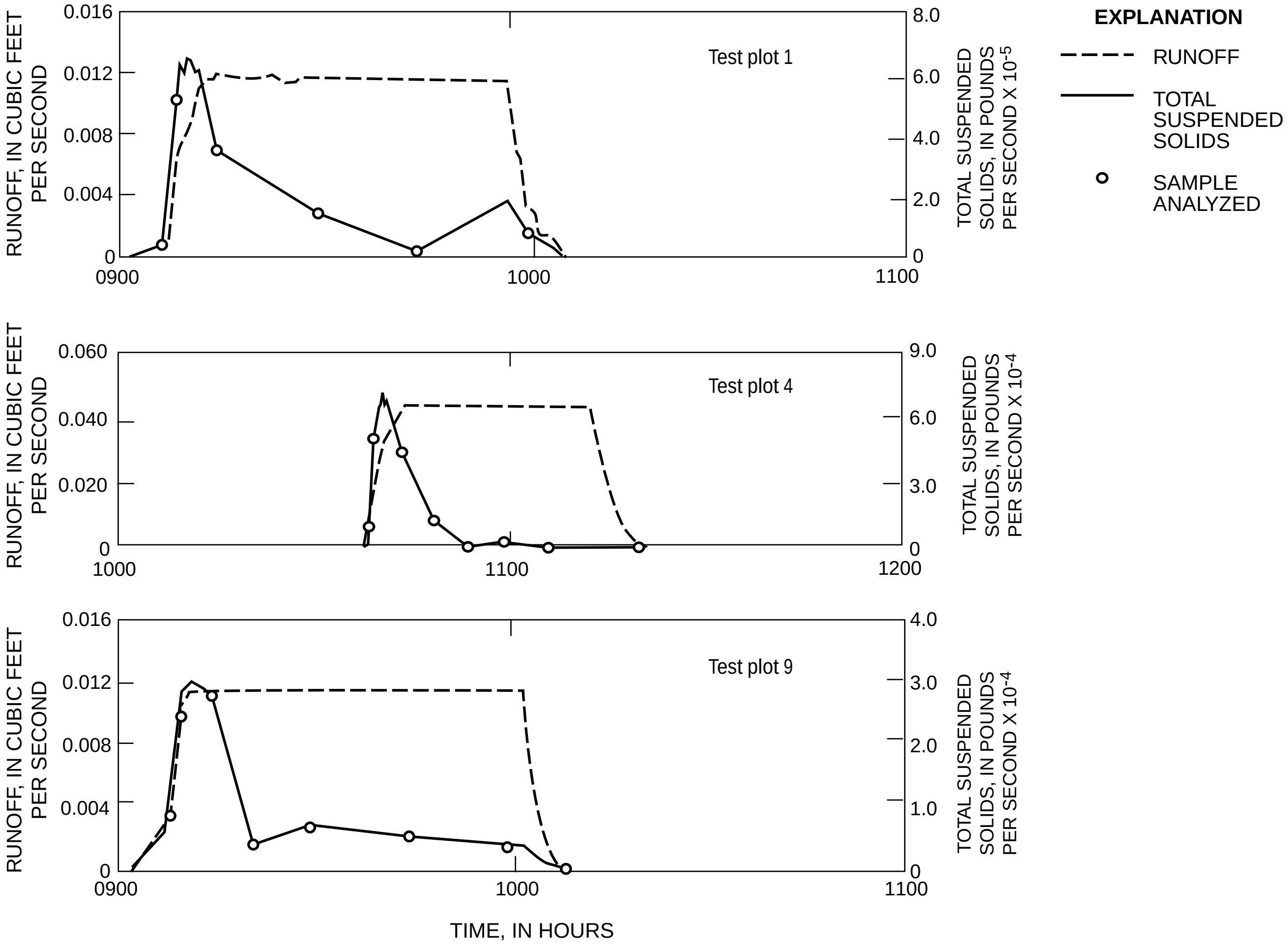


Figure 2. Runoff and washoff load of total suspended solids from test plots in Lakewood, Colorado, June 3, 1980 (modified from Mustard and others, 1987).

drainage conveyance structures from, or since, the last runoff period. For example, Gupta and others (1981) reported that 85 to 90 percent of street debris (solids) was within 12 in. of the curb. However, sediment transport at many highway and urban sites may vary with precipitation intensity and therefore the “first flush” may not represent the maximum sediment concentration or load that occurs during a runoff period.

Characteristics important to the monitoring, analysis, interpretation, and ultimately the treatment of water quality in highway and urban runoff include sediment concentrations and PSDs. Review of studies from the United States, Australia, Canada, France, Sweden, and the United Kingdom related to sediment runoff from highways, streets, and urban areas over the last 25 years (table 1) have shown concentrations of total suspended solids (TSS) ranging from 4 to 129,000 mg/L (table 2). In comparison, mean TSS concentrations in table 2 range from 29 to about 18,000 mg/L. The median particle size (d_{50}) of sediments collected in these studies range from 0.013 to 1.00 mm (table 3). These particle sizes range from about medium silt to very coarse sand (Guy, 1969; Folk, 1980), with sand-size particles being those larger than 0.062 mm (table 4).

Table 1. List of selected studies of sediment in highway and urban runoff

[**Report type:** D/I, data and interpretation; S, summary. **Location:** I, Interstate; SR, State Route. >, greater than; %, percent]

Reference	Report type	Location	Site type	Study year
United States				
Asplund and others, 1982	D/I	Seattle, Wash. (I-5)	urban highway	1979–80
	D/I	Seattle, Wash. (I-5 with grit)	urban highway	1979–80
	D/I	Montlake, Wash. (SR-520)	suburban highway	1979–80
	D/I	Vancouver, Wash.	highway	1979–80
	D/I	Snoqualmie Pass, Wash.	agricultural highway	1979–80
	D/I	Montesano, Wash.	agricultural highway	1979–80
	D/I	Pasco, Wash.	urban highway	1979–80
	D/I	Spokane, Wash.	agricultural highway	1979–80
	D/I	Pullman, Wash. (site 9)	agricultural highway	1979–80
Mustard and others, 1987	D/I	Lakewood, Colo. (4-lane street)	city street	1980
Smith and Lord, 1990	S	Selected Highways	highway	1976–77
Driscoll and others, 1991	S	Selected Urban Highways	urban highway	1980–90
	S	Selected Rural Highways	rural highway	1980–90
	S	Selected Urban Highways	urban highway	1980–90
	S	Selected Rural Highways	rural highway	1980–90
Moser, 1996	D/I	Silverthorne, Colo. (I-70)	highway	1994
	D/I	Silverthorne, Colo. (I-70)	highway	1994
	D/I	Silverthorne, Colo. (I-70)	highway	1994
Sansalone and Buchberger, 1996	D/I	Cincinnati, Ohio (I-75)	urban highway	1995
Sansalone and others, 1996	D/I	Cincinnati, Ohio (I-75)	urban highway	1995
Corsi and others, 1997	D/I	Southeastern Wisconsin	>90% urban land use	1975–96
Dudley and others, 1997	D/I	New Sharon, Maine (SR-2)	rural highway	1992–93
	D/I	New Sharon, Maine (SR-27)	rural highway	1992–93
Sansalone and others, 1998	D/I	Cincinnati, Ohio (I-75)	urban highway	1995–97
Waschbusch and others, 1999	D/I	Madison, Wisc.	residential streets	1994–95
Austrialia				
Ball and Abustan, 1995	D/I	Sydney	residential area	1994
Canada				
Vermette and others, 1987	D/I	Hamilton, Ontario	street	Not Reported
France				
Roger and others, 1998	D/I	Herault Region	highway	1993–94
Andral and others, 1999	D/I	France	highway	1993–94
Legret and Pagotto, 1999	D/I	Loire-Atlantique	rural highway	1995–96
Sweden				
Viklander, 1998	D/I	Lulea	street	1996
United Kingdom				
Ellis and others, 1981	D/I	London, England	residential and others	Not Reported
Pratt and Adams, 1981	D/I	Nottingham, England	residential streets	1979–80
Ellis and Harrop, 1984	D/I	London, England	highway	Not Reported
Ellis and others, 1987	D/I	London, England	highway	Not Reported
Butler and others, 1992	D/I	Lambeth, London, England	urban highway	Not Reported
Boxall and Maltby, 1995	D/I	United Kingdom	urban highway	Not Reported

Table 1. List of selected studies of sediment in highway and urban runoff—*Continued*

Reference	Report type	Location	Site type	Study year
United Kingdom—*Continued*				
Butler and others, 1996a	S	United Kingdom	Not Reported	Not Reported
	S	United Kingdom	Not Reported	Not Reported
No Specified Location				
Bertrand-Krajewski and others, 1993	S	Not Reported	Not Reported	Not Reported

Table 2. Sediment concentrations measured in highway and urban runoff

[**n:** number of sediment concentration analyses (data points); g/m^3, grams per cubic meter; mg/L, milligrams per liter; --, no data]

Reference	Sediment concentrations reported (mg/L)			Comments
	n	Range	Mean	
Asplund and others, 1982	54	32–848	--	Urban highway
	9	50–1,370	--	Urban highway
	43	76–894	--	Suburban highway
	61	13–168	--	Highway
	12	23–586	--	Agricultural highway
	27	51–1,260	--	Agricultural highway
	17	19–587	--	Urban highway
	6	67–2,490	--	Agricultural highway
	6	14–522	--	Agricultural highway
Mustard and others, 1987	9	27–150	83	City street
Smith and Lord, 1990	159	4–1,156	261	Highway
Driscoll and others, 1991	16	51–406	--	Rainfall, urban highway
	8	9–126	--	Rainfall, rural highway
	9	61–752	--	Snowmelt, urban highway
	6	11–465	--	Snowmelt, rural highway
Moser, 1996	30	12–854	213	Rainfall, highway
	9	1,948–69,141	18,036	Snowmelt, highway
Sansalone and Buchberger, 1996	2	84–127	--	Rainfall, urban highway
Sansalone and others, 1996	8	510–3,200	1,419	Snowmelt, urban highway
Corsi and others, 1997	--	17–297	139	>90% urban land use
Dudley and others, 1997	35	18–129,000	--	Rural highway
	27	92–114,000	--	Rural highway
Sansalone and others, 1998	13	29–259	131	Rainfall, urban highway
Waschbusch and others, 1999	--	--	67–99	Residential streets
Andral and others, 1999	8	15–58	29	Highway
Legret and Pagotto, 1999	49	16–267	71	Rural highway
Ellis and others, 1987	34	--	156 g/m^3 and 194 g/m^3	Highway
Butler and others, 1996a	--	50–1,000	--	Stormwater solids
		10–200	--	Grit
Bertrand-Krajewski and others, 1993	--	21–2,582	--	Roads, curbs, runoff, and sewers

Table 3. Particle-size distribution measured in highway and urban runoff

[**n:** number of particle-size analyses (data points). **Median (d_{50}):** d_{50} median diameter of particles. **Comments:** Modal is the value of the most commonly occurring particle size. phi, log2 of the particle diameter; µm, micrometers; %, percent; >, actual value is greater than value shown; <, actual value is less than value shown; --, no data]

Reference	Particle-size distribution				Comments
	n	Median (d_{50})	Mean	Range	
Sansalone and others, 1998	13	555 µm	570 µm	370–875 µm	d_{50}
	13	--	--	1–10%	>62 µm
Waschbusch and others, 1999	--	--	--	75%	>250 µm
		--	--	85%	>62 µm
		--	--	5%	<63 µm
Ball and Abustan, 1995	--	40-60 µm	--	--	--
Vermette and others, 1987	8	--	--	354–707 µm	modal size class
	8	--	2.1 phi	1.7–2.9 phi	--
Roger and others, 1998	--	--	--	86%	<50 µm
		--	--	53%	500–1,000 µm
Andral and others, 1999	8	86%	86%	82–91%	<50 µm
	8	13 µm	--	10–16 µm	d_{50}
Viklander, 1998	--	--	--	1,000–3,000 µm	d_{50}
Ellis and others, 1981	--	--	--	2 and 20 µm	bimodal
Pratt and Adams, 1981	1	500 µm	--	--	--
Ellis and Harrop, 1984	2	--	--	650–1,400 µm	--
Butler and others, 1996a	--	60 µm	--	20–100 µm	d_{50}
		750 µm	--	300–1,000 µm	d_{50}
Bertrand-Krajewski and others, 1993	--	30–1,000 µm	--	--	--

Table 4. Recommended particle-size classes for sediment analysis

[Modified from Guy, 1969. **Phi value:** Maximum size of the given class. --, not expressed in terms of micrometers; NA, not applicable]

Class name	Metric units		Phi value
	Millimeters	Micrometers	
Boulders	>256	--	NA
Large cobbles	256–128	--	-8
Small cobbles	128–64	--	-7
Very coarse gravel	64–32	--	-6
Coarse gravel	32–16	--	-5
Medium gravel	16–8.0	--	-4
Fine gravel	8.0–4.0	--	-3
Very fine gravel	4.0–2.0	--	-2
Very coarse sand	2.0–1.0	2,000–1,000	-1
Coarse sand	1.0–0.50	1,000–500	0
Medium sand	0.50–0.25	500–250	+1
Fine sand	0.25–0.125	250–125	+2
Very fine sand	0.125–0.062	125–62	+3
Coarse silt	0.062–0.031	62–31	+4
Medium silt	0.031–0.016	31–16	+5
Fine silt	0.016–0.008	16–8	+6
Very fine silt	0.008–0.004	8–4	+7
Coarse clay	0.004–0.0020	4–2	+8
Medium clay	0.0020–0.0010	2–1	+9
Fine clay	0.0010–0.0005	1–0.5	+10
Very fine clay	0.0005–0.00024	0.5–0.24	+11

SAMPLE-COLLECTION METHODS

The collection of representative samples for measurement of sediment in highway and urban runoff involves a number of interrelated issues. The temporal and spatial variability in runoff can be large because of a combination of factors including volume and intensity of precipitation, rate of snowmelt, and features of the drainage basin such as drainage area, slope, infiltration capacity, channel roughness, and storage characteristics. As the runoff rate increases, the stage (water level) and (or) mean velocity increases also. Rapid changes in flow may be associated with rapid changes in the sediment concentration, PSD, and density distribution. For example, Butler and others (1996a, 1996b) indicate that sediments accumulated in pipes may be mobilized (as bedload or suspended load) or remain immobile depending on concentration and size distribution of the sediment, and the energy of flow. Therefore, measurement of precipitation and flow are necessary for measurement and interpretation of sediment transport in highway and urban runoff systems (Church and others, 1999). Information necessary for measurement and interpretation of precipitation and runoff flows in highway and urban systems is discussed by Church and others (1999) and so is not included herein. The complexity of the precipitation-runoff-transport process necessitates sampling plans and methods that characterize the temporal and spatial variability in sediment transport in these systems.

Sampling plans for the study of nonpoint-source contamination may include discrete and (or) composite sampling by manual and (or) automatic sampling methods (U.S. Environmental Protection Agency, 1992). Discrete samples (also referred to as grab or dip samples) may represent sediment concentrations for only a short period of time. Composite samples are mixed or combined samples that should be flow-weighted to represent concentrations and loads during the monitoring period (U.S. Environmental Protection Agency, 1992; Gray and Fisk, 1992). Discrete samples collected during a runoff period may be physically composited and analyzed as one sample or mathematically composited from an analysis of multiple discrete samples (Driscoll and others, 1991). Discrete and (or) composite samples may be spatially representative—such as those collected by the Equal Discharge Increment (EDI) or Equal Width Increment (EWI) methods (Edwards and Glysson, 1999)—or may be representative of only the point in the stream from which the sample was collected. Automatic sampling methods include pumping samplers as well as passive devices that are designed to collect a discrete sample. The U.S. Environmental Protection Agency (1992) describes some of the relative advantages and disadvantages of manual and automatic sampling techniques (table 5). The remoteness or inaccessibility of some study sites makes it difficult to monitor runoff periods manually, and it can be difficult to get personnel to the sites before the onset of runoff. Costs associated with deployment of trained and properly equipped personnel, in addition to uncertainties related to the location and timing of runoff, can be prohibitive for manual sampling of storm-runoff periods. For example, Thiem and others (1998) employed a meteorologist to predict storm events and still had difficulty in implementing manual sampling efforts because storm runoff was predicted with an accuracy of about 50 percent. The difficulty in collecting a relatively large number of samples during storm runoff and the dangers to field personnel operating in adverse conditions (including traffic, weather, reduced visibility, and rapid changes in discharge) reduces the practicality of manual sampling efforts. In contrast, automatic samplers can be deployed before, and samples can be retrieved after cessation of storm runoff, thereby reducing logistics and increasing the safety for field personnel (Federal Interagency Sedimentation Project, 1981; U.S. Environmental Protection Agency, 1992). Also, the large temporal and spatial uncertainty in precipitation and runoff, and the coordination possible between automatic precipitation, flow, and water-quality-measurement instruments and automatic samplers (Church and others, 1996) favor the use of these devices in the monitoring of runoff quality in highway and urban systems. For example, Lewis (1996) describes a means for activating an automatic sediment sampler based on real-time turbidity measurements. Edwards and Glysson (1999) describe manual methods for sediment sample collection, which are typically more suitable for monitoring receiving waters than highway- and urban-drainage systems. The automatic samplers commonly used to sample highway- and urban-drainage systems are discussed as follows.

Table 5. Comparison of manual and automatic sampling techniques

[Modified from U.S. Environmental Protection Agency, 1992.]

Sample method	Advantages	Disadvantages
Manual grabs	Appropriate for all pollutants Minimum equipment required	Labor-intensive Environment possibly dangerous to field personnel May be difficult to get personnel and equipment to the storm water outfall within the 30-minute requirement Possible human error
Manual flow-weighted composites (multiple grabs)	Appropriate for all pollutants Minimum equipment required	Labor-intensive Environment possibly dangerous to field personnel Human error may have significant impact on sample representativeness Requires flow measurements taken during sampling
Automatic grabs	Minimizes labor requirements Low risk of human error Reduced personnel exposure to unsafe conditions Sampling may be triggered remotely or initiated according to present conditions	Samples collected for oil and grease may not be representative Automatic samplers can not properly collect samples for volatile organic compounds analysis Costly if numerous sampling sites require the purchase of equipment Requires equipment installation and maintenance Requires operator training May not be appropriate for pH and temperature May not be appropriate for parameters with short holding times (for example, fecal streptococcus, fecal coliform, chlorine) Cross-contamination of aliquot if tubing/bottles not washed
Automatic flow-weighted composites	Minimizes labor requirements Low risk of human error Reduced personnel exposure to unsafe conditions May eliminate the need for manual compositing of aliquots Sampling may be triggered remotely or initiated according to on-site conditions	Not acceptable for volatile organic compounds sampling Costly if numerous sampling sites require the purchase of equipment Requires equipment installation and maintenance, may malfunction Requires initial operator training Requires accurate flow-measurement equipment tied to sampler Cross-contamination of aliquot if tubing/bottles not washed

Automatic Samplers

Automatic samplers include active (pumping samplers) and passive sampling devices. Automatic pumping samplers typically collect water from the water column by suction and control the sampling rate using the pump speed (Dick, 1996). Passive sampling devices typically are installed in the flow path and control the sampling rate by placement, orientation, and design of the water intake. Each type of sampler has benefits and design limitations, which must be recognized and quantified to produce representative data.

