

Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data

By John R. Gray, G. Douglas Glysson, Lisa M. Turcios, and Gregory E. Schwarz
Water-Resources Investigations Report 00-4191

COMPARABILITY OF SUSPENDED-SEDIMENT CONCENTRATION AND TOTAL SUSPENDED SOLIDS DATA

By John R. Gray, G. Douglas Glysson, Lisa M. Turcios, and Gregory E. Schwarz

U. S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 00-4191

Reston, Virginia 2000

U.S. Department of the Interior
Bruce Babbitt, Secretary

U.S. Department of the Interior
Charles G. Groat, Director

The use of firm, trade, or brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey

For additional information write to:

U.S. Geological Survey
Chief, Office of Surface Water
Mail Stop 415
12201 Sunrise Valley Drive
Reston, VA 20192

Copies of this report can be purchased from:

U.S. Geological Survey
Information Services
Box 25286, Mail Stop 417
Denver Federal Center
Denver, CO 80225-0286

CONTENTS

Abstract	1
Introduction	1
Field Techniques and Laboratory Methods	2
Field Techniques	2
Laboratory Methods	3
Suspended-Sediment Concentration Analytical Method	3
Total Suspended Solids Analytical Method	3
Differences Between the Suspended-Sediment Concentration and Total Suspended Solids Analytical Methods	4
Description of Data Used in the Evaluation	5
Arizona	5
Hawaii	5
Illinois	5
Kentucky	5
Maryland	5
Virginia	6
Washington	6
Wisconsin	6
Quality-Control Data	6
Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data	6
Natural-Water Data	6
Quality-Control Data	10
Conclusions	11
References Cited	12

List of Tables:

1. State in which natural-water samples were collected, collecting organization, collection methods, and devices for obtaining subsamples for suspended-sediment concentration and total suspended solids analyses	2
2. Statistical characteristics of paired suspended-sediment concentrations (SSC) and total suspended solids (TSS) data for each of eight States, and for the combined data from all States	7

List of Figures:

1. Bar graph showing number of paired suspended-sediment concentration values and total suspended solids values of the 3,235 data pairs for selected suspended-sediment concentration ranges	6
2. Scatter plot showing relation between untransformed values of suspended-sediment concentration and total suspended solids for 3,235 data points	7
3. Scatter plot showing relation between the base-10 logarithms of suspended-sediment concentration and total suspended solids for 3,235 data pairs in the scattergrams plotted	8
4. Scatter plots showing relation between the base-10 logarithms of suspended-sediment concentration and total suspended solids for the data pairs from each State used in the analysis	9
5. Scatter plot showing relation between percent sand-size material in the sample analyzed for suspended-sediment concentration and the remainder of suspended-sediment concentration minus total suspended solids	10
6. Scatter plot showing relation between total suspended solids and the concentration of suspended sediments finer than 0.062 mm in paired suspended-sediment concentration samples	10
7. Graph showing instantaneous water discharges and sediment discharges computed from total suspended solids and suspended-sediment concentration data for a stream in the northeastern United States, 1998	11
8. Boxplot showing variability in results of suspended-sediment concentrations and total suspended solids analytical methods in quality-control water samples analyzed by a cooperator laboratory	11

CONVERSION FACTORS

Multiply SI units	By	To obtain inch-pound units
<hr/>		
Length		
millimeter (mm)	0.03937	inch (in)
<hr/>		
Volume		
liter (L)	33.82	ounce fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
<hr/>		
Flow		
cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
<hr/>		
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
gram (g)	0.002205	ounce, avoirdupois (oz)
megagram (Mg)	1.102	ton, short
<hr/>		
Temperature		
degree Celsius (°C)	$F = 1.8 \times ^\circ\text{C} + 32$	degree Fahrenheit (°F)
<hr/>		
Concentration (Mass/Volume)		
milligrams per liter (mg/L)	1.0	parts per million (ppm) ¹
milligrams per liter (mg/L)	0.0000334	ounces per quart (oz/qt)