Pumping Samplers

Automatic pumping-type samplers (fig. 3) generally consist of (1) a pump to draw suspended-sediment samples from the water column and, in some cases, to provide a back flush to clear the sampler intake before

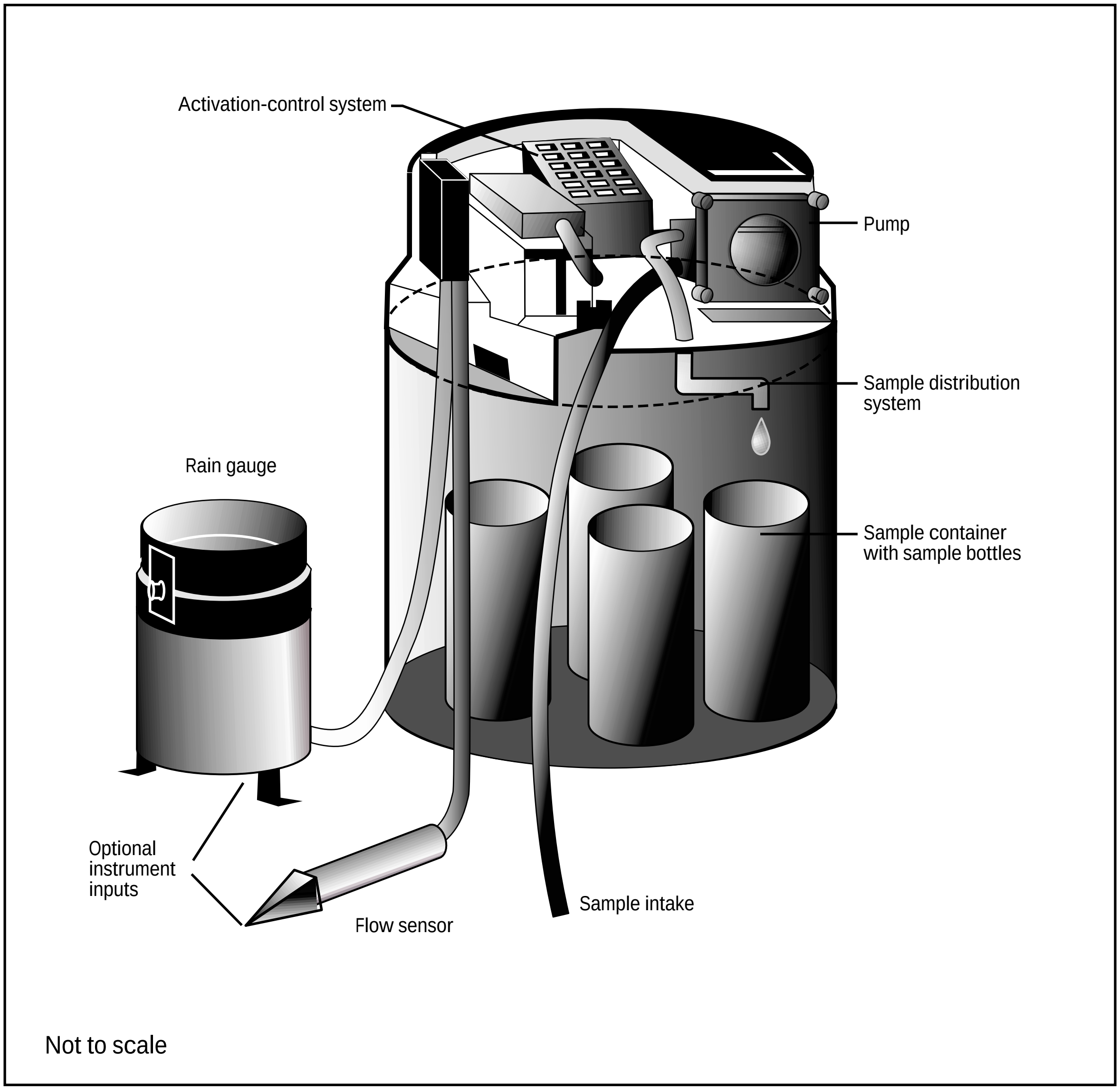


Figure 3. Automatic pumping sampler (modified from U.S. Environmental Protection Agency, 1992).

or after each sampling cycle; (2) a sample-container unit to hold sample bottles in position for filling; (3) a sample distribution system to divert a pumped sample to one or more sample collection bottle(s); (4) an activation-control system that activates the sampling cycle on a time interval, stage, rate-of-stage-change, or from an external signal (such as in response to a telephone call or a signal generated by a data logger); and (5) an intake system through which samples are drawn from a point in the water column's cross-section. Ideally, this combination of components should be designed to meet the following criteria based on site-specific conditions:

- A suspended-sediment sample should be delivered from the water column to the sample container without a change in sediment concentration or PSD.
- Cross contamination of a sample caused by residual sediments in the system between sample-collection periods should be minimized.

- The sampler should be capable of sample collection over the full range of sediment concentrations and particle sizes up to about 4 mm (very fine gravel). For example, about 90 percent of the sediment retained in a highway catch basin was less than 4 mm and about 80 percent was less than 2 mm in a highway-runoff study in eastern Massachusetts (Smith, 2000).
- Sample-container volumes should meet minimum sample analysis volume requirements.
- The intake’s inside diameter should be maximized to facilitate representative concentrations and PSD of samples [typically 9.5- or 19.0-millimeter- (3/8- or 3/4-inch-) diameter intakes depending on the minimum pumping rate of the sampler used].
- The sampler should be capable of vertical lifts large enough to maintain sample PSD integrity.
- The sampler should be capable of collecting a reasonable number of samples, depending on the purpose of sample collection and the flow conditions.
- Some provision should be made to protect against freezing, evaporation, and dust contamination.
- The sample-container unit should be constructed to facilitate removal and transport as a unit.
- The sampling cycle should be initiated in response to a timing device, flow change, or external signal.
- The capability of recording the sample-collection date and time should exist.
- The provision for operation using alternating current power or direct current (battery) power should exist.

Recent field tests conducted by the USGS in cooperation with the Federal Highway Administration (FHWA) indicate that newer types of automatic pumping samplers meet these criteria, but older vintage (before about 1993) samplers typically do not meet all these criteria (David Owens, USGS, written commun., 2000). For example, several vacuum and peristaltic samplers of post-1993 design used for the field test collected samples with representative PSDs from 20 to 128 µm, but samplers operating on older technologies and construction were not able to collect representative samples when the sampler elevation exceeded the sampler intake elevation by 12 ft or more. In highway systems, it is important to be able to sample larger grain sizes that may be in transport. For example, sediment particle sizes as large as fine gravel (table 4) were collected by an automatic sampler in a highway-runoff study in eastern Massachusetts (Smith, 2000).

Automatic samplers also have technical limitations that must be identified and addressed for representative data-collection and interpretation. Tai and others (1991) and Horowitz and others (1992) provide information and evaluations of automatic-pumping samplers to collect dissolved and solid-phase water-quality constituents, including sediment. Technical limitations may be substantial depending on site and runoff-quality characteristics. Proper site selection and sampling design may compensate for limitations if they are recognized. These limitations include the following:

- Automatic samplers generally are not capable of collecting an isokinetic sample (which is defined as the velocity in the sampler's nozzle being about equal to that of the stream velocity incident on the nozzle because intake velocity is fixed).
- Sample line velocity is reduced with increased elevation between the automatic pumping sampler and the water surface (head), which can compromise measured suspended-sediment concentration (SSC) and PSD values. This effect is caused by the reduced ability of the sampler to lift larger particles (assuming similar particle densities and shapes) over greater heads.
- No currently available samplers are capable of collecting samples at sites where the elevation of the sampler is more than about 28 ft above the sampler intake while maintaining a line speed greater than the minimum of 2.0 ft/s specified by the U.S. Environmental Protection Agency (1982) without the addition of an auxiliary pump (David Owens, written communication, 2000).
- Line lengths greater than about 100 ft may impair the sampler's ability to collect water samples due to line friction.
- Increased intake diameters may be necessary to capture larger grain sizes, but an increase in the inside diameter leads to reduced intake velocities at the same pumping rate.
- Cross contamination of the sample line is a concern and is a function of the line-length (for example, a 1 ft section of a 3/8-inch-diameter tube has an inside surface area of about 0.1 ft^2), and the

quality of runoff (for example, runoff water that contains other viscous liquids, such as oil and grease) may increase sediment retention.

- Composite samples may be affected by sample volume repeatability, which should be tested for each sampler at each site (David Owens, written commun., 2000).

Samples collected non-isokinetically by automatic samplers may not provide data representative of the mean cross-sectional concentrations and PSDs, particularly when sand-size material is in transport (Edwards and Glysson, 1999). In one study, however, the constituent concentrations of samples collected with an automatic pumping sampler were shown to be similar to those of manually collected, cross-sectionally integrated water-quality samples (Krug and Goddard, 1986). Research is needed to develop relations between data collected by automatic and isokinetic sampling methods in highway and urban drainage systems. In fluvial systems, a depth-integrated sample is required because of potential variations in the cross-sectional distribution of sediment (Guy, 1970). Use of depth-integrating samplers typically requires depths exceeding a foot, and minimum mean flow velocities of about 2 ft/s. In highway and urban drainage structures, however, depth- and width-integrated sampling techniques may not be possible for a number of reasons, such as brief duration of runoff, limited access to the drainage structure, size of the conduit, depths and velocities of water in the conduit, and rapidly varying flows. Also, because of the turbulent flows and rapid mixing characteristic of highway and urban drainage systems, these methods may not be necessary depending on site-specific conditions. If use of the EDI or EWI method to collect samples is possible, samples can be collected over a range of flows on the rising and falling limbs of the hydrograph during different runoff periods to document the difference between the collection of a representative sample and the collection of a sample at a single point by an automatic pump sampler. EDI and EWI samples can be used to develop a cross-section coefficient with concentration values from samples collected with an automatic sampler (Porterfield, 1972) as part of the quality-assurance and quality-control (QA/QC) activities.

To obtain the most reliable and representative data, the automatic sampler intake should be placed at the point at which the concentration approximates the mean sediment concentration for the cross section over a full range of flows. This idealistic concept has great merit, but the mean cross-section concentration almost never exists at the same point or vertical under varying flow conditions. It is even less likely that specific guidelines for locating an intake under given flow conditions at one stage would produce the same intake location relative to the flow conditions at a different stage. For example, there are five possible intake orientations (fig. 4), including (A) horizontal and against flow, (B) horizontal and perpendicular to flow, (C) upward and perpendicular to flow, (D) downward and perpendicular to flow, and (E) horizontal and with flow (Edwards and Glysson, 1999). In laboratory tests of several nozzle orientations, including orientations (C), (D), and (E), Winterstein and Stefan (1986) found orientation (E) to provide the most representative sample in spite of the fact that this is counterintuitive when considering isokinetic manual sampling techniques (Edwards and Glysson, 1999, p. 14). Winterstein and Stefan (1986) hypothesized that this downstream (with flow) intake minimizes debris accumulation and a small eddy is formed at the intake, which envelops the sand particles and thus allows the sampler to collect a more representative sample of the coarse load than intakes located in other directions with respect to the flow. There are, however, many site-specific issues that must be considered. Therefore, objectives for placing a sampler intake in the flow at any given cross section are as follows:

- Select the intake location so that, if possible, it is submerged for the complete range of flows.
- Identify or install a means to fix the intake at the desired location in flow. The attachment feature and intake should have a high probability of remaining in place at high flows, and should not be prone to collecting debris.
- Make sure the sampler intake is not located where bed material can be drawn into or can bury the intake.
- Locate and configure the sample intake to reduce any potential for debris collection, such as in the downstream direction.
- Sample intake location should be in areas of high velocities and turbulence that offer the greatest potential for mixing, that provide for rapid removal of any particles disturbed during a purge cycle of sample line, (such as downstream of

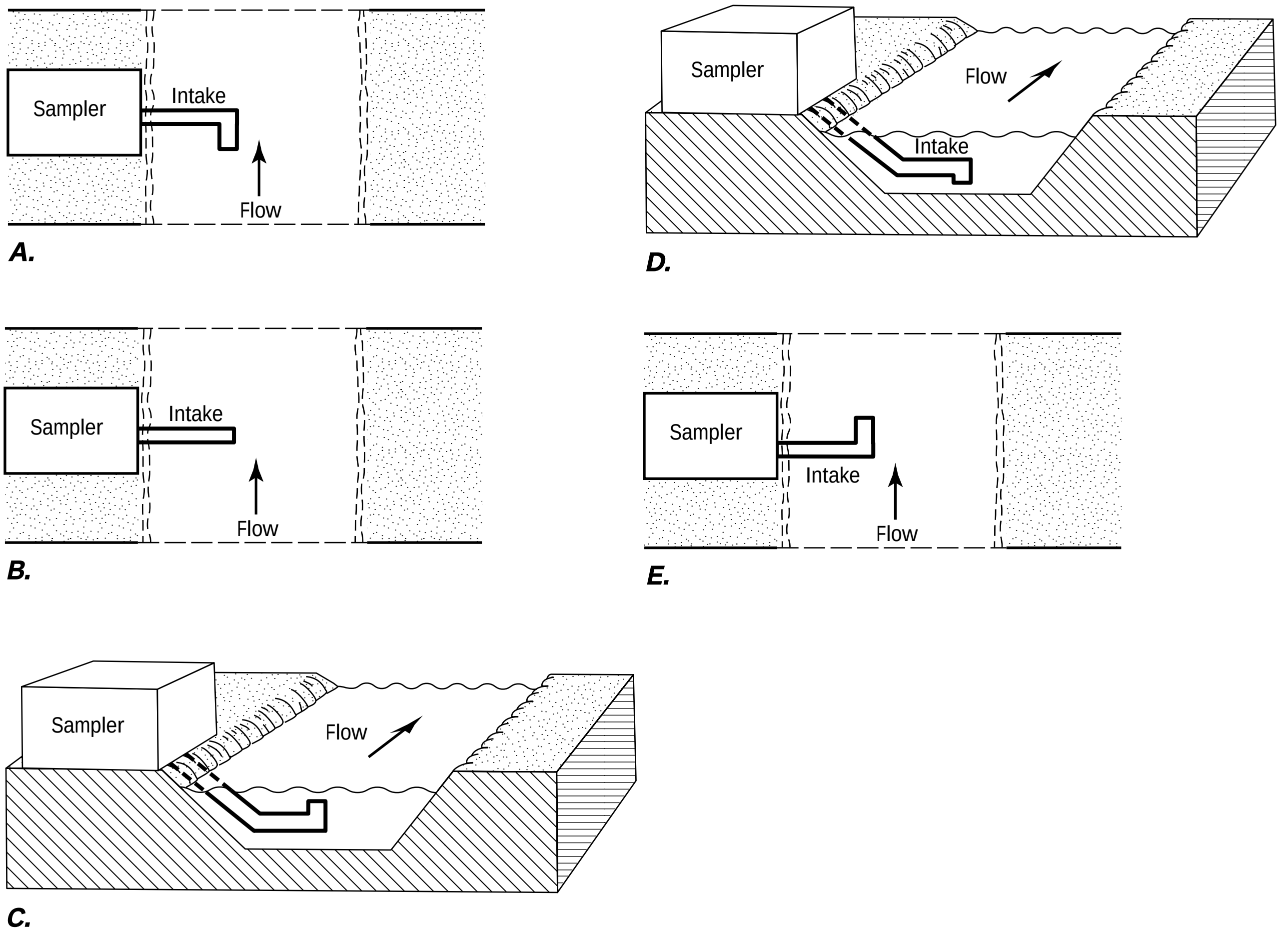


Figure 4. Pumping sampler intake orientations: (*A*) horizontal and against flow; (*B*) horizontal and perpendicular to flow; (*C*) upward and perpendicular to flow; (*D*) downward and perpendicular to flow; and (*E*) horizontal and with flow (modified from Edwards and Glysson, 1999).

storm drainage distribution boxes), or that incorporate static mixing devices just upstream of the sampler intake.

- Mount the tubing with a slope from the intake to the sampler intake to minimize low points in tubing that may retain water and sediment after pumping has ceased. This will reduce the potential for cross contamination between subsequent samples.
- Position one or more intakes as a manifold to collect the most representative (mean) SSC and PSD samples.

Site conditions commonly preclude sampling arrays that meet these guidelines. The investigator should endeavor to install a sampling system that minimizes deviations from these guidelines. It is therefore incumbent upon the investigator to clearly document site-specific conditions and to implement QA/QC measures to quantify the performance of sampling efforts.

Automated pumping samplers can be controlled by a data logger with sampling criteria based on time, stage, rate-of-stage change, or water-quality measurements. An operator can optimize sampling rates in response to changes in expected precipitation volumes during a storm from a remote location, using a communication device such as a cell phone. Gray and Fisk (1992) describe a method for controlling an automatic water sampler based on time, stage, and rate-of-stage-change criteria. Their technique is designed to provide an adequate definition of the flood hydrograph to enable reliable computations of daily sediment and associated chemical constituent discharges. Gray and deVries (1984) describe a system for measuring surface runoff and collecting sediment samples from small areas (on the order of hundreds of square feet). Their automatic pumping mechanism splits the sample into 10 equal parts and retains one or more parts as a representative composite sample for the entire runoff period. A technique for controlling an automatic water sampler based on a time-stratified sampling technique is described by Thomas (1985, 1991), and Thomas and Lewis (1993). This capability increases the amount and quality of data derived at a sampling site, and provides a resource to enable the project manager to make informed decisions on allocations of human resources during runoff at one or more sampling sites.

Automatic pumping samplers, however, are not well suited for all sampling sites. The cost, complexity, and logistics (power, communication requirements, and installation) associated with automatic samplers can discourage their use. Also, the sampler intakes need to be positioned in a location with a sufficient cross-sectional area and flow rate to be submerged enough to obtain representative samples. When automatic pumping samplers are impractical, passive automatic samplers may be a viable alternative.

Commercially available automatic samplers are not designed for collection of bedload. Bedload may represent a part of the sediment carried in highway and urban runoff (Bertrand-Krajewski and others, 1993; Waschbusch, 1999). Although newer samplers have collected sediment with particle sizes as large as fine gravel (Smith, 2000), these samplers do not meet specifications for bedload samplers. For example, manual bedload samplers developed by the Federal Interagency Sedimentation Project (2000a; 2000b), such as the BL-84 or the BLH-84 samplers, are designed to collect particles from about 0.25 to 35 mm in diameter using a pressure-difference principle and a nylon mesh screen to retain the sample (Helley and Smith, 1971; Hubbell and others, 1981; Edwards and Glysson, 1999). The necessary tube diameters, pumping rates, and sample volumes required to collect representative samples by automatic samplers may be prohibitive. Research may be needed to develop and test adaptations of automatic pumping samplers to collect representative samples of bedload material for highway runoff studies.