¹This conversion is true for concentration values <8,000 mg/L. The equivalent value in mg/L for concentrations ≥8,000 ppm can be calculated from table 1, American Society of Testing Material (2000), or by using the following equation:

$$C_{\text{mg/L}} = C_{\text{ppm}} / (1 - C_{\text{ppm}}(6.22 \times 10^{-7}))$$

where:

$C_{\text{mg/L}}$ = sediment concentration, mg/L, and

C_{ppm} = sediment concentration, ppm

Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data

By John R. Gray, G. Douglas Glysson, Lisa M. Turcios, and Gregory E. Schwarz

ABSTRACT

Two laboratory analytical methods — suspended-sediment concentration (SSC) and total suspended solids (TSS) — are predominantly used to quantify concentrations of suspended solid-phase material in surface waters of the United States. The analytical methods differ. SSC data are produced by measuring the dry weight of all the sediment from a known volume of a water-sediment mixture. TSS data are produced by several methods, most of which entail measuring the dry weight of sediment from a known volume of a subsample of the original. An evaluation of 3,235 paired SSC and TSS data, of which 860 SSC values include percentages of sand-size material, shows bias in the relation between SSC and TSS — SSC values tend to increase at a greater rate than their corresponding paired TSS values. As sand-size material in samples exceeds about a quarter of the sediment dry weight, SSC values tend to exceed their corresponding paired TSS values. TSS analyses of three sets of quality-control samples (35 samples) showed unexpectedly small sediment recoveries and relatively large variances in the TSS data. Two quality-control data sets (18 samples) that were analyzed for SSC showed both slightly deficient sediment recoveries, and variances that are characteristic of most other quality-control data compiled as part of the U.S. Geological Survey's National Sediment Laboratory Quality Assurance Program. The method for determining TSS, which was originally designed for analyses of wastewater samples, is shown to be fundamentally unreliable for the analysis of natural-water samples. In contrast, the method for determining SSC produces relatively reliable results for samples of natural water, regardless of the amount or percentage of sand-size material in the samples. SSC and TSS data collected from natural water are not comparable and should not be used interchangeably. The accuracy and comparability of suspended solid-phase concentrations of the Nation's natural waters would be greatly enhanced if all these data were produced by the SSC analytical method.

INTRODUCTION

The importance of fluvial sediment to the quality of aquatic and riparian systems is well established. The U.S. Environmental Protection Agency (1998) identifies sediment as the single most widespread cause of impairment of the Nation's rivers and streams, lakes, reservoirs, ponds, and estuaries.

Reliable, quality-assured sediment and ancillary data are the underpinnings for assessment and remediation of sediment-impaired waters. The U.S. Geological Survey (USGS) has protocols for the collection of sediment data (Edwards and Glysson, 1999) and for laboratory analysis of suspended-sediment samples (Guy, 1969; Matthes and others, 1991; Knott and others, 1992 and 1993; U.S. Geological Survey, 1998 and 1999a). Most of the laboratory analytical methods were adapted or developed by the Federal Interagency Sedimentation Project (1941), approved by the Technical Committee (Glysson and Gray, 1997), and used by most Federal agencies that analyze fluvial-sediment data.

Data collected, processed, and analyzed using consistent protocols are comparable in time and space. Conversely, data obtained using different protocols may not be comparable. The focus of this study is the comparability of suspended-sediment concentration (SSC) and total suspended solids (TSS) data. 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, usually expressed in milligrams per liter (mg/L) (Gregory Granato, U.S. Geological Survey, oral commun., 1999; James, 1999). However, given that all other factors are held constant (such as particle density and shape), the analytical procedures for SSC and TSS differ and may produce considerably different results, particularly when sand-size material composes a substantial percentage of the sediment in the sample.

This report compares the SSC and TSS analytical methods and derivative data, and demonstrates which of the data types is the more accurate and reliable. The evaluation is based on historical SSC and TSS data collected and analyzed by the USGS and selected cooperators.

The authors appreciate the assistance of: Stephen S. Anthony, Donna L. Belval, James G. Brown, Ronald D. Evaldi, Herbert S. Garn, John D. Gordon, Stephen D. Preston, Daniel J. Sullivan, Richard J. Wagner and Henry Zajd, Jr. for providing the data used in this report. The formal reviews of Herbert S. Garn, Mary Ellen Ley, and Henry Zajd, Jr., were most appreciated, as were informal reviews by Anne Hoos and Harvey Jobson. Kenneth Pearsall's insights and research significantly enhanced the report. Patricia Greene's and Roger K. Chang's support for developing the tables and figures was invaluable.

Table 1. State in which natural-water samples were collected, collecting organization, collection methods, and devices for obtaining subsamples for suspended-sediment concentration (parameter code 80154) and total suspended solids (parameter code 00530) analyses
[SSC, suspended-sediment concentration; TSS, total suspended solids; USGS, U.S. Geological Survey]

State	Sample Collecting Organization		Sample Collection Method		Subsampling Device	
	SSC (80154)	TSS (00530)	SSC (80154)	TSS (00530)	SSC (80154)	TSS (00530)
Arizona ^a	USGS	USGS	USGS, 1999 ⁱ	USGS, 1999 ⁱ	Churn Splitter	Churn Splitter
Hawaii ^b	USGS	USGS	Automatic Sampler	Automatic Sampler	None	Churn Splitter
Illinois ^c	USGS	USGS	USGS, 1999 ⁱ ; Open Bottle	USGS, 1999 ⁱ	Churn Splitter	Churn Splitter
Kentucky ^d	USGS	USGS	USGS	Open Bottle	None	None
Maryland ^e	USGS	USGS	Open Bottle USGS, 1999 ⁱ ; Automatic Sampler	USGS, 1999 ⁱ ; Automatic Sampler	Churn Splitter	Churn Splitter
Virginia ^f	USGS and Cooperator	USGS and Cooperator	USGS, 1999 ⁱ	USGS, 1999 ⁱ	None	Churn Splitter
Washington ^g	USGS	USGS	USGS, 1999 ⁱ	USGS, 1999 ⁱ	None	Churn Splitter
Wisconsin ^h	USGS	Cooperator	USGS, 1999 ⁱ	Open Bottle	Cone Splitter	Cone Splitter

^a James G. Brown, U.S. Geological Survey, written commun. (1999).

^b Stephen S. Anthony, U.S. Geological Survey, written commun. (1999).

^c Daniel J. Sullivan, U.S. Geological Survey, written commun. (1999).

^d Ronald D. Evaldi, U.S. Geological Survey, written commun. (1999).

^e Stephen D. Preston, U.S. Geological Survey, written commun. (1999).

^f Donna L. Belval, U.S. Geological Survey, written commun. (1999).

^g Richard J. Wagner, U.S. Geological Survey, written commun. (1999).

^h Herbert S. Garn, U.S. Geological Survey, written commun. (1999).

ⁱ See Edwards and Glysson (1999).

FIELD TECHNIQUES AND LABORATORY METHODS

The paired SSC and TSS results used in this evaluation were derived from analyses of natural-water samples collected by the USGS and selected cooperators (table 1). Analyses of all SSC data from natural water were made by USGS sediment laboratories, and analyses of the TSS data were made by USGS and cooperating laboratories. Additionally, 53 quality-control samples were prepared by the USGS and analyzed by a laboratory that provides data to the USGS.

Field Techniques

The large majority of water samples were collected using either the equal-width-increment or the equal-discharge-increment method to obtain a composite sample that is representative of the discharge-weighted SSC (Edwards and Glysson, 1999). Some samples, including those obtained by at least one cooperating agency, were collected by dipping an open bottle to obtain samples for subsequent TSS analysis. Some of the paired SSC and TSS samples were collected in-stream sequentially and submitted to laboratories for analysis as whole samples. The remaining samples were split into subsamples by using a churn splitter or cone splitter (Ward and Haar, 1990; Capel and Larson, 1996; Capel and others, 1995).