Passive Samplers

Passive automatic samplers are designed to collect a proportion of flow during the time when runoff submerges the sampler intake port(s). Passive samplers generally include a sample intake, an inflow control assembly, a sampling container, and a housing designed to emplace the sampling container and facilitate sample retrieval. A number of automatic types of passive samplers are available. The following are described in greater detail in the noted references.

- A flow splitter described by Clark and others (1981) uses baffles on a steep inclined plane—to cause supercritical flows—(fig. 5) to obtain a representative and flow-proportional sample of an entire storm. Clark and others (1981) indicate that the composite sample reflects the event mean concentrations calculated from a series of discrete samples taken during a monitored storm. To use this sampler, however, the site must be on a fill section of highway so that this sampler may be employed on the highway shoulder at a steep enough slope to function hydraulically. Racin (1995) also describes use of a similar sampler for NPDES monitoring of highway runoff quality in California.
- A catch-basin sampler described by Pratt and Adams (1981) utilizes a series of five conical mesh screens with decreasing slot sizes to capture sediment greater than 1.25, 0.60, 0.40, 0.15, and 0.09 mm, respectively, while allowing runoff water to pass through (fig. 6). Sediments are retained on the screen and concentrations may be estimated by calculating the total flow passing through the screens during the monitoring period.
- A catch-basin sampler described by Ellis and Harrop (1984) uses a number of sieve trays with decreasing mesh sizes from 2.00 to 0.63 mm to capture sediment while allowing runoff water to pass through (fig. 7). This device is similar to the device described by Pratt and Adams (1981) in that sediment loads are retained on the screen and

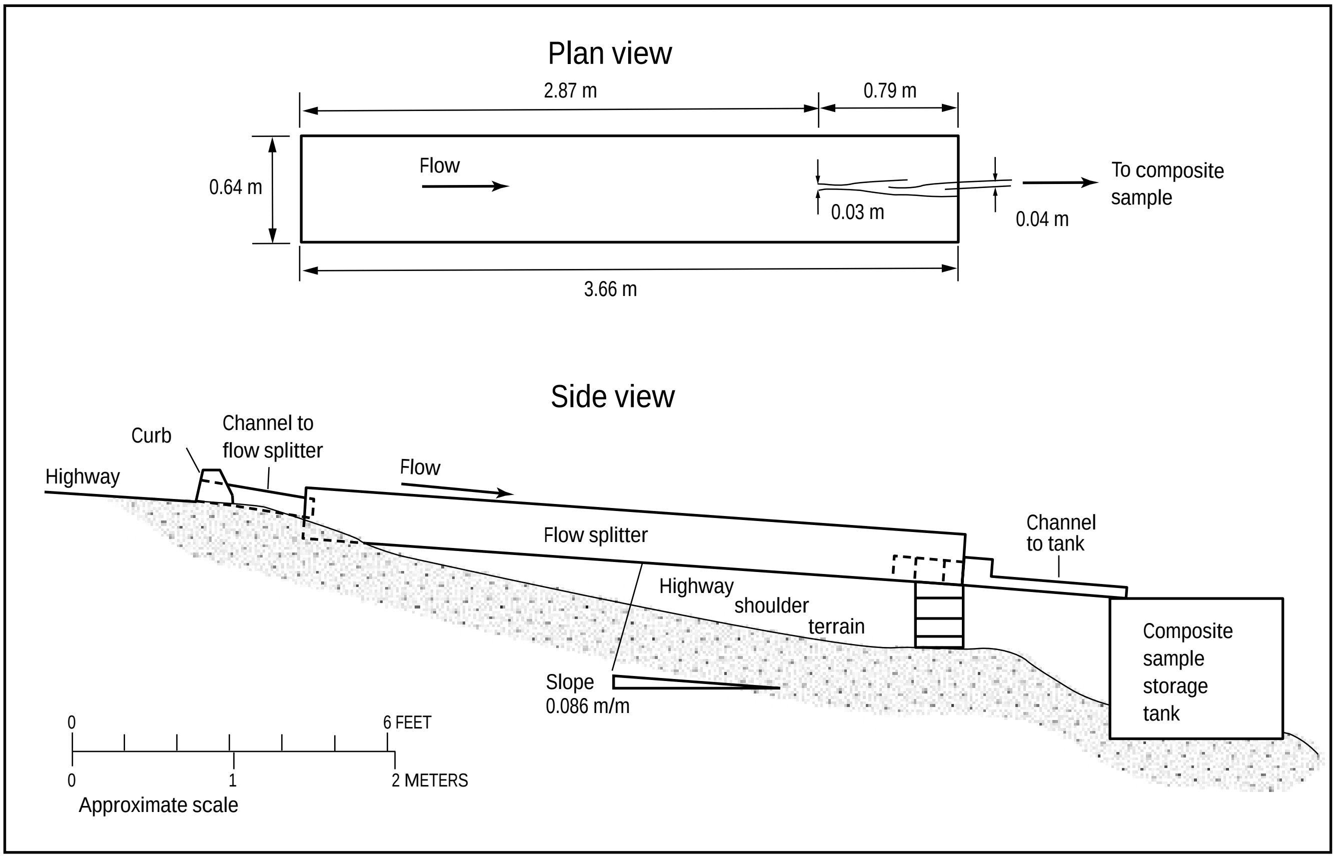


Figure 5. Typical flow splitter (modified from Clark and others, 1981).

concentrations may be estimated by calculating the total flow passing through the screens during the monitoring period.

- A modified single-stage sampler described by Gray and Fisk (1992) is used for passively collecting water samples when the water surface reaches each inlet port in a vertical array of sampling ports (fig. 8).
- A “gully pot” (catch basin) insert described by Spangberg and Niemczynowicz (1992) includes a funnel inlet, water-quality measurement chamber, and a v-notch weir for flow measurement (fig. 9). This device uses a turbidity meter and sampling port to measure turbidity and sediment, respectively.
- A flush mounted sampler (fig. 10*A*) and an “in the pipe” sampler (fig. 10*B*) are described by Dudley (1995). These samplers are designed to collect a water sample by employing a double ball valve so that the sampler is only open during periods of flow immersion and so that the sampler will close once the sample bottle is full.
- A sheet-flow sampler described by Stein and others (1998) is designed to be mounted flush with the pavement (fig. 11). This sampler is normally open to the atmosphere and has a buoyant flap designed to close each inlet port once the receptacle is full.
- A sheet-flow collection system described by Sansalone and others (1998) utilizes a gutter at the pavement edge to concentrates flow through a Parshall flume (to measure flow volume) into a 2,000-liter runoff collection tank (fig. 12). This

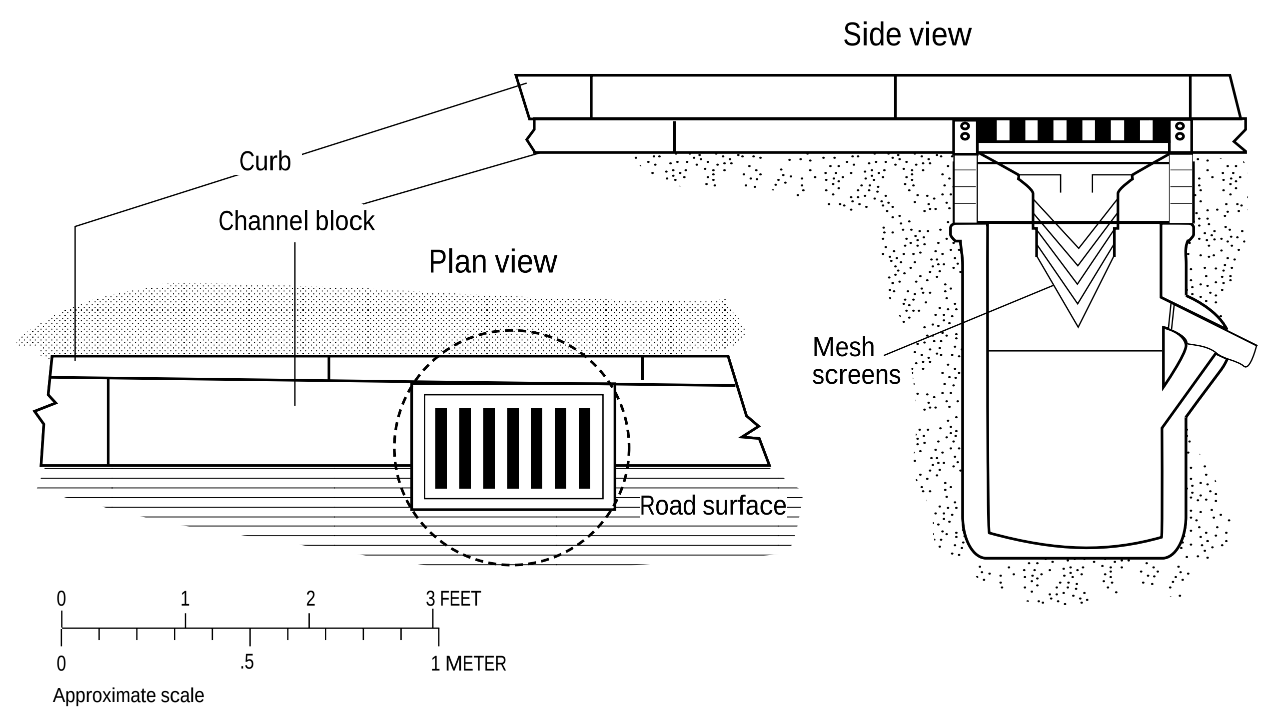


Figure 6. Road washoff material collector for a catch basin (modified from Pratt and Adams, 1981).

passive sampling design also enables use of an automatic pumping sampler by collecting runoff in the flume where flows are concentrated.

- A street-runoff sampler described by Waschbusch and others (1999) is designed to be mounted flush with the pavement for collection of a water sample (fig. 13). This device is normally open and has a setscrew designed to control the inflow volume. Waschbusch and others (1999) also described driveway, lawn, roof, parking lot, and storm-sewer outfall samplers of similar design.

Passive samplers also have technical limitations that must be understood and addressed for representative data collection and interpretation. The quality-control data needed to establish that these samplers perform as expected under the normally harsh highway- and urban-monitoring conditions is not extensive enough to establish comparability and repeatability with other methods. Technical limitations may or may not be substantial depending on site characteristics. Proper site selection and sampling design can compensate for limitations if they are recognized. These limitations include the following:

- Most passive samplers do not have provisions for recording the period of flow sampled.
- Debris buildup on sampler intake(s) can alter the flow of water and sediments completely, precluding sample collection, or partially, thereby affecting the representativeness of samples collected. This may not be apparent, as debris could accumulate and wash off during a single runoff period. However, pumping samplers of relatively recent vintage usually have a purge cycle that may minimize debris buildup.

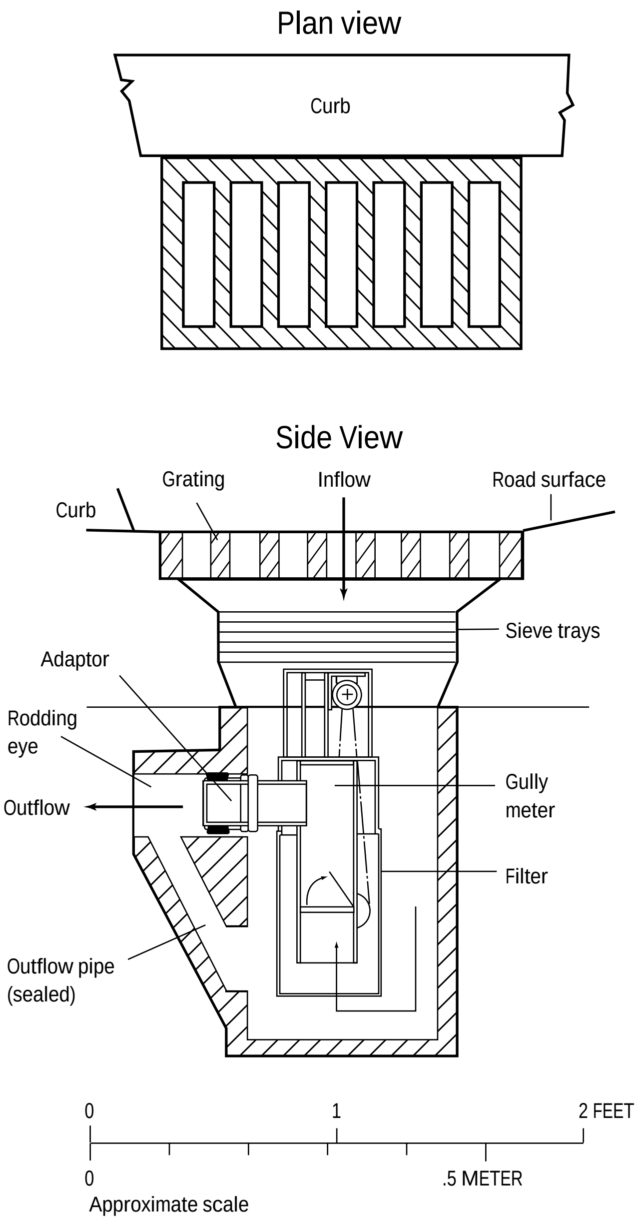


Figure 7. Road washoff material collector for a catch basin (modified from Ellis and Harrop, 1984).

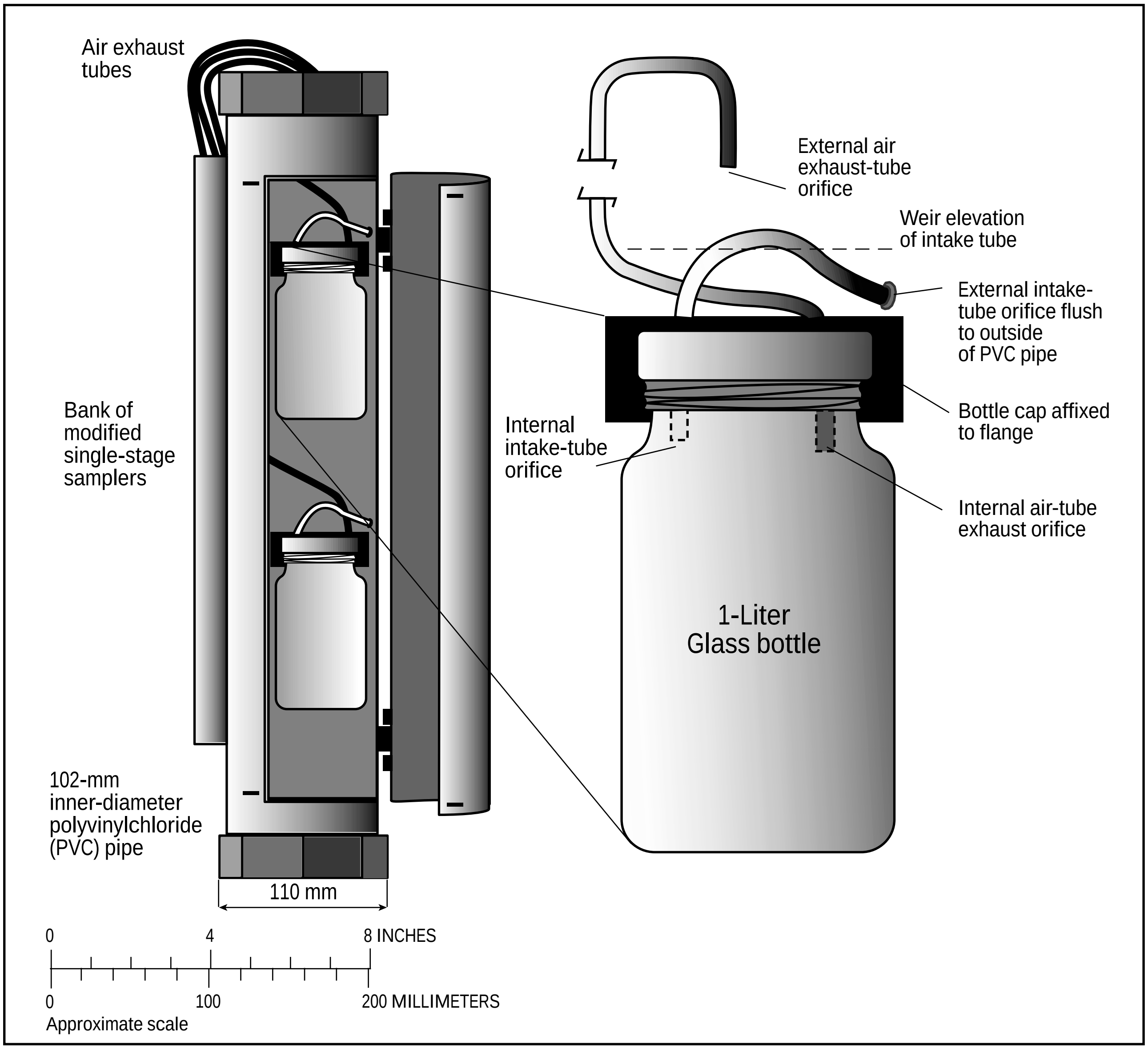


Figure 8. Single-stage sampler (modified from Gray and Fisk, 1992).

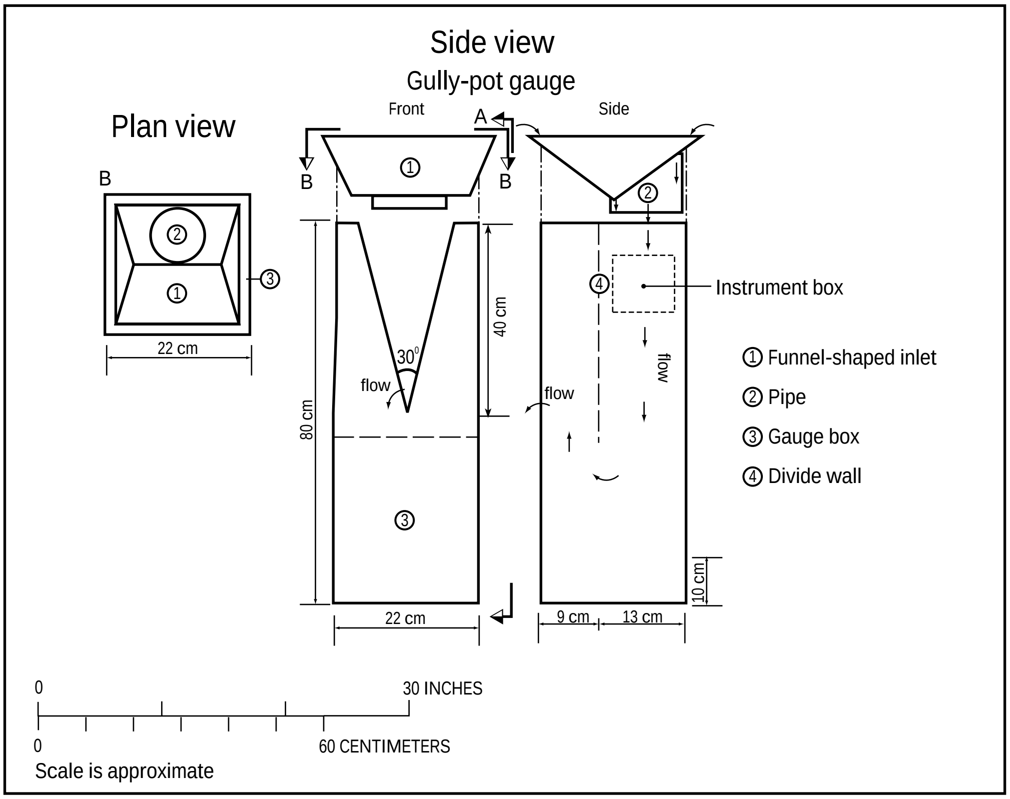


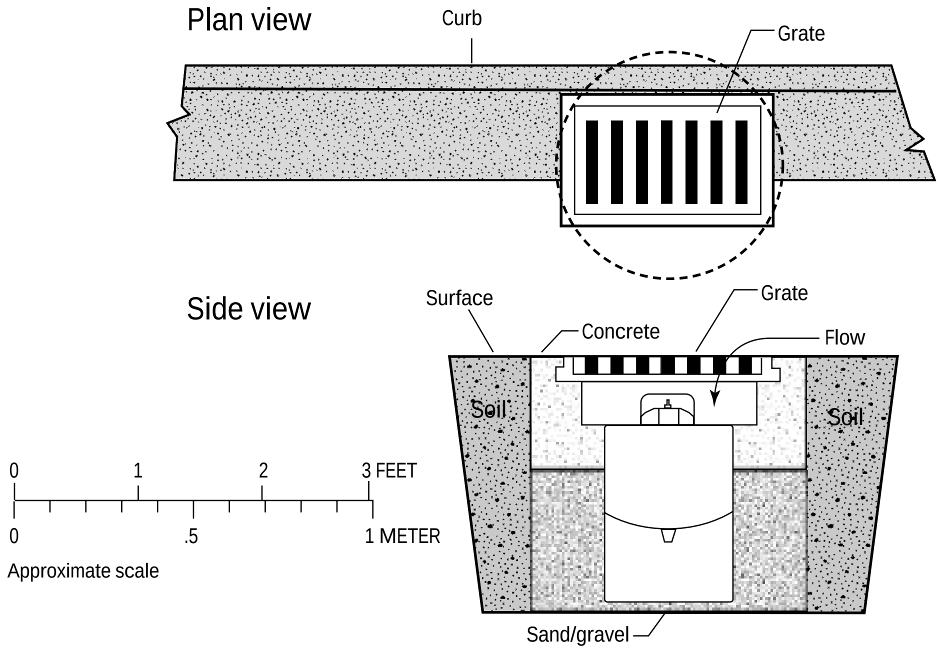
Figure 9. Road washoff material collector for a catch basin (modified from Spangberg and Niemczynowicz, 1992).

- Relatively small contributing areas magnify problems of determining the effective drainage area, and the effects of traffic, bypass flow, and surcharging.
- Relatively small flow-contributing areas also may affect the representativeness of the area sampled and variability in measured concentrations. For example, one piece of rust or tire from a vehicle in a small sampling area could substantially affect a storm load calculated for that area of the highway.
- Samples collected by passive samplers installed on the pavement may be dangerous to retrieve under heavy traffic conditions.
- Passive samplers that are open to the atmosphere may collect debris, sediments, and atmospheric dust blown toward the pavement edge by vehicle action between storms.

To obtain the most reliable and representative data, the passive sampler intake should be placed carefully at a point where sediment concentrations are characteristic of the larger system under study. Therefore, objectives for placing a sampler intake in the flow at any given cross section are as follows:

- Select locations representative of larger study areas.
- Select the intake location so that if possible it is submerged over the complete range of flows or, for single stage sampler(s), the intake is submerged during the intended sampling stage(s).
- Identify or install the device in a position that would not be prone to collecting debris.
- Position one or more intakes to collect the most representative (mean) SSC and PSD samples.

A. **Flush mounted sampler, sump and grate set in ground**



B. **Pipe sampler**

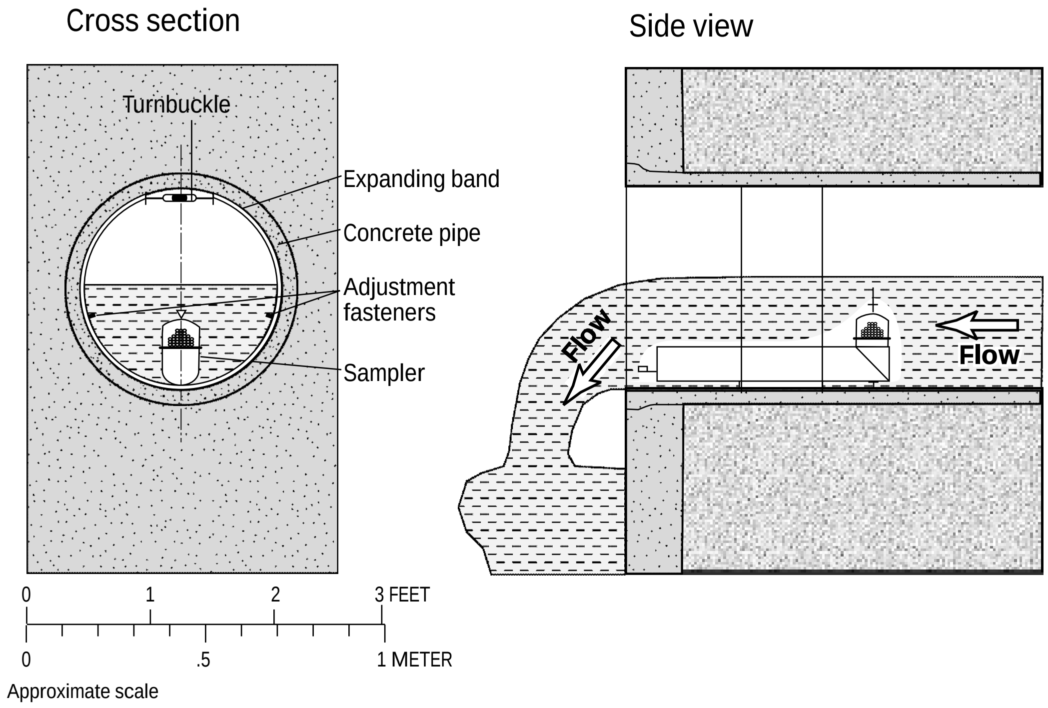


Figure 10. Road washoff material collector for a catch basin and an “in the pipe sampler” (modified from Dudley, 1995).

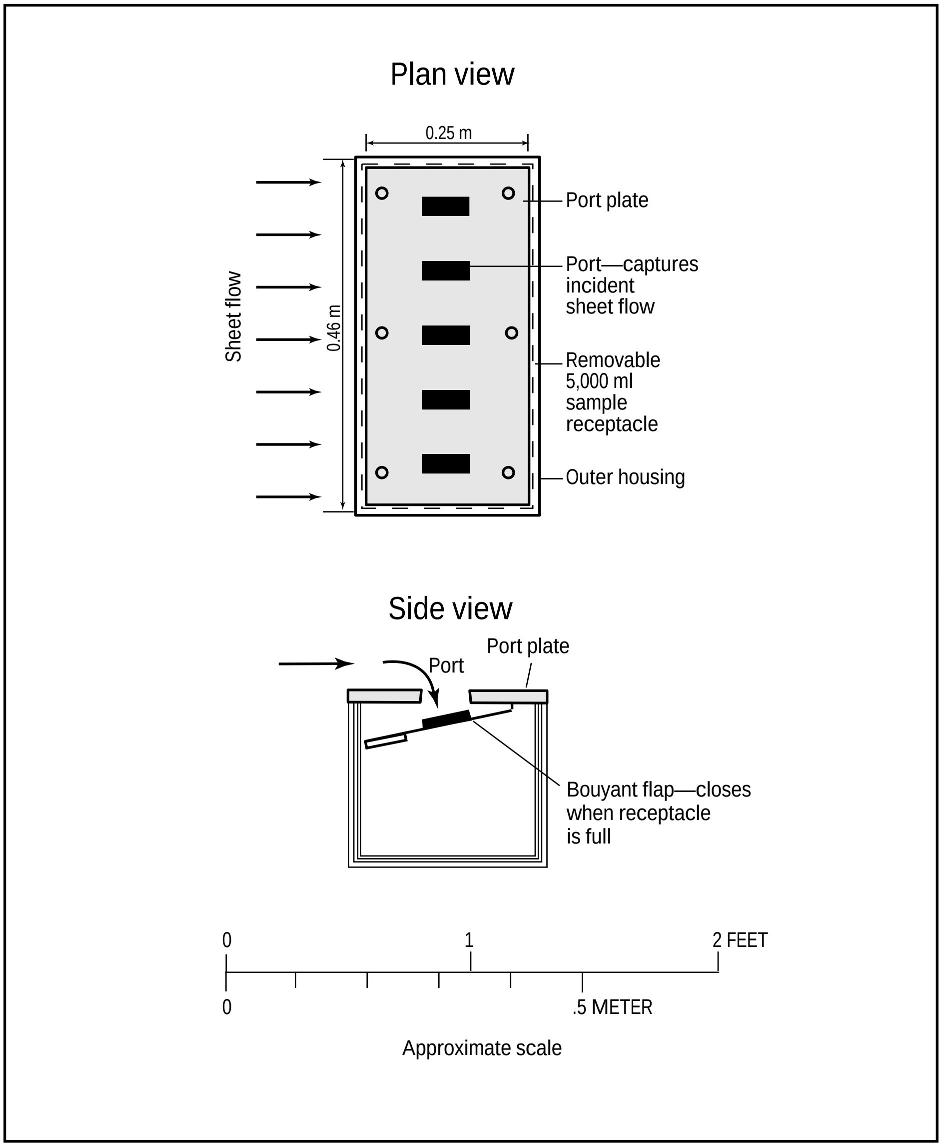


Figure 11. Sheet-flow sampler for a road surface (modified from Stein and others, 1998).

- Emplace multiple samplers to address the problems of small-scale spatial variability and the potential for problems with individual passive samplers.

Site conditions often preclude sampling arrays that meet these guidelines. It is therefore incumbent upon the investigator to clearly document site-specific conditions and to implement QA/QC measures to quantify the performance of sampling efforts.

Some passive samplers are designed for collection of bedload materials. The samplers described by Pratt and Adams (1981); Clark and others (1981); Ellis and Harrop (1984); and Sansalone and others (1998) would be suitable for collection of bedload and suspended sediments. However, research is needed to determine the capture efficiency and other measures of performance for these devices so that the comparability and representativeness of data for highway and urban runoff studies could be assessed. For example, Graczyk and others (2000) compared SSCs of 41 paired samples collected by a single-stage sampler and an automatic pumping sampler and found that mean and median differences (single-stage sampler

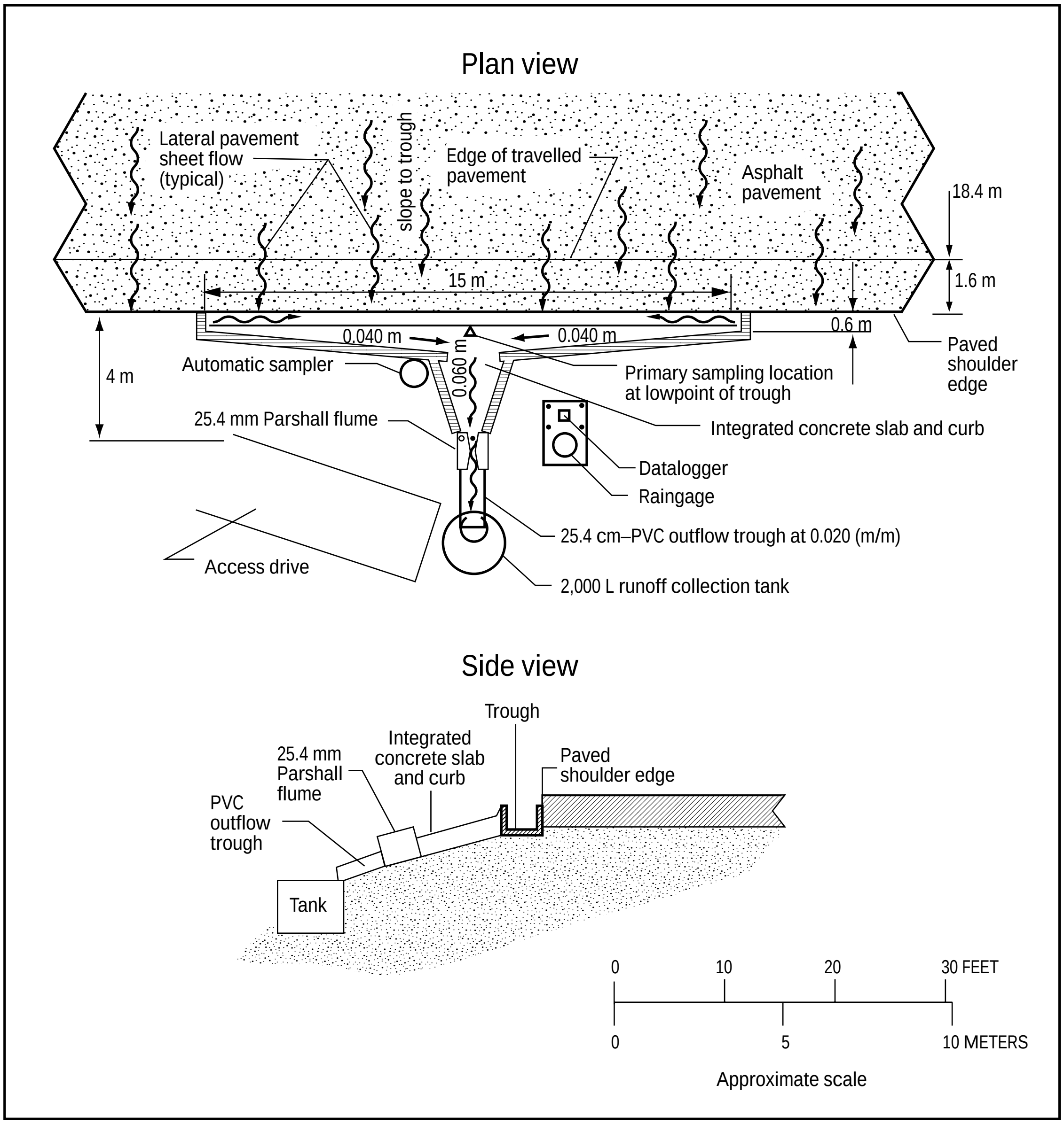


Figure 12. Sheet-flow collection trough for a road (modified from Sansalone and others, 1998).

concentration—automatic pumping sampler concentration) were reasonably similar (14 and 5 mg/L, respectively), but the individual differences had a standard deviation of 133 mg/L and ranged from about -300 mg/L to about 600 mg/L. Therefore, on average, the single-stage samplers may provide representative data but individual sample concentrations collected may vary substantially from samples collected with an automatic pumping sampler (Graczyk and others, 2000).

Indirect Methods for Measuring Sediment

Indirect methods for measuring sediment may be useful as a supplementary and (or) surrogate means to monitoring sediment in runoff. These methods include analysis of available bottom material, measurement of turbidity, and other indirect methods. Each method has benefits and design limitations, which must be recognized and quantified if representative data are to result.

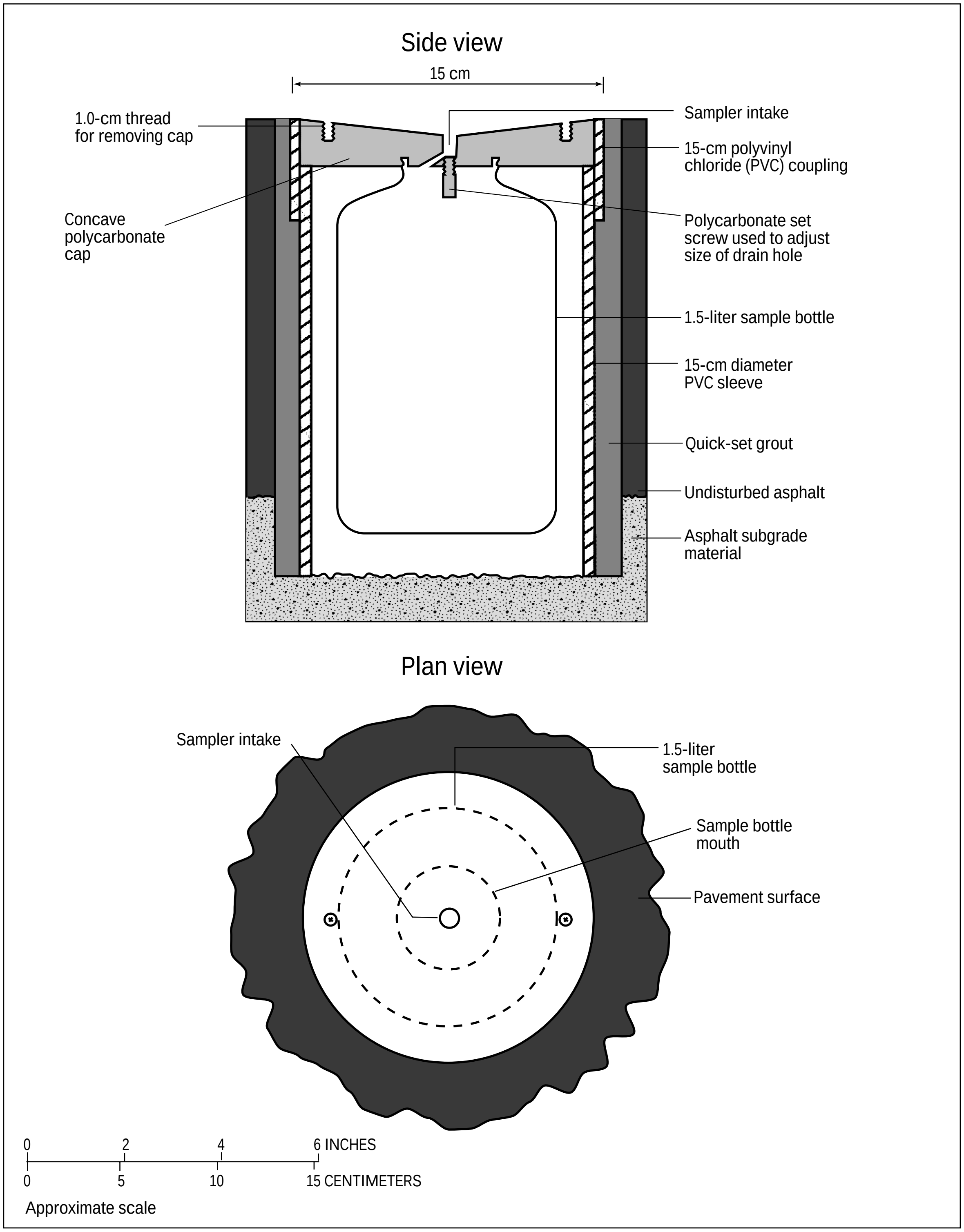


Figure 13. Street-runoff sampler (modified from Waschbusch and others, 1999).