Tests performed by the USGS demonstrate that the churn splitter and cone splitter can provide unbiased and acceptably precise (generally within 10 percent of the known value) SSC values as large as about 1,000 mg/L when the mean diameter of sediment particles is less than about 0.25 mm. At SSC values of 10,000 mg/L or more, the bias and precision of SSC values in churn splitter subsamples are considered unacceptable (U.S. Geological Survey, 1997; Wilde and others, 1999).

Cone splitters produce subsamples with SSC values that are adequately representative of the original sample at 10,000 mg/L, but not at 100,000 mg/L. The accuracy of the cone splitter for SSC values between 10,000 mg/L and 100,000 mg/L is unknown and is considered unacceptable at concentrations larger than 100,000 mg/L (U.S. Geological Survey, 1997; Wilde and others, 1999).

Subsampling will typically increase the variance and (or) create bias in the concentration and size distribution of solid-phase material in a subsample. Significant differences in the amount of solid-phase material in some paired samples may have occurred as a result of non-representative splitting of the original samples, or by collecting consecutive in-stream samples under conditions of rapidly varying SSC. Similarly, because the data were obtained by field personnel in eight States as part of unrelated studies, significant differences

may have resulted because of differences in data-collection techniques. However, the probability of significant bias resulting from consistently selecting samples with larger concentrations of sediment for analyses by one of the methods would be small based on the large number of paired data used in the analysis. There is no evidence indicating that methods used for collecting, processing, or selecting subsamples for subsequent analysis introduced bias in the relations between SSC and TSS identified in this evaluation.

Laboratory Methods

Two standard methods are widely cited in the United States for determining the total amount of suspended material in a water sample. These are:

1. Method D 3977-97, "Standard Test Method for Determining Sediment Concentration in Water Samples" of the American Society for Testing and Materials (American Society for Testing and Materials, 2000), and
2. Method 2540 D, "Total Suspended Solids Dried at 103°–105° C" (American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1995).

The differences in these analytical methods, and some variations used to produce TSS data are described below.

Suspended-Sediment Concentration Analytical

Method. ASTM Standard Test Method D 3977-97 lists three methods that result in a determination of SSC values in water and wastewater samples:

1. Test Method A – Evaporation: The evaporation method may only be used on sediment that settles within the allotted storage time, which can range from a few days to several months. If the dissolved-solids concentration exceeds about 10 percent of the SSC value, an appropriate correction factor must be applied to the SSC value. The precision and bias of Method A are shown as follows:

[mg/L, milligrams per liter]

Concentration Added, (mg/L)	Concentration Recovered, (mg/L)	Standard Deviation of Test Method (mg/L)	Standard Deviation of Single Operator (mg/L)	Bias, percent
10	9.4	2.5	2.3	-6
1,000	976	36.8	15.9	-2.4
100,000	100,294	532	360	0.3

2. Test Method B- Filtration: 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 concentrations of clay-size material of about 200 mg/L. No dissolved-solids correction is needed. The precision and bias of Method B are shown as follows:

[mg/L, milligrams per liter]

Concentration Added, (mg/L)	Concentration Recovered, (mg/L)	Standard Deviation of Test Method (mg/L)	Standard Deviation of Single Operator (mg/L)	Bias, percent
10	8	2.6	2	-20
100	91	5.3	5.1	-9
1,000	961	20.4	14.1	-3.9

3. Test Method C - Wet-sieving filtration: The wet-sieve-filtration method also yields a SSC value, but the method is not as direct as Methods A and B. Method C is used if the percentage of material larger than sand-size particles is desired. The 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 be needed, depending on the type of analysis done on the fine fraction of the samples and the dissolved-solids concentration of the sample. The precision and bias of Method C are shown as follows:

[mm, millimeters; mg/L, milligrams per liter]