Bottom Material

Bottom material is the sediment mixture remaining on the bottom of the channel (Edwards and Glysson, 1999). More specifically for highway- and urban-runoff studies, it is the sediment retained on the road, in drainage structures, in structural BMPs, or near drainage outfalls in receiving waters between storms. Repeated analysis of the PSD of bottom material provides information about the sediments transported during runoff events at various flow rates. However, bottom-material samples may not include fine material that moved through the system as washload.

Many of the bed-material samplers designed for fluvial systems may also be suitable for bottom material sampling in runoff conveyances. Edwards and Glysson (1999) describe the samplers developed by the Federal Interagency Sedimentation Project for collecting bed sediments in natural waters. Radtke (1997) lists these and several other bed-material samplers. Yuzyk (1986), Ashmore and others, (1988), Diplas and Fripp (1991), Yuzyk and Winkler (1991), American Society for Testing and Materials (1994), Environment Canada (1994), Shelton and Capel (1994), International Standards Organization (1997b), and Edwards and Glysson (1999) provide bed-material sampling guidelines for subsequent physical and (or) chemical analyses. Kobriger and Geinopolos, (1984) discuss bottom-material sampling in a study of sources and migration of highway runoff pollutants. Materials and methods for collection of bottom-material samples need to be evaluated carefully, especially if these materials will also be used for chemical analysis. As with other methods designed for use in natural (fluvial) systems, the design and implementation of these methods need to be evaluated and QA/QC data need be documented so that the comparability and representativeness of data obtained for highway- and urban-runoff studies may be assessed.

Turbidity

Turbidity is a measure of the light attenuation caused by interference from suspended materials and dissolved materials that produce color. Suspended materials that affect turbidity include organic matter (anthropogenic materials, leaves, and aquatic biota), and natural and anthropogenically derived particulates. Color-producing dissolved materials include iron (as ferric humate) and colloids from the decomposition of organic debris. Turbidity is measured either by a turbidimeter or by an optical backscatterance sensor (OBS) (Downing and others, 1981). Turbidity has been a common surrogate used to estimate SSCs in fluvial systems (Brown and Ritter, 1971; Brown, 1973; Reed, 1978; Beschta, 1980; Smith, 1986; Gippel, 1995; Lewis, 1996 and Schoellhammer and Buchanan, 1998). Turbidity also has been measured in many highway- and urban-runoff studies, including those by Irwin and Losey, (1978), Cramer and Hopkins (1981), McKenzie and Irwin (1983); Dupuis and others (1985), Schiffer (1989); Spangberg and Niemczynowicz (1992); and Barrett and others (1996).

Turbidity can be measured to provide real-time estimates of SSCs in flowing waters. To date, several researchers (Reed, 1978; Lewis, 1996; and Eychaner, 1997; Buchanan and Schoellhamer, 1998; Schoellhamer and Buchanan, 1998) have used continuous turbidity data from turbiditimeters or OBS as a surrogate for SSCs. Spangberg and Niemczynowicz (1992) used turbidity measurements to estimate sediment runoff from a parking lot on a 10-second interval. They found substantial variations—related to variations in flow—at time scales on the order of about one minute. In many highway- and urban-runoff studies, however, turbidity is at best a qualitative indication of sediment concentration because measured turbidity depends on many factors, including the PSD of sediments, the quality and maintenance of the probe, the effects of degree of fouling (trash, sediment, and biota) and temperature on the probe. Laboratory analysis of turbidity and SSC data for 1,135 runoff samples collected in a highway drainage pipe in eastern Massachusetts (Smith, 2000) indicates that the relation between measured values is qualitative over the full range of measured sediment concentrations. For example, at a measured turbidity of 100 nephelometric turbidity units (NTU), the SSC ranged from about 70 to 2,000 mg/L, and at a turbidity of 1,000 NTU the SSC ranged from about 700 to 3,000 mg/L (fig. 14). These data do not include the additional variability of measuring turbidity in a harsh field environment that would further reduce the reliability of any quantitative relation developed between turbidity and SSC.

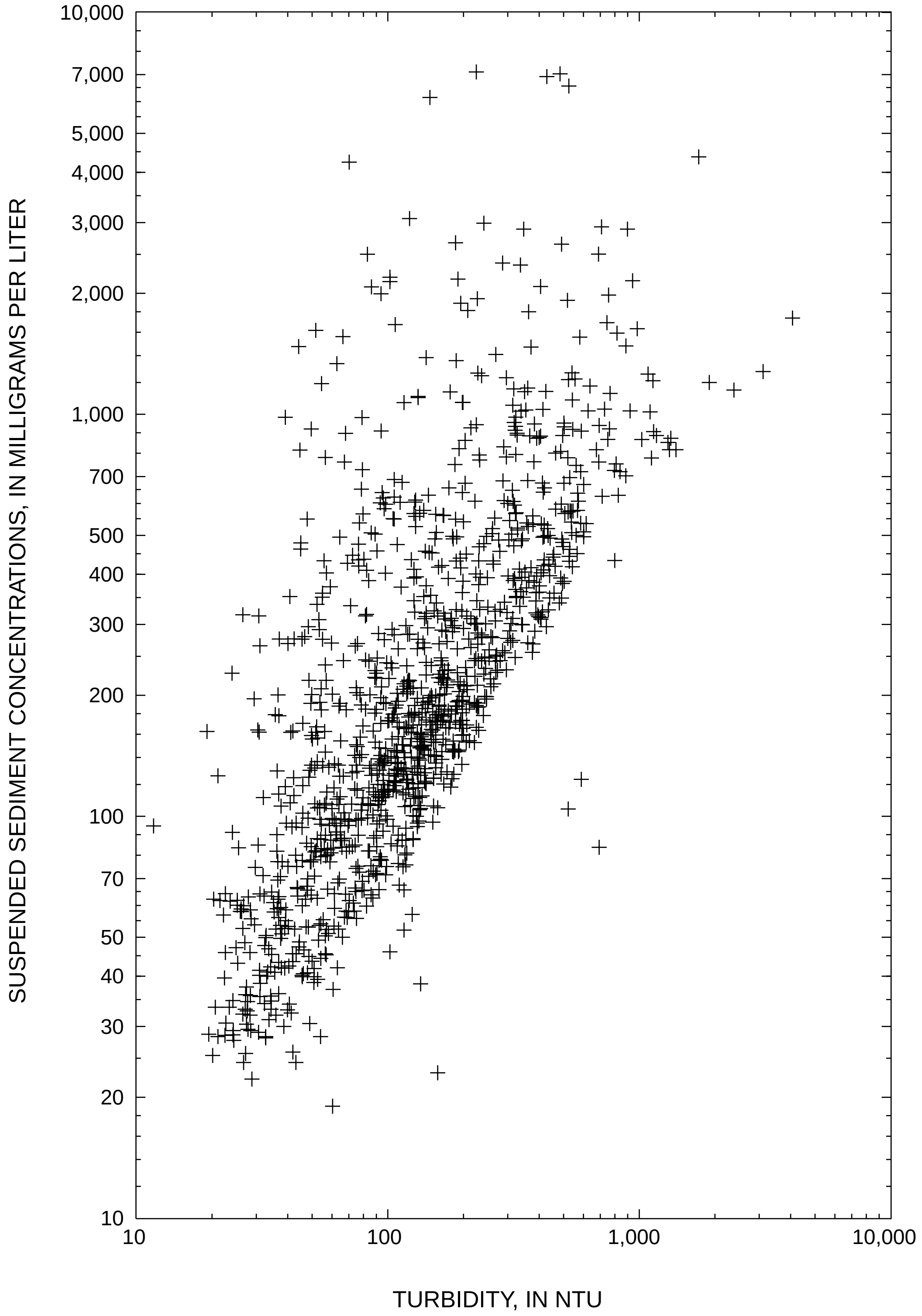


Figure 14. The relation of suspended-sediment concentration to turbidity in highway-runoff samples collected along I-93 in Boston, Massachusetts, 1999–2000 (data from Smith, 2000).

Turbidity as an optical measurement is easily fouled by oil and grease, biofilm, and other materials found in highway runoff. Also, field measurements are affected by temperature, color, bubbles, and larger particles, which may disproportionally influence turbidity in the small field of view of the instrument.

Calibration and maintenance of in-situ turbidimeters and OBS, can be expensive and time consuming. Each instrument must be calibrated periodically on-site with standards. The accuracy of these instruments often tends to vary in one direction, or “drift,” as the sensor becomes fouled with sediment or biota. In spite of these problems, Lewis (1996), and Buchanan and Schoellhamer (1998) recently demonstrated improved accuracy in measuring continuous turbidity data to calculate suspended-sediment discharges in fluvial systems. Highway and urban conveyances, however, can be more challenging because of intermittent flows; large variations in the concentrations and PSDs of sediment, and because of the difficult monitoring environment. As with other sediment monitoring methods, use of turbidity data needs to be evaluated and QA/QC data need be documented so that the comparability and representativeness of data obtained for highway- and urban-runoff studies may be assessed.

Other Indirect Methods

Skinner and others (1986), Ficken (1986), and Skinner and Szalona (1991) describe other surrogate measurement techniques to infer SSCs. These include a transmissometer, x-ray particle size analyzer, ultrasonic suspended-solids meter, radioisotope gage, vibrating U-tube fluid density tube, vibrating straight tube, and the plummet gage. They report limited successes with these technologies in estimating SSCs in fluvial systems, and none is currently being deployed by the USGS in large-scale monitoring programs. Wren and others (2000) describe emerging technologies as surrogates for measuring SSCs. A suite of emerging technologies for the measurement of suspended sediment, bed material, and bedload, is described by Gray and Schmidt (1998). New technologies that measure suspended sediment and (or) bed topography include acoustic (Kuhnle and others, 1998; Mueller, 1998; Derrow and others, 1998; Garcia and Admiraal, 1998), optic (Muste and Kruger, 1998; Schmidt, 1998a, 1998b), fluid density (William Fletcher, Design Analysis Associates, Inc., written commun., 2000; Dirk de Hoop, Hope Hydrology, written commun., 2000), satellite (Chavez, 1998), laser techniques (Yogi Agrawal, Sequoia Scientific, Inc., written commun., 1998), and electro-mechanical techniques (Jobson, 1998). These technologies are being developed for fluvial systems and show some promise to automate and (or) improve the quality of sediment data collection in that environment. These techniques may also be applicable for future highway- and urban-runoff studies including the monitoring of BMP structures and receiving waters. Currently, the difficult highway- and urban-monitoring environment may preclude use of these devices, but future technical developments may improve the potential utility of these methods. Mineral magnetic techniques, however, may be useful for source identification and may be used to follow the transport and sequencing of surface sediments through a stormwater conveyance systems (Beckwith and others, 1990). As with other methods designed for use in natural (fluvial) systems, the design and implementation of these methods need to be evaluated and QA/QC data need to be documented so that the comparability and representativeness of data obtained for highway- and urban-runoff studies may be assessed

SAMPLE-PROCESSING METHODS

Appropriate sample processing methods are determined by the characteristics of the water sampled and by the analytical and interpretive methods used for data reduction. Water-quality data for highway and urban runoff are generally reported as event mean concentrations (EMC) to provide summary values that can be used to compare measurements from individual runoff periods at a site or from populations of storms between sites. Theoretically, the EMC for suspended sediments is the cumulative storm load (mass) of suspended sediment divided by the total runoff volume for the storm period (event) (Driscoll and others, 1991). An EMC may be determined by collecting a bulk sample, by physically compositing a number of discrete samples, or by mathematically calculating a flow-weighted composite value from analysis of multiple discrete samples taken during the runoff period. The composite sample can be obtained manually from discrete stormwater samples by methods described by Gray and Fisk (1992), or automatically by methods described by Heaney and Huber (1979).

Each sample type has certain pre-analysis processing requirements that may affect measured sediment concentrations. Large bulk samples require homogenization and subsampling to produce an aliquot suitable for laboratory analysis and (or) for concurrent analysis of other water-quality constituents. When discrete samples are physically composited, the resulting bulk volume must also be homogenized and representatively subsampled to produce an aliquot suitable for laboratory analysis and (or) for concurrent analysis of other water-quality constituents. Discrete samples, however, need not be homogenized and subsampled unless laboratory analysis for concurrent analysis of other water-quality constituents is necessary. This requirement can be avoided by collection of duplicate discrete samples for analysis of sediment and other water-quality constituents.

Homogenization

Homogenization is necessary when subsamples will be extracted from an aliquot for analysis. Also, large bulk-samples collected by passive samplers such as described by Clark and others (1981) need to be homogenized and subsampled to obtain volumes that are feasible for laboratory analysis. The objectives of a homogenization process are to provide a uniform distribution of sediment concentrations and PSDs in each subsample extracted. Homogenization is accomplished by imparting kinetic energy to the solution to uniformly suspend all particles in solution. The presence of particles larger than medium sands (about 0.25 mm, table 4) increases difficulties associated with obtaining representative subsamples. Additionally, it may be impossible to evenly distribute several sediment grains throughout a sample container for representative subsampling.

Before 1976, USGS guidelines on manual sample splitting required compositing the water sample into a large, clean jug or bottle, and shaking it for uniform mixing (U.S. Geological Survey, 1976). In 1976, the 14-liter churn splitter, which utilizes a large plunger to mix a composite water sample was introduced to facilitate the withdrawal of a representative subsample of a water-sediment mixture (Capel and Larson, 1996; Wilde and others, 1998). Demonstrating the comparability of the homogenization process among different samples is important to establish that sediment subsamples are representative and that sediments included in each subsample used for chemical analysis are comparable. It is therefore incumbent upon the investigator to use consistent homogenization protocols, to clearly document site-specific conditions (such as the range of concentrations and PSDs) and to implement QA/QC measures to quantify the performance of this sample processing method.

Subsampling Water-Sediment Mixtures

Samples of water-sediment mixtures are sometimes subsampled, or split into multiple parts to enable different analytical determinations on the subsamples. The validity of data obtained from subsamples depends on the comparability of selected constituent concentrations in the subsample to those in the original sample. Subsamples tend to have larger constituent variances than the original, and may also be biased. Subsampling should be avoided unless it is necessary to achieve the ends of the sampling program. Currently, the 14-liter churn splitter is commonly used to collect subsamples for analysis of sediment concentrations (Capel and Larson, 1996; Wilde and others, 1998). The cone splitter, developed to split water samples for suspended sediment and other water-quality constituents into ten equal and representative aliquots, was introduced for wide-scale use in 1980 (Capel and Nacionales, 1995; Capel and Larsen, 1996). Results of tests on the sediment-splitting efficiency of the churn and cone splitters were published in 1997 (U.S. Geological Survey, 1997). The churn splitter was approved for providing subsamples when the original sample's sediment concentration is less than 1,000 mg/L at mean particle sizes less than 0.25 mm. At SSC concentrations of 10,000 mg/L or more, the bias and precision of sediment concentrations in churn splitter subsamples are considered unacceptable (U.S. Geological Survey, 1997; Wilde and others, 1999b). The cone splitter was approved for providing subsamples at sediment concentrations up to 10,000 mg/L at mean particle sizes less than 0.25 mm. The test data suggest that the cone splitter's acceptable concentration range exceeds 10,000 mg/L, and may approach 100,000 mg/L at PSDs less than 0.25 mm.

The usefulness of data obtained from subsamples depends on their comparability of selected constituent concentrations to those in the original sample. Demonstrating the comparability of the subsampling process is important to establish that sediment subsamples are representative and comparable. It is therefore incumbent upon the investigator to select consistent subsampling protocols, to clearly document site-specific conditions (such as the range of concentrations and PSDs) and to implement QA/QC measures to quantify the performance of this sample processing method.

SAMPLE-ANALYSIS METHODS

Representative analysis of concentrations and physical characteristics of sediment in highway and urban runoff is an integral step toward assuring data quality. Methods for determining the physical characteristics of sediment that are pertinent to the study of highway and urban runoff include PSD, specific gravity, settling velocity, and the organic content of sediment.

Measurement of Sediment Concentration

Virtually all solid-phase concentration values determined in the United States are obtained by one of two analytical methods: the suspended-sediment concentration (SSC) method (American Society for Testing and Material, 2000) and the total suspended solids (TSS) method (American Public Health Association and others, 1995). Analytical methods used to produce SSC and TSS data differ; however, the terms are often used interchangeably to describe the concentration of solid-phase material suspended in a water-sediment mixture, usually expressed in milligrams per liter (G.E. Granato, USGS, oral commun., 1999; James, 1999). Extensive review of highway- and urban-runoff water-quality literature indicate that these studies commonly do not define the analysis method, but almost all describe the total concentration of suspended solid-phase material in terms of TSS, regardless of the method used (G.E. Granato, USGS, written commun., 2000). For example, the draft report, “Proposed Sediment Total Maximum Daily Load for Stekoa Creek, Georgia” (U.S. Environmental Protection Agency, Region 4, written commun., 2000) uses “regional TSS data” that are compiled from U.S. Geological Survey records; the TSS data referred to are actually SSC data. Buchanan and Schoellhamer (1998) refer to sediment data collected as “suspended-solids concentration data” for San Francisco Bay monitoring efforts. These data would more appropriately be referred to as SSC, because the total water-sediment mass and all sediment are measured in the analysis (Alan Mlodnosky, USGS, oral commun., 1999).

Use of SSC and TSS in load calculations can produce substantially different results (Glysson and others, 2000, 2001; Gray and others, 2000, 2001a; Gordon and others, 2001). Although these methods are often expected to produce comparable results, recent research indicates that there are systematic differences between methods (Glysson and others, 2000, Gray and others, 2000).

The SSC method (American Society for Testing and Materials, 2000) uses standardized procedures and equipment to measure all of the sediment and the net weight of the water-sediment mixture to calculate concentration. Three analytical methods are used to produce SSC data: Evaporation, filtration, and wet-sieving filtration of the entire sample volume received by the laboratory. The evaporation method is applicable for all concentrations; if the dissolved-solids concentration exceeds about 10 percent of the sediment concentration, an appropriate correction factor must be applied to the suspend-sediment concentration value derived by the evaporation method because these solids are included in the analysis. The filtration method is used only on samples with concentrations of sand-size material (diameters greater than 0.062 mm) less than about 10,000 mg/L and clay-size material concentrations of about 200 mg/L or less. No dissolved solids correction is needed. The wet-sieve-filtration method yields a concentration for the total sample, a concentration of the sand-size particles, and a concentration for the silt- and clay-size particles. A dissolved-solids correction may or may not be needed, depending on the type of analysis done on the fine fraction and the dissolved-solids concentration of the sample. These three methods are virtually the same as those used by USGS sediment laboratories and described by Guy (1969). USGS sediment laboratories, however, use the Whatman grade 934AH, 24-millimeter-diameter filter for purposes of standardization. Each method includes retaining, drying at 103˚ to 105˚C, and weighing all of the sediment in a known mass of a water-sediment mixture. The USGS analyzes sediment samples using methods described by Guy (1969), Matthes and others (1991), Knott and others (1992, 1993), and U.S. Geological Survey (1998a; 1998b; 1999a). Most of these methods were developed by the Federal Interagency Sedimentation Project, were approved by the Technical Committee (Glysson and Gray, 1997), and are used by most Federal agencies that analyze fluvial sediment data.

According to Gray and others (2000), all three SSC test methods have analytical uncertainties (precision and bias) on the order of plus or minus:

- 6 to 40 percent at low concentrations (about 10 mg/L),
- 2 to 20 percent in midrange concentrations (from 100 to about 1,000 mg/L), and uncertainties decrease proportionally with increasing concentrations (greater than 1,000 mg/L).

Tests of SSC quality-control samples by sediment laboratories participating in the USGS National Sediment Laboratory Quality Assurance Program (Gray and others, 2000; 2001a; 2001b) provide estimates of bias and variance associated with sediment data. The median concentration bias for all participating laboratories is -1.83 percent, and the 25th and 75th percentile values are -4.39 and 0.00 percent, respectively (Gray and others, 2000). The bias primarily reflects a loss of some sediment, such as through a filter or an inability to weigh accurately very small amounts of sediment. Gordon and others (1999) show that the concentration bias is largest at smaller concentrations, and very small at concentrations exceeding about 2,000 mg/L.

The TSS analytical method (American Public Health Association and others, 1995) originated as an analytical method for wastewater samples. The fundamental difference between SSC and TSS analytical results stems from preparation of the sample for subsequent filtering, drying, and weighing. In contrast with the SSC analytical method, the TSS method requires analysis of a subsample extracted from the original. The standard method requires a subsample, or aliquot volume of 100 mL, unless more than 200 mg of residue is expected to collect on the filter, in which case a proportionally smaller volume is removed. The standard specifies that a subsample be extracted from the original water sample by pipette while the entire sample volume is being mixed with a magnetic stirrer. The subsample is filtered, and the filter and contents are removed and dried at 103˚ to 105˚C, and weighed. No dissolved-solids correction is required and the standard provides no indication of the size of particles used in the testing for the method. The percentage of sand-size and finer material cannot be determined using the TSS method.

In practice, TSS data are produced by a number of variations to the processing methods described in the American Public Health Association and others (1995). For example:

- For the collection of TSS samples from the Chesapeake Bay Program, field staff pump water from a specified depth into a plastic gallon container. The container is vigorously shaken, and 200–1,000 mL of the water-sediment mixture is poured for field filtering and subsequent analysis. (Mary Ley, Interstate Commission on the Potomac River Basin, the State of Maryland, and the Commonwealth of Virginia, written commun., 2000).
- A State government laboratory in Virginia produces TSS data by vigorously shaking the sample and pouring the sample into a crucible for subsequent analysis. All of the sample is poured into the crucible unless “there is a lot of suspended material,” in which case only part of the sample is poured (Lori Sprague, U.S. Geological Survey, written commun., 1999).
- One laboratory analyzed TSS quality-control samples using Method 2540D of the American Public Health Association and others (1995), with the following variation: The sample is shaken vigorously and a third of the desired subsample volume is decanted to a secondary vessel. This process is repeated twice to obtain a single subsample for subsequent filtration, drying, and weighing.

The reduction in TSS data comparability by variations in protocols used is not limited to lack of consistency in processing and analytical methods. According to James (1999), there is generally no agreed upon definition of TSS in regard to stormwater runoff, in part because the settleable part of TSS is not reported in most stormwater studies.

If a sample contains a substantial percentage of sand-size material, stirring, shaking, or otherwise agitating the sample before obtaining a subsample will rarely produce an aliquot representative of the sediment concentration and PSD of the original sample. This is a by-product of the rapid settling properties of sand-size material, compared to those for silt- and clay-size material, given virtually uniform densities as described by Stokes' Law. Aliquots obtained by pipette might be withdrawn from the lower part of the sample where the sand concentration tends to be enriched immediately after agitation, or from a higher part of the sample where the sand concentration is rapidly depleted. Additionally, the physical characteristics of a pipette used to withdraw an aliquot can introduce bias in the subsample (Gray and others, 2000).

The physical characteristics of a pipette used to withdraw an aliquot, or subsample, can introduce additional errors in subsequent analytical results. The tip opening of pipettes recommended for use is about 3 mm in diameter (Kimble-Contes, Inc., 2000). The upper limit of sand-size particles, which is expressed as the median diameter, is 2 mm (Folk, 1980). A natural sediment particle's long axis is almost always larger than its median diameter and can be substantially larger. Hence, a single coarse-grained sand particle or multiple sand-size particles, particularly when present in large concentrations, may clog a 3-millimeter tip pipette under suction.

Subsampling errors are hardly limited to use of a pipette to withdraw a sample. Methods that include pouring of a subsample can introduce additional errors in subsequent analytical results. This is because, based on Stokes' Law, subsamples obtained by pouring a sand-rich water-sediment mixture likely will be deficient in sand-size material due to settling in the original sample. Fine-material concentrations will not normally be altered by the removal of an aliquot.

Bias in results produced by the SSC and TSS analytical methods tends to become apparent when sand-size material exceeds about a quarter of the sediment mass in the sample (Gray and others, 2000). This has important ramifications with respect to transport calculations. Solid-phase concentrations tend to increase with discharge for a stream, as does the percentage of sand-size material in transport. High flows tend to be inordinately influential in mass transport. Bias in TSS data would probably be largest at higher flows, and therefore transport calculations based on TSS data are prone to be biased. Glysson and others (2000; 2001) indicate that transport estimates using TSS data can be orders of magnitude in error. Gray and others (2000) show an example of a stream at low flow where instantaneous-value sediment discharges calculated from SSC data are more than an order of magnitude larger than those calculated from TSS data at similar flow rates. Glysson and others (2000; 2001) conclude that there appears to be no simple, straightforward way to relate TSS and SSC data unless pairs of TSS and SSC results are available for a site.

Part of the problem may be attributable to the origin of the TSS method and subsequent changes in the types of water for which it is recommended for use. The American Public Health Association and others (1971) intended the Total Suspended Matter Method (a precursor to the TSS method) to be suitable for "wastewaters, effluents, and polluted waters." In 1976, the American Public Health Association and others deemed the Total Suspended Matter Method as suitable for “residue in potable, surface, and saline waters, as well as domestic and industrial wastewaters in the range up to 20,000 mg/L.” Gray and others (2000) conclude that the TSS analytical method is being misapplied to natural-water samples, and that the TSS method is fundamentally unreliable for that purpose. Additionally, the percentage of sand-size and finer particles can not be determined as a part of the TSS method, whereas it can be determined as a part of the SSC method.

The USGS (2000) policy on the collection and use of TSS data establishes that TSS concentrations and resulting load calculations of suspended material in water samples collected from open channel flow are not appropriate. The TSS analytical method can result in unacceptable large errors and is fundamentally unreliable to determine concentrations of suspended material in open channel flow. Therefore, based on these issues, the USGS standard for determining concentrations of suspended material in surface-water samples continues to be the SSC method of analysis (USGS, 2000).

These findings are directly relevant to sediment-load estimates in runoff from highways and urban areas. Highway and urban runoff tends to be rich in sand-size material (table 3); hence, TSS analytical results from samples collected may be substantially biased. As described previously, load estimates using TSS data can deviate by orders of magnitude from those calculated from SSC data.

To examine the applicability of TSS data in highway and urban runoff, analyses of paired SSC and TSS samples collected by the USGS from studies of highway sediments along I-93 in Boston, Mass. (Smith, 2000), and along I-894 in Milwaukee, Wisc. (Waschbusch, 2000), were examined (fig. 15). As with the natural water samples examined by Glysson and others (2000) and Gray and others (2000), results from the TSS analytical method have a substantial negative bias when compared to the SSC method. These data sets (Smith, 2000; Waschbusch, 2000) also indicate that the sand-size fractions can be substantial, and that the grain-size distributions vary considerably between samples within a storm and also vary considerably among storm-runoff periods (fig. 16). These TSS data are not representative of sediment loads from highways and cannot be quantitatively adjusted to produce SSC estimates because of the large variability in grain-size distributions from storm to storm. Analyses of these data sets, obtained from a coastal site and an interior sites in the conterminous United States, indicate substantial differences between TSS and SSC in highway-runoff data that are consistent with those reported by Glysson and others (2000) and Gray and others (2000). It is therefore incumbent upon the investigator to select consistent subsampling protocols, to clearly document

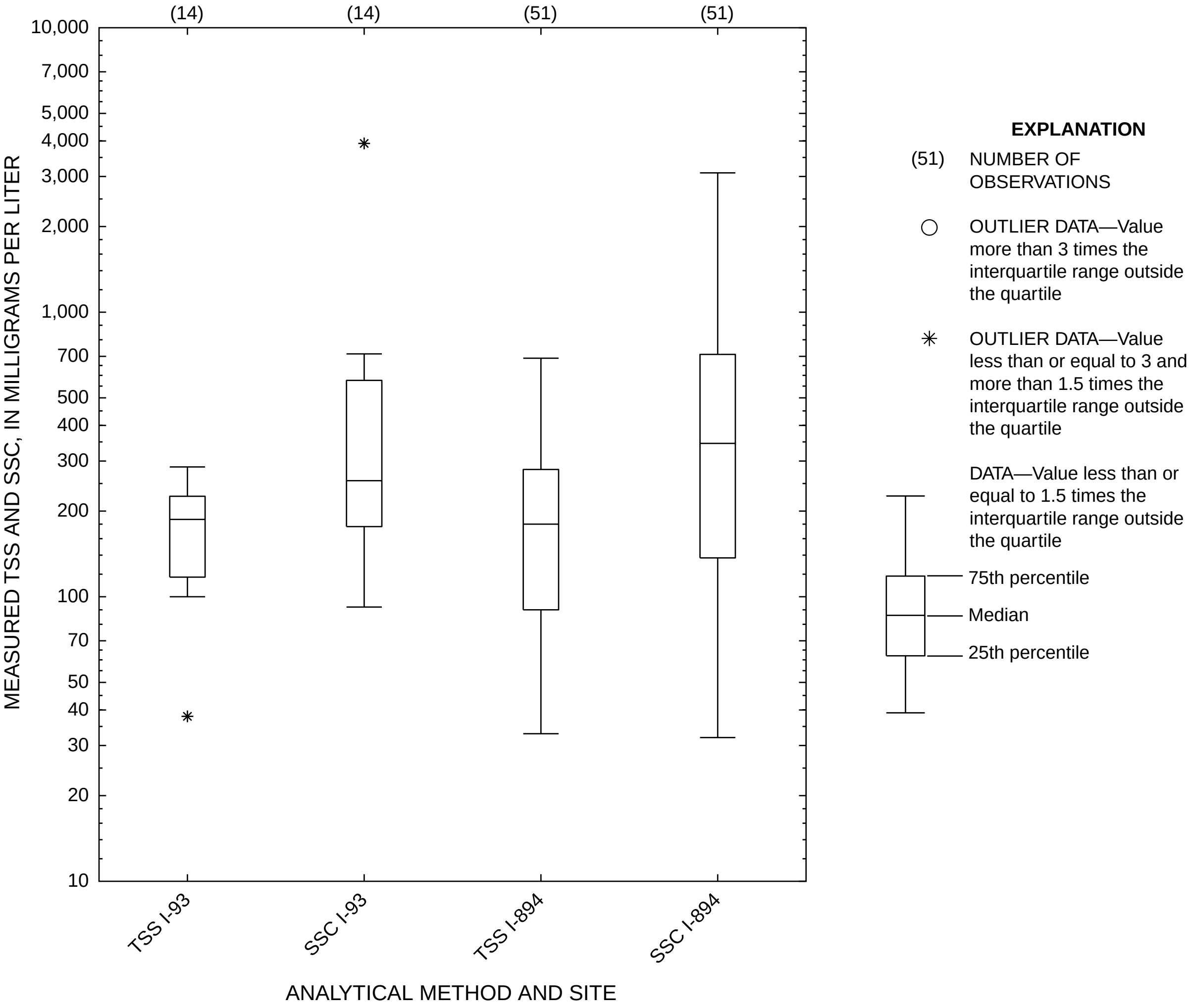


Figure 15. Distribution of measured total suspended solids (TSS) and suspended-sediment concentration (SSC) in highway-runoff samples collected along I-93 in Boston, Massachusetts, and I-894 in Milwaukee, Wisconsin, 1999–2000 (data from Smith, 2000 and R.J. Waschbusch, U.S. Geological Survey, written commun., 2000, respectively).

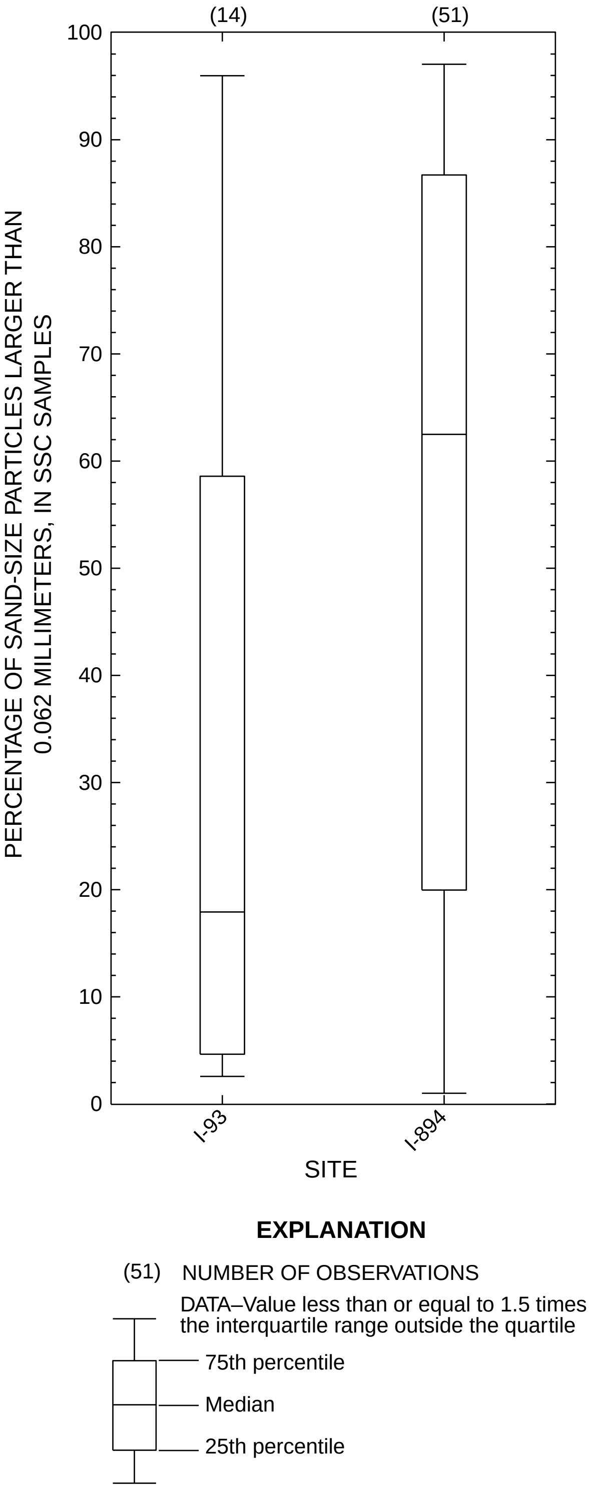


Figure 16. Distribution of the percentage of sand-size particles measured in suspended-sediment concentration (SSC) in highway-runoff samples collected along I-93 in Boston, Massachusetts, and I-894 in Milwaukee, Wisconsin, 1999–2000 (data from Smith, 2000, and R.J. Waschbusch, U.S. Geological Survey, written commun., 2000, respectively).

site-specific conditions (such as the range of concentrations and PSDs) and to implement QA/QC measures to quantify the performance of the sample-analysis methods used.

Perhaps the broadest implication of this systematic problem in the TSS analysis method is for interpretation of the performance of sediment-removal BMPs. For example, figure 17 demonstrates the effect of the analysis method on the calculated removal efficiency of catch basins and oil-grit separators. These devices have a median removal efficiency of about 50 percent when the SSC analysis is used because these BMPs are relatively effective for removing sand-size particles. When the proportion of SSC associated with fine sediments (diameters of less than 0.063 mm) are calculated, this "efficiency" compares well with the TSS efficiency calculated using the TSS analysis (fig. 17). These efficiencies are less than the efficiencies calculated using the SSC analysis because these devices do not effectively retain fine-grained sediments. When the TSS analysis method is used, these artifacts will have several important consequences for the assessment, design, and maintenance of BMPs, including:

- the variability in grain-size distributions for different periods of storm runoff and site to site may confound meaningful analysis of BMP effectiveness;
- the necessary volume of sediment-retention structures may be underdesigned; and
- maintenance schedules for sediment removal from these structures may not be adequate because sedimentation rates may be greater than expected.

These problems may arise if decisions are based on expected TSS capture efficiencies because the TSS values do not reflect the actual sediment retention of larger grain sizes, which are characterized by the SSC method. Problems in analysis, interpretation, and design using the TSS method would be exacerbated in areas where sand is used for winter maintenance.