Mixture Number	Sieve Diameter (mm)	Concentration Added (mg/L)	Concentration Recovered (mg/L)	Standard Deviation of Test Method (mg/L)	Standard Deviation of Single Operator (mg/L)	Bias, percent
1	>0.062	1	3.4	2.8	2.4	240
1	<0.062	10	8.7	4.3	2.9	-13
2	>0.062	9	5	5.9	1.9	-44
2	<0.062	91	79	15.2	11	-13
3	>0.062	91	107	12.3	5.9	18
3	<0.062	909	832	87.2	61	-8

These three methods are virtually the same as those used by USGS sediment laboratories and described by Guy (1969). Only the Whatman grade 934AH, 24-mm-diameter filter is used for purposes of standardization. Each method includes retaining, drying at 103°C ±2°C, and weighing all of the sediment in a known mass of a water-sediment mixture (U.S. Geological Survey, 1999a).

Total Suspended Solids Analytical Method. According to the American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1995), the TSS analytical method uses a predetermined volume from the original water sample obtained while the sample is being mixed with a magnetic stirrer. An aliquot of the sample — usually 0.1 L, but a smaller volume if more than 200 mg of residue may collect on the filter — is withdrawn by pipette. The aliquot is passed through a filter, the diameter of which usually ranges from 22 to 125 mm. The filter may be a Whatman grade 934AH, Gelman type A/E, Millipore type AP40; E-D Scientific Specialties grade 161, or another product that gives demonstrably equivalent results. After filtering, the filter and contents are removed and dried at 103° to 105° C, and weighed. No dissolved-solids correction is required. The percentages of sand-size and finer material cannot be determined using the TSS method.

The American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1995) describe the precision for this method as follows: "The standard deviation was 5.2 mg/L (coefficient of variation 33 percent) at 15 mg/L, 24 mg/L (10 percent) at 242 mg/L, and 13 mg/L (0.76 percent) at 1,707 mg/L in studies by two analysts of four sets of 10 determinations each. Single-laboratory analyses of 50 samples of water and wastewater were made with a standard deviation of differences of

2.8 mg/L.” The standard provides no indication of the size of particles used in the testing for the method.

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

- For the collection of TSS samples as part of the Chesapeake Bay Program, field staff pump water from a specified depth into a plastic gallon container. The container is vigorously shaken, and 0.2 – 1.0 L 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).
- One State government laboratory produces TSS data by vigorously shaking the sample and pouring it 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).
- Another laboratory analyzed quality-control samples by using Method 2540D of the American Public Health Association, American Water Works Association, and Water Pollution Control Federation (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 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 storm-water runoff, in part because the settleable part of TSS is not reported in most storm-water studies.

The problem extends to nomenclature. The terms “SSC” and “TSS”, or variations thereof, are sometimes attributed to an incorrect data type. For example, a proposed Total Maximum Daily Load for sediment in Stekoa Creek, Georgia (U.S. Environmental Protection Agency, Region 4, written commun., 2000) is based on regional TSS data, which are compiled from U.S. Geological Survey records; the TSS data referred to are actually SSC data. Buchanan and Schoellhamer (1998) refer to “suspended-solids concentration data” for San Francisco Bay. Those data would more appropriately be referred to as SSC, because the total water-sediment mass and all sediment were measured in the analysis (Alan Mlodnosky, USGS, oral commun., 1999).

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. Information available from the American Public Health Association and American Water Works Association (1946) makes it clear that the Suspended Solids Method was intended for use for wastewater effluents (Kenneth Pearsall, U.S. Geological Survey, written commun., 2000). This is more or less consistent with the Total Suspended Matter Method, which was “in-

tended for use with wastewaters, effluents, and polluted waters,” as listed in the American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1971). A fundamental change took place in 1976, when the Total Suspended Matter Method was deemed 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” by the American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1976). The Suspended Solids and Total Suspended Matter Methods described above are predecessors of the “Total Suspended Solids Dried at 103°-105°C” Method, which first appeared in 1985 by that title in the American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1985).

In summary, the evidence indicates that the TSS method was originally designed for wastewater analyses, presumably on samples collected after a settling step at a wastewater treatment facility (hence the term “suspended” in TSS). The American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1976) expanded the TSS Method’s applicability in 1976 to include natural water.