Particle-Size Distribution

Particle-size distribution (PSD) is the percentage measured by mass, volume, or number of particles in a range of specific sizes, such as those shown in table 4. The American Society for Testing and Materials (ASTM) (American Society for Testing and Materials, 1997a; 1997b) has identified information about the

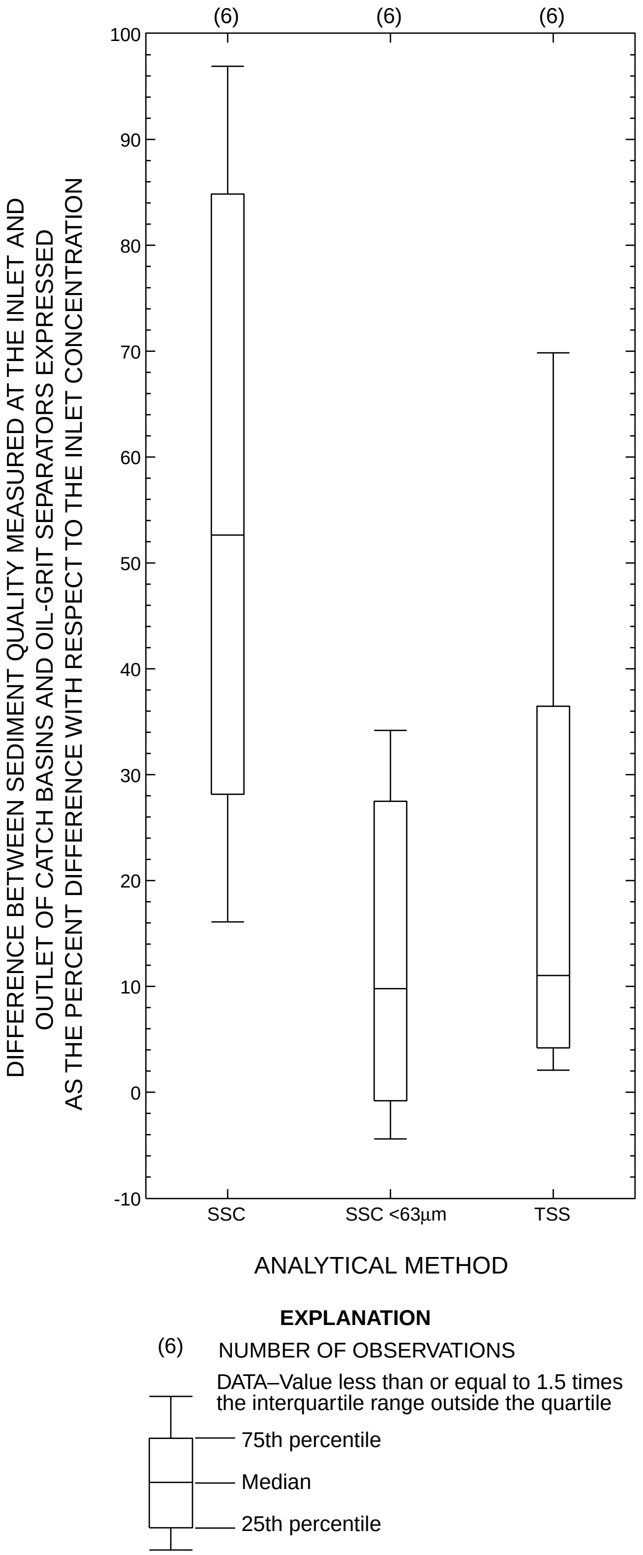


Figure 17. Distribution of differences in sediment measured at the inlet and outlet of catch basins and oil-grit separators in highway-runoff samples collected along I-93 in Boston, Massachusetts (data from Smith, 2000).

PSD to be a necessary component of data sets for environmental sediments. Particle-size analysis is useful for study of the chemistry (Breault and Granato, 2001), transport, and fate of sediment in highway and urban runoff, BMPs, and receiving waters (Kobriger and Geinopolos, 1984). Particle-size analysis may be a measure of sample integrity because the representativeness of individual samples collected may be compared to the grain-size distributions measured for each site. For example, an unusually high sediment concentration may be caused by relatively few sand-size particles in a sample in which the materials at a site are predominantly fine grained, because one medium-size sand grain has the equivalent mass of about 1,000 medium-size silt grains given equal densities. Traditional manual methods used for determining particle size are dry sieve, wet sieve, visual-accumulation (VA) tube, bottom withdrawal (BW) tube, pipet, and microscopy (Guy, 1969; International Standards Organization, 1997a; Percival and Lindsay, 1997; American Society for Testing and Materials, 1999). Electronic methods used for determining particle size include the electrical sensing-zone principal (Coulter Counter), x-ray sedimentation (Sedigraph), laser time of transition (Brinkman Particle Size Analyzer), laser diffraction spectroscopy, and light-optically based image analysis (Matthes and others, 1991; Percival and Lindsay, 1997; Jongedyk, 1999). Each method has different effective size ranges, effective analysis concentrations, and sediment quantity requirements (Guy, 1969; Percival and Lindsay, 1997). For example, sieve analysis has a lower limit of about 0.062 mm, whereas pipet analysis is most effective in the range between 0.002 and 0.062 mm (Guy, 1969; Matthes and others, 1991). Each method is also based on design assumptions that may affect the interpretation of results. For example, grain sizes produced by the pipet and Sedigraph methods are based on the assumption that all sediments in the sample have the specific gravity (and therefore the effective fall velocity) of similar shaped quartz particles (Percival and Lindsay, 1997). It is therefore incumbent upon the investigator to select consistent PSD analysis protocols designed for the concentrations, size range, and other characteristics typical of highway- and urban-runoff sediments. It is also necessary to clearly document the methods used to implement QA/QC measures to quantify the performance of PSD methods (Matthes and others, 1991; Knott and others, 1992; 1993).

Specific Gravity

Specific gravity is the ratio of the unit weight of the sediment to the unit weight of water at 4˚C. It is a unitless measure of density determined by direct measurement of the weight and volume of the sediment sample (Guy, 1969). The ASTM (American Society for Testing and Materials, 1997a) has identified specific gravity as a necessary component of data sets for characterization of environmental sediments. Knowledge of specific gravity of runoff sediments provides information about the settleability of these sediments. For example, Whipple and Hunter (1981) measured substantial differences among the settling rates of different fractions in urban-runoff samples. As previously mentioned, knowledge of the specific gravity may affect interpretation of PSD analysis. It may also provide information about the relative contribution of inorganic and organic components in runoff sediments because the organic fraction is usually less dense than the inorganic (soil) fractions (Butler and others, 1996a). Typically, mineral species (inorganics) have specific gravities that are generally between about 2.5 and 3.5, (Dunn and others, 1980), whereas the organic fraction of stormwater solids are between about 1.1 to 2.5 (Butler and others, 1996a).

Other Sediment Measurements

Other sediment measurements of potential interest for highway and urban runoff and the design and maintenance of structural BMPs include those of settling velocity, the organic content of sediment, particle shape, and specific surface area. The settling velocity is a primary measure that incorporates a number of factors (grain size and shape, and specific gravity) germane to the treatability of solids in runoff. Methods for determination of settling velocity are described by Guy (1969) and Clesceri and others (1998). As presented previously, the organic content of suspended sediments affects the average specific gravity and could thereby affect the interpreted PSD (Guy, 1969). Particle shape represents the aspect ratios of individual sediments and affects settling velocities and PSD measurements (Vanoni, 1975; American Society for Testing and Materials, 1997a). The specific surface area is a function of the shape and texture of the sediments and is an important characteristic of the sediment's ability to act as a carrier of contaminants (Horowitz and Elrick, 1987; Sansalone and others, 1996; Percival and Lindsay, 1997; Sansalone and others, 1998).

DATA-QUALITY CONSIDERATIONS

Data quality, comparability, and utility are important considerations when collecting, processing, and analyzing sediment samples and interpreting sediment data for studies of highway and urban runoff. Results from a sediment study must also be readily transferable from electronic databases, and useful to resource managers and regulators. To meet these objectives, supporting ancillary information must be available that documents the methods and procedures that are used and describes QA/QC procedures that are employed.

Documentation of Methods

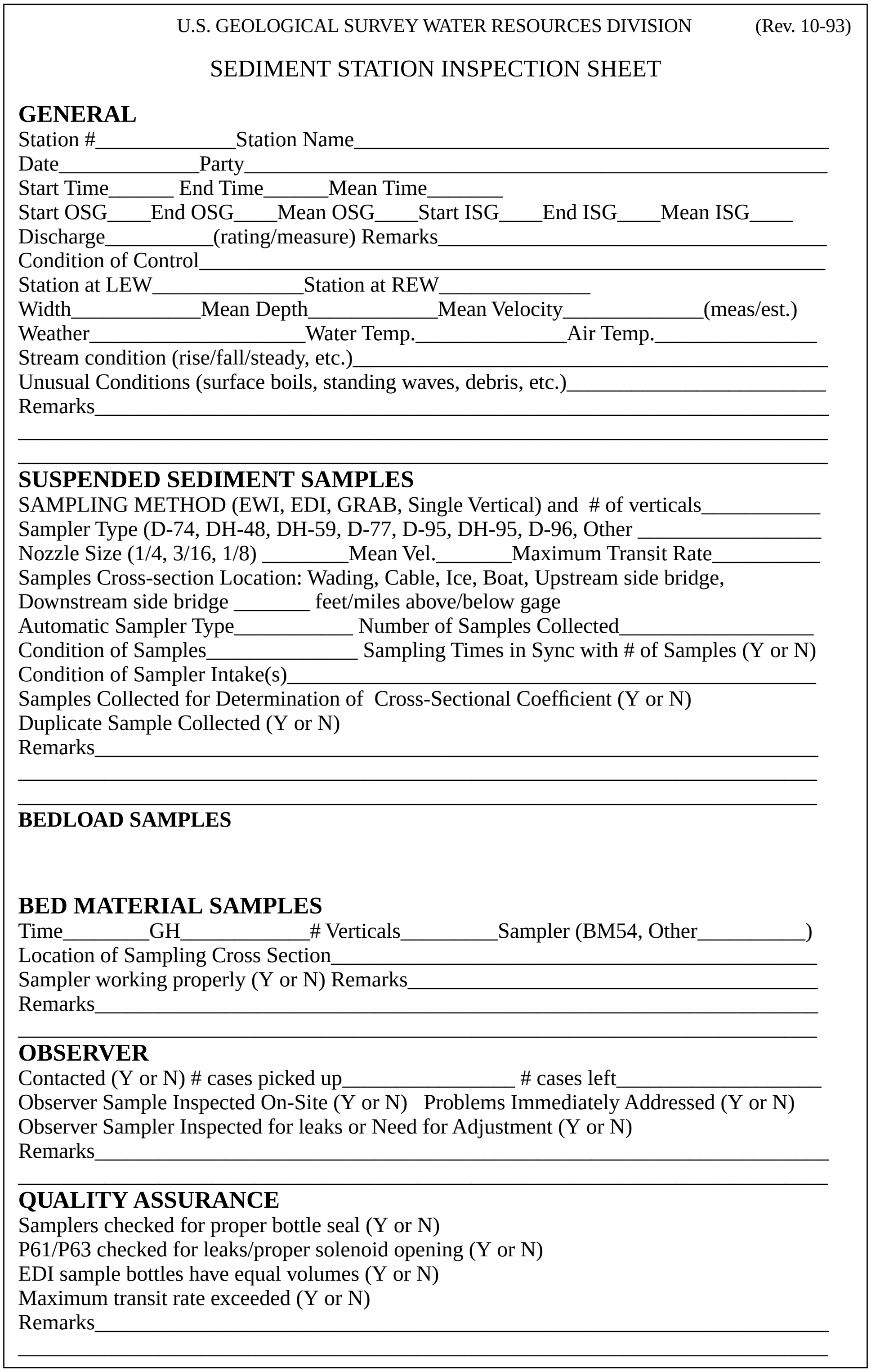
Techniques for the collection, processing, and analysis of sediments in highway and urban runoff and in fluvial systems are continually being developed and refined. New techniques and improvements of existing techniques serve to enhance the accuracy and cost-effectiveness of monitoring programs. This evolution of the science, however, makes it increasingly difficult to compare data over time. This is of particular concern to long-term and broad-scale monitoring and assessment programs that draw upon the expertise of a wide range of scientists. The exclusive use of published and proven procedures would help alleviate this concern, but could impede scientific advancement. Studies designed to compare the results of new and existing methods and the practice of thoroughly documenting and describing all techniques employed, however, can help resolve these problems (U.S. Geological Survey, 1991, Intergovernmental Task Force on Monitoring Water Quality, 1995a; 1995b).

Many of the data elements necessary to document methods and procedures used are discussed in Glysson (1989), U.S. Geological Survey (1991), American Society for Testing and Materials (1997a), and Edwards and Glysson (1999), and are include on sediment-station inspection sheets developed by the

U.S. Geological Survey (1991). Standard sediment-station field inspection forms were designed to record who visited the site, the date and time of each visit, site conditions, the status of equipment and instrumentation, records of instrument calibration, and other information pertinent to the operation of the station that are necessary for data verification (U.S. Geological Survey, 1991). One example of a modified sediment station inspection sheet (Robert Holmes, USGS, written commun., 1994) is provided to illustrate information necessary for documentation of local, regional, and national data sets (fig. 18). The general elements necessary to document the station and field conditions include: station information (linked to detailed location and site characteristics data in the USGS national water data bases), the date and time sediment data are collected, and climatic and hydrologic conditions. Elements necessary to document sample collection methods include the type of sampler, the location in the channel where samples are collected, and the number of and condition of samples collected. When bed-material samples are collected, sampling methods for these samples must be documented as well. Information about the observer is also necessary, especially if sampling is conducted for regulatory programs, which may require chain-of-custody information (U.S. Environmental Protection Agency, 1992; Granato and others, 1998). Information about field quality-assurance steps also are recorded appropriately on the field inspection sheet. Inspection sheets also represent checklists to improve the consistency and comparability of data-collection efforts. For example, if sample water is spilled during transport to the laboratory, field sheet records and practices, such as marking the bottle's water level, may facilitate analysis and interpretation of data. These field sheets should have sufficient space to record remarks describing field conditions such as trash accumulation at the sampling sites, malfunctioning equipment, and other factors that may affect the validity, comparability, or representativeness of samples. These field sheets may be customized to address the data-quality objectives of an individual study and to address site-specific conditions (U.S. Geological Survey, 1991). For example, a water-quality field inspection form designed for use of automated data-collection methods and automatic pumping samplers at a highway-runoff monitoring station is presented in figure 19 (Smith, 2000). All sediment data as well as methods and procedures used in data collection and analysis should be stored in an electronic database(s) with several hard copies stored in alternative locations to avoid the loss of valuable information.

Quality Assurance/Quality Control

In sediment data-collection programs, quality assurance/quality control (QA/QC) efforts are an integral component of all sample collection processing, and analysis operations. Quality-assurance protocols for water-quality data collection have improved substantially since the early 1980s. The guidelines developed by Edwards and Glysson (1999) serve as protocols for sediment data collection by most Federal agencies that collect these data as part of their mission. These guidelines also are consistent with the Wilde and others (1999a) protocols for collection of water samples. Knott and others (1993) provide a quality-assurance plan for field collection, laboratory processing, and office analysis of sediment data. Protocols for collecting stream-water and bed-sediment samples for the National Water-Quality Assessment Program (Shelton, 1994; Shelton and Capel, 1994) are consistent with Edwards and Glysson (1999). Among the protocols relevant to sediment data developed by the International Standards Organization (ISO) are Methods for Measurement of Suspended Sediment (International Standards Organization, 1993), Guidance on Sampling Rivers and Streams (International Standards Organization, 1990b), Guidance on Sampling of Bottom Sediments (International Standards Organization, 1995), and Determination of Turbidity (International Standards Organization, 1990a). Standards relevant to sediment by the ASTM include Terminology for Fluvial Sediment (American Society for Testing and Materials, 1998c), Standard Guide for Sampling Fluvial Sediment in Motion (American Society for Testing and Materials, 1998a), Standard Guide for Core-Sampling Submerged, Unconsolidated Sediment (American Society for Testing and Materials, 1995), Standard Guide for Elements of a Complete Data Set for Non-Cohesive Sediments (American Society for Testing and Materials, 1997a), Standard Guide for the Selection of Maximum Transit Rate Ratios and Depths for the U.S. Series of Isokinetic Suspended-Sediment Samplers (American Society for Testing and Materials, 1998b), Standard Guide for Monitoring Sediment in Watersheds (American Society for Testing and



U.S. GEOLOGICAL SURVEY WATER RESOURCES DIVISION (Rev. 10-93)

SEDIMENT STATION INSPECTION SHEET

GENERAL

Station #_____________Station Name____
Date_____________Party____
Start Time______ End Time______Mean Time_______
Start OSG____End OSG____Mean OSG____Start ISG____End ISG____Mean ISG____
Discharge__________(rating/measure) Remarks____________________________________
Condition of Control____
Station at LEW______________Station at REW______________
Width____________Mean Depth____________Mean Velocity_____________(meas/est.)
Weather____________________Water Temp._______________Air Temp.________________
Stream condition (rise/fall/steady, etc.)____
Unusual Conditions (surface boils, standing waves, debris, etc.)_________________________
Remarks____
____
____

SUSPENDED SEDIMENT SAMPLES

SAMPLING METHOD (EWI, EDI, GRAB, Single Vertical) and # of verticals___________
Sampler Type (D-74, DH-48, DH-59, D-77, D-95, DH-95, D-96, Other _________________
Nozzle Size (1/4, 3/16, 1/8) ________Mean Vel._______Maximum Transit Rate__________
Samples Cross-section Location: Wading, Cable, Ice, Boat, Upstream side bridge,
Downstream side bridge _______ feet/miles above/below gage
Automatic Sampler Type___________ Number of Samples Collected__________________
Condition of Samples______________ Sampling Times in Sync with # of Samples (Y or N)
Condition of Sampler Intake(s)____
Samples Collected for Determination of Cross-Sectional Coefficient (Y or N)
Duplicate Sample Collected (Y or N)
Remarks____
____
____

BEDLOAD SAMPLES

BED MATERIAL SAMPLES

Time________GH____________# Verticals_________Sampler (BM54, Other__________)
Location of Sampling Cross Section____
Sampler working properly (Y or N) Remarks_______________________________________
Remarks____
____

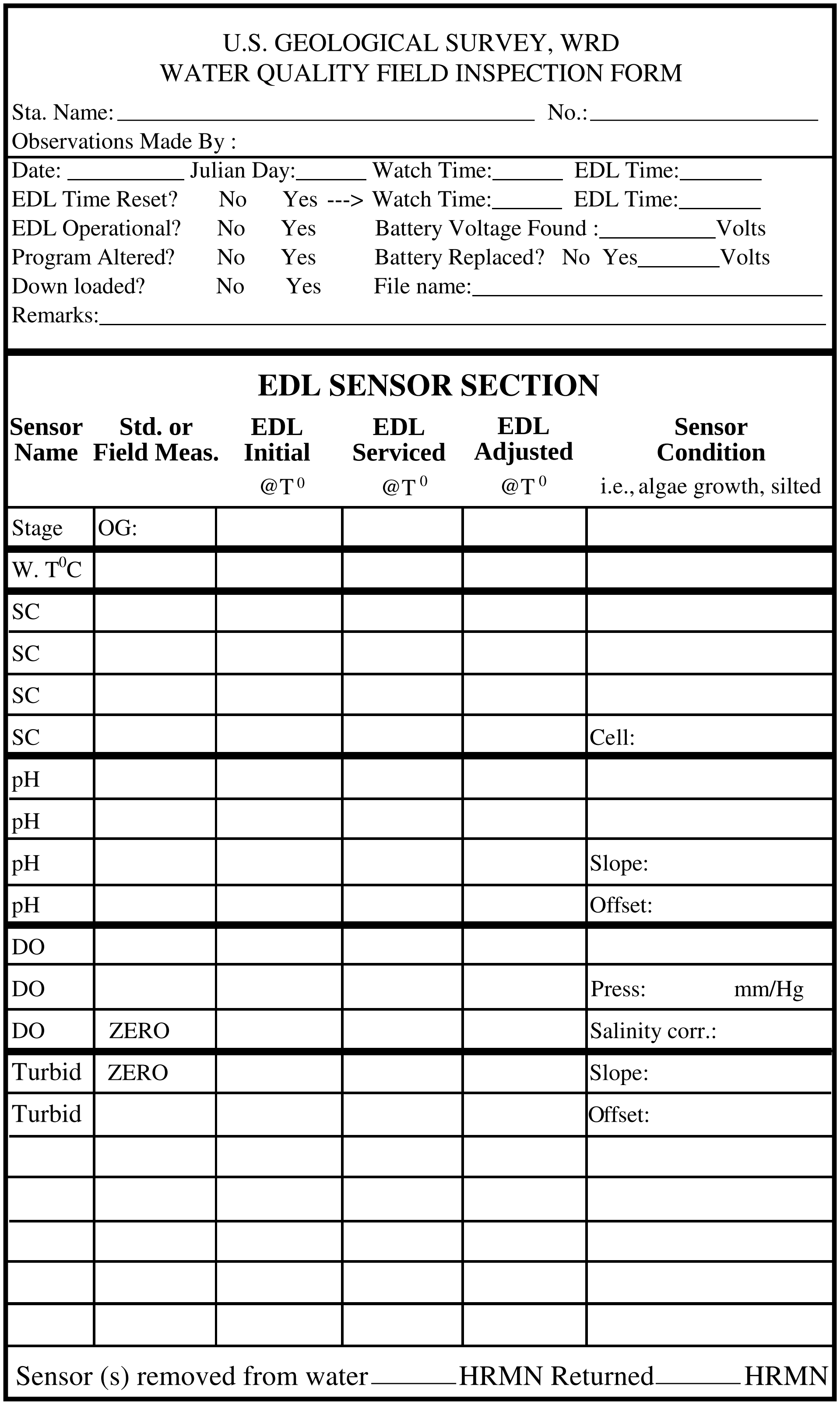
OBSERVER

Contacted (Y or N) # cases picked up________________ # cases left___________________
Observer Sample Inspected On-Site (Y or N) Problems Immediately Addressed (Y or N)
Observer Sampler Inspected for leaks or Need for Adjustment (Y or N)
Remarks____
____

QUALITY ASSURANCE

Samplers checked for proper bottle seal (Y or N)
P61/P63 checked for leaks/proper solenoid opening (Y or N)
EDI sample bottles have equal volumes (Y or N)
Maximum transit rate exceeded (Y or N)
Remarks____
____

Figure 18. Field inspection sheet to record measurements and stream conditions observed during a visit to a sediment-measurement site (modified from Robert Holmes, U.S. Geological Survey, written commun., 1994).



U.S. GEOLOGICAL SURVEY, WRD
WATER QUALITY FIELD INSPECTION FORM

Sta. Name:____________________________________ No.:____________________
Observations Made By :

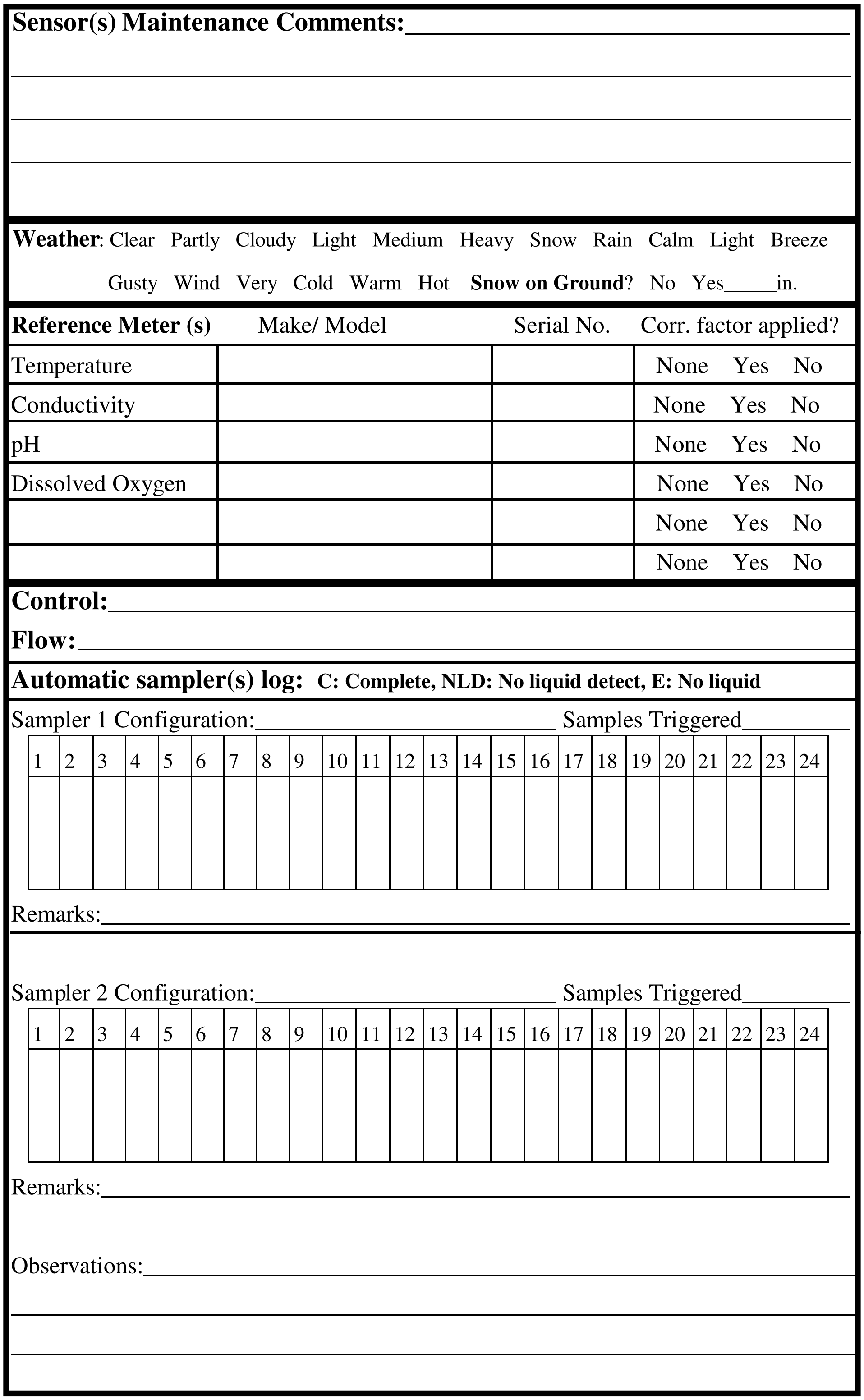
Date: __________ Julian Day:______ Watch Time:______ EDL Time:_______
EDL Time Reset? No Yes ---> Watch Time:______ EDL Time:_______
EDL Operational? No Yes Battery Voltage Found :__________Volts
Program Altered? No Yes Battery Replaced? No Yes_______Volts
Down loaded? No Yes File name:______________________________
Remarks:____

EDL SENSOR SECTION

Sensor Name	**Std. or Field Meas.**	**EDL Initial** @T^0	**EDL Serviced** @T^0	**EDL Adjusted** @T^0	**Sensor Condition** i.e., algae growth, silted
Stage	OG:				
W. T^{0}C					
SC					
SC					
SC					
SC					Cell:
pH					
pH					
pH					Slope:
pH					Offset:
DO					
DO					Press: mm/Hg
DO	ZERO				Salinity corr.:
Turbid	ZERO				Slope:
Turbid					Offset:

Sensor (s) removed from water______HRMN Returned______HRMN

Figure 19. Field inspection sheet customized for automatic data collection at a highway-runoff monitoring station (Smith, 2000).



Sensor(s) Maintenance Comments:__________________________________

Weather: Clear Partly Cloudy Light Medium Heavy Snow Rain Calm Light Breeze

Gusty Wind Very Cold Warm Hot **Snow on Ground**? No Yes_____in.

Reference Meter (s)	Make/ Model	Serial No.	Corr. factor applied?
Temperature			None Yes No
Conductivity			None Yes No
pH			None Yes No
Dissolved Oxygen			None Yes No
			None Yes No
			None Yes No

Control:____

Flow:____

Automatic sampler(s) log: C: Complete, NLD: No liquid detect, E: No liquid

Sampler 1 Configuration:__________________________ Samples Triggered__________

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Remarks:____

Sampler 2 Configuration:__________________________ Samples Triggered__________

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Remarks:____

Observations:____

Figure 19. Field inspection sheet customized for automatic data collection at a highway-runoff monitoring station (Smith, 2000)—*Continued*.

Materials, 1997b), and Standard Guide for Collection, Storage, Characterization, and Manipulation of Sediments for Toxicological Testing (American Society for Testing and Materials, 1994). QA/QC efforts need to be established at the beginning of a project to ensure that sediment measurements are accurate and representative of the hydrologic system investigated (Guy 1969; Matthes and others 1991; Knott and others 1992 and 1993; and U.S. Geological Survey, 1998a; 1998b; 1999a). QA/QC programs are especially important for all phases of stormwater-flow and water-quality investigations (Clark and Whitfield, 1993; Brown and others, 1995; and Jones, 1999). An effective QA/QC program for sediment data-collection programs would include:

- Frequent and routine site visits by trained/experienced field personnel;
- Redundant methods for measuring precipitation and stormwater flow (Church and others, 1999);
- Technical training for project personnel;
- Frequent review by project personnel of field and laboratory sediment data;
- Quality audits, in the form of periodic internal reviews; and
- Quality audits, in the form of periodic external reviews.

Field instrumentation must be maintained operational and in good working order to ensure the integrity of the data collected, and derivative data must be reviewed on-site or immediately in the office following the site visit. The site must be inspected for debris accumulation, natural corrosion of equipment, vandalism, and other potential problems. Debris can affect measurements by blocking sample-collection intakes and by affecting necessary flow measurements (Church and others, 1999). Frequent maintenance and calibration of equipment and instrumentation is necessary because of the difficult monitoring environment. Field inspection sheets also are part of quality-assurance efforts and these inspection sheets should be archived with project records, and at the least, use of these forms should be mentioned in the QA/QC documentation in project reports (Guy, 1969; Matthes and others, 1991; Knott and others, 1992 and 1993; U.S. Geological Survey, 1998a).

Periodically, it is necessary to do a more detailed review using the entire data record, field notes, and other available information to detect errors or anomalous data. For example, a comparison between flow, turbidity, and measured sediment concentrations for a given runoff period could indicate a bias in one or the other measurement system if the relation for this storm departed from normal values for the site in question. Analysis of field records, including calibration records, adjustments to measured values, and other information, when compared to the data record, may indicate systematic bias, long-term drift, or an abrupt change in the performance of the instrumentation. Quality audits, in the form of periodic internal reviews, are necessary to monitor and implement the project QA/QC program (Jones, 1999). Internal audits establish that the project has a QA/QC plan and that it is being implemented and documented. Also, periodic internal reviews serve as a method to provide technical feedback from subject-matter experts to examine and address problems and (or) potential problems in the data-collection program. Internal reviews should ensure that trained/experienced personnel are available for frequent and routine site visits, that appropriate and robust monitoring systems are in place and collecting data, and that project personnel are examining and interpreting data using appropriate methods on a timely basis. These internal reviews could take place at the proposal stage of the project and then again when the project is about 10-, 40-, and 70-percent complete, or at fixed intervals, such as quarterly or semiannually.

Quality audits, in the form of periodic external reviews, are also necessary to monitor and implement the project QA/QC program (Jones, 1999). External audits should examine project plans, project data, project records, and QA/QC documentation to ensure that study objectives are being met, and to ensure that study objectives will meet the goals of the monitoring project. External reviews should ensure that the project information is properly documented and that the documentation is accessible. Within the USGS, external quality audits include periodic reviews by technical specialists at different levels in the chain of command above the local organizational unit and by technical specialists from discipline offices such as the Office of Surface Water, the Office of Ground Water, the Office of Quality Water, and the Branch of Quality Systems.

To ensure that the sediment data produced or used for highway- and urban-runoff studies are of a known quality and are sufficient to provide long-term comparability and consistency, sediment laboratory quality-assurance programs are needed (U.S. Geological Survey, 1998a; Gordon and Newland, 2000; Gordon and others, 2000). It is therefore necessary to document the name and location of the laboratory, methods used, and the performance of the laboratory in one or more quality-assurance programs. The parameters that are typically evaluated as indicators of quality include accuracy, precision, bias, detection limits or performance range, and interference. In analytical chemistry, these performance parameters can be addressed by the use of internal standards and spiked, blind, and blank samples (Jones, 1999).

SUMMARY

This report addresses technical issues pertinent to the methods for the collection, processing, and analysis of water samples for concentrations and physical characteristics of sediment in highway and urban runoff, best management practice (BMP) structures, and receiving waters. The report focuses on sediment-transport issues related to highway use, as opposed to highway construction. Information presented in this report is also applicable for many issues related to sediment in urban runoff from stormwater. Many technical issues associated with sample collection, processing, and analysis must be addressed in order to produce valid (useful for intended purposes), current, and technically defensible data for local, regional, and national information needs. All aspects of sediment data-collection programs need be evaluated and quality-assurance and quality-control (QA/QC) data need be documented so that the comparability and representativeness of data obtained for highway- and urban-runoff studies may be assessed.

The erosive capacity of runoff from highways and urban areas can be substantial because runoff from paved areas, ditches, and storm drains can be hydraulically supercritical and turbulent. The area contributing to surface runoff is usually small, water-surface slope is relatively steep, runoff is concentrated, and surface roughness is low. The mode of transport can be described from the origin of the material as bed-material load and wash load, or operationally (as measured by sediment samplers) as suspended load and bedload. As particle-size distributions (PSDs) increase to include sand-size material, a vertical gradient tends to form with larger particles concentrating nearer the bed. Although some coarser sediment can move as bedload, most highway drainage systems are designed to carry water and maintain sediments in suspension so that the volumetric capacity of the highway conveyance structures is not diminished. Sediment in highway runoff comprises particles derived from atmospheric dust, pavement degradation, vehicle rust, tire degradation, trash, rocks, natural soils, biological materials, or chemical precipitates that are transported by, suspended in, or deposited in flowing water. The rapid response of flow volume and velocity to changes in precipitation of highway and urban runoff drainages complicates the sampling and analysis of sediment in these systems. Therefore, it is necessary to use methods that are suitable to this harsh monitoring environment and to support data collected using QA/QC for these methods.

Representative sample collection for measurement of sediment in highway and urban runoff involves a number of interrelated issues. Temporal and spatial variability in runoff can be large, based on a combination of factors including volume and intensity of precipitation, rate of snowmelt, and features of the drainage basin such as drainage area, slope, infiltration capacity, channel roughness, and storage characteristics. The remoteness or inaccessibility of sites makes it difficult to monitor runoff manually, and it can be difficult to get personnel to the site before the onset of runoff. Costs associated with deployment of trained and properly equipped personnel in addition to uncertainties related to the location and timing of runoff, can be prohibitive for manual sampling of storm-runoff periods. The difficulty in collecting a relatively large number of samples during storm runoff and the dangers to field personnel operating in adverse conditions (including traffic, weather, reduced visibility, and rapid changes in discharge) reduces the practicality of manual sampling efforts. In contrast, automatic samplers can be deployed before and samples can be retrieved after storm runoff, reducing logistics and increasing the safety for field personnel. Automatic pumping samplers typically collect water from the water column by suction and control the sampling rate using the pump speed. Passive sampling devices typically are installed in the flow path and control the sampling rate by placement, orientation, and design of the water intake. Each type of sampler has benefits and design limitations, which must be recognized and quantified to produce representative data. Indirect sediment-measurement methods also may be useful as supplementary and (or) surrogate means for monitoring sediment in runoff. These methods include analysis of available bottom materials, turbidity, and other indirect sediment-measurement methods. All these methods have benefits and design limitations, which must be recognized and quantified to produce representative data.

Appropriate sample processing methods are determined by the characteristics of the water sampled and by the analytical and interpretive methods used for data reduction. Water-quality data for highway and urban runoff are generally reported as event-mean concentration EMC to provide summary values that can be used to compare measurements from individual runoff periods at a site or to compare, between sites, measurements from populations of storms. An EMC may be determined by collecting a bulk sample, by physically compositing a number of discrete samples, or by mathematically calculating a flow-weighted composite from analysis of multiple discrete samples taken during the runoff period. Each sample type has certain pre-analysis processing requirements that may affect measured sediment concentrations. Each sample type has certain pre-analysis processing requirements that typically include homogenization and subsampling. Homogenization methods are designed to produce representative subsamples for the analysis process. Subsampling methods are designed to enable different analytical determinations to be made on the subsamples. Processing artifacts can be substantial if the methods used are not appropriate for the concentrations and PSDs present in the samples collected.

Representative analysis of concentrations and physical characteristics of sediment in highway and urban runoff involves a number of complex issues. The two analytical methods most commonly used to determine sediment concentration in a water sample are the suspended-sediment concentration (SSC) method and the total suspended solids (TSS) method. The terms SSC and TSS are often used interchangeably in the literature to describe the concentration of solid-phase material suspended in a water-sediment mixture. The SSC analytical procedure, entails measurement of the entire mass of sediment and the net weight for the entire sample, whereas only a part of the water-sediment mixture (a subsample) is typically analyzed in the TSS method. Although these methods are commonly expected to produce comparable results, recent research indicates systematic differences between the methods. Two studies comparing laboratory analysis results for TSS and SSC found that TSS analysis does not represent the larger grain-size fractions, and therefore, consistently tends to underrepresent the true sediment concentrations. Furthermore, these studies determined that relations between TSS and SSC concentrations are not transferable among sites, even when grain-size distribution information is available. An analysis of data from a coastal and an interior highway in the United States indicates that TSS underrepresents the true sediment concentration, and that relations between TSS and SSC concentrations are not transferable from site to site even when grain-size distribution information is available. TSS data may be fundamentally unreliable and published TSS data may not represent sediment concentrations and loads from highways. When the TSS analysis method is used, these artifacts may have important consequences for the assessment, design, and maintenance of sediment removal BMPs, including consideration that the variability in grain-size distributions from storm to storm and site to site will confound meaningful analysis of BMP effectiveness, that the necessary volume of sediment retention structures may be underdesigned, and that maintenance of these structures may not be adequate because sedimentation rates are greater than expected. These common problems arise if decisions are based on expected TSS capture efficiencies because the TSS values do not reflect the actual sediment retention of larger grain sizes, which are characterized by the SSC method. Further research, however, may be necessary to quantity the scope of this issue in different highway and urban settings.

Data quality, comparability, and utility are important considerations for the collection, processing, and analysis of sediment samples and interpretation of sediment data for highway- and urban-runoff studies. Results from a sediment study must also be readily transferable and useful to resource managers and regulators. To meet these objectives, supporting ancillary information must be available that documents the methods and procedures that are used and describes QA/QC procedures that are employed for highway-runoff studies. Valid, current, and technically defensible protocols for collecting, processing, and analyzing sediment data for the determination of highway-runoff quality therefore need to be documented with study results.

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