Differences Between the SSC and TSS Analytical Methods. The fundamental difference between the SSC and TSS analytical methods stems from preparation of the sample for subsequent filtering, drying, and weighing. A TSS analysis normally entails withdrawal of an aliquot of the original sample for subsequent analysis, although as previously noted, there is evidence of inconsistencies in methods used in the sample preparation phase of the TSS analyses. The SSC analytical method measures all sediment and the mass of the entire water-sediment mixture. Additionally, the percentage of sand-size and finer material can be determined as part of the SSC method, but not as part of the TSS method.

If a sample contains a substantial percentage of sand-size material, then stirring, shaking, or otherwise agitating the sample before obtaining a subsample will rarely produce an aliquot representative of the SSC and particle-size distribution 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 and shapes 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.

The physical characteristics of a pipette used to withdraw an aliquot, or subsample, can introduce additional errors in subsequent analytical results. The American Public Health Association, American Water Works Association, and Water Pollution Control Federation (1995) specifies use of “wide-bore pipettes” to withdraw aliquots. The tip opening of those recommended for use is about 3 mm in diameter (Kimble-Contes Inc., accessed May 1, 2000). By definition, the upper limit of sand-size material, 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 me-

dian axis 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-mm tip pipette under suction.

If the aforementioned lack of consistency in the TSS analytical procedure extends to variability in diameters of pipette tips used to withdraw TSS aliquots, the size of particles being excluded from the subsample could vary with the type of pipette used. Hence, use of a pipette may cause concentration bias when subsampling if sand-size material is present in the sample.

Based on Stokes' Law, subsamples obtained by pouring sand-rich water-sediment mixtures should be deficient in sand-size material. Because the fine material concentration will not normally be altered by the removal of an aliquot, the differences between the two methods will tend to be more pronounced as the percentage of sand-size material in the sample increases.

Samples collected sequentially in-stream may have different concentrations and size characteristics of solid-phase material. This may be due to natural variations in the amounts and composition of solid-phase material in transport, and to variance and (or) bias that is introduced by sampling procedures. Likewise, a subsample may contain an amount and size distribution of sediment atypical to that of the original. However, any differences in SSC and size-distribution data from paired samples resulting from in-stream variations or sampling procedures would likely occur randomly among the 3,235 paired analyses used in this evaluation.

DESCRIPTION OF DATA USED IN THE EVALUATION

Results of analyses of natural-water samples and of quality-control samples prepared by the USGS were used for this evaluation. Natural-water samples for determination of SSC (parameter code 80154) were collected and analyzed by the USGS (table 1). Natural-water samples for determination of TSS, (parameter code 00530) were collected by the USGS and cooperating agencies, and analyzed by the USGS and cooperating laboratories. A total of 3,235 pairs of SSC and TSS data for natural water were obtained from the files of USGS District offices.

The paired SSC and TSS data were collected at 65 sampling sites in Arizona, Hawaii, Illinois, Kentucky, Maryland, Virginia, Washington, and Wisconsin. All but the 12 sampling sites in Kentucky were at USGS streamflow-gaging stations. The percentage of sand-size material was available for 860, or about 27 percent, of the SSC samples. The SSC and TSS natural-water data used in this evaluation were augmented by analytical results of 53 quality-control samples prepared by the USGS National Sediment Laboratory Quality Assurance Program (Gordon and others, 2000, U.S. Geological Survey, 1998; 1999a; 1999b; 2000b).

Arizona. A total of 122 SSC and TSS sample pairs were collected at a USGS streamflow-gaging station on Pinal Creek at Inspiration Dam near Globe (station number 09498400) in central Arizona from 1982-98. The samples

were collected about monthly or bimonthly using techniques described by Edwards and Glysson (1999). A churn splitter was used to obtain subsamples of the water-sediment mixture. The USGS sediment laboratory in Iowa City, Iowa, analyzed the subsamples for SSC and TSS (James G. Brown, U.S. Geological Survey, written commun., 1999).

Hawaii. According to Hill (1996), 13 SSC and TSS sample pairs were collected at three streamflow-gaging stations in the Kamooalii drainage basin, Oahu, Hawaii, from 1985-89, as a component of a large-scale highway-construction study. The SSC samples were collected by a US PS-69 automatic pumping sampler. The TSS samples were collected by a Manning automatic pumping sampler. A churn splitter was used to obtain subsamples for TSS analyses. The SSC samples were analyzed by the USGS sediment laboratory in Oahu. The TSS samples were analyzed by the USGS National Water Quality Laboratory in Denver, Colorado (Stephen S. Anthony, U.S. Geological Survey, written commun., 1999).

Illinois. A total of 223 SSC and TSS sample pairs were collected at 8 USGS streamflow-gaging stations in the upper Illinois River Basin from 1988-90 (Sullivan and Blanchard, 1994). Samples were collected according to techniques described by Edwards and Glysson (1999). A churn splitter was used to obtain subsamples for SSC and TSS analyses. SSC samples were analyzed at the USGS sediment laboratory in Iowa City, Iowa, using the evaporation method. TSS samples were analyzed by an Illinois State laboratory using the nonfilterable residue, gravimetric method (Daniel Sullivan, U.S. Geological Survey, written commun., 1999).

Kentucky. A total of 95 SSC and TSS sample pairs were collected at 12 sampling locations in the Ohio River Basin in May 1999. SSC and TSS samples were collected at each site for one day over several hours at about 1-hour intervals. Samples were collected using an open-bottle sampler because of the low stream velocities. No splitting devices were used to obtain subsamples. The USGS sediment laboratory in Louisville, Kentucky, analyzed the SSC samples. A contract laboratory performed the TSS analyses (Ronald Evaldi, U.S. Geological Survey, written commun., 1999).

Maryland. A total of 1,561 SSC and TSS sample pairs were collected at 6 streamflow-gaging stations in the Patuxent River Basin, Maryland, as part of the USGS Patuxent Nonpoint Source study during the years 1985-98 (Preston and Summers, 1997). The sampling frequency was monthly, with additional samples collected during periods of storm runoff. The monthly base-flow samples were collected using the equal-width-increment method (Edwards and Glysson, 1999), and the storm-runoff samples were collected using an automatic sampler. A churn splitter was used for both monthly and storm samples of both SSC and TSS. The SSC samples were analyzed at USGS sediment laboratories in Lemoyne, Pennsylvania, and Louisville, Kentucky. The TSS samples were analyzed using a pipette and filtration method by a Maryland State laboratory (Stephen D. Preston, U.S. Geological Survey, written commun., 1999).

Virginia. A total of 188 SSC and TSS sample pairs were collected at 7 streamflow-gaging stations in Virginia during the years 1975-95. Paired SSC and TSS samples were collected every other month by the USGS except during some low-flow periods as part of the River Input Monitoring Program (U.S. Geological Survey, 2000a). Techniques described by Edwards and Glysson (1999) were used to collect all samples. A churn splitter was used to obtain subsamples for TSS analyses. The USGS collected most of the samples, except during some low-flow periods when the Virginia Department of Environmental Quality collected the samples. SSC analyses were performed by USGS sediment laboratories. A Virginia State laboratory performed the TSS analyses (Donna L. Belval, U.S. Geological Survey, written commun., 1999).

Washington. A total of 817 SSC and TSS sample pairs were collected at 25 streamflow-gaging stations in Washington during the years 1973-98, as part of various projects. Techniques described by Edwards and Glysson (1999) were used to collect all SSC and TSS samples. A churn splitter was used to obtain subsamples for TSS analyses. The SSC and TSS samples were analyzed at a USGS sediment laboratory in Tacoma, Washington, through September 1982. Thereafter, samples were analyzed at the USGS Cascades Volcano Observatory Sediment Laboratory (Richard J. Wagner, U.S. Geological Survey, written commun., 1999).

Wisconsin. A total of 216 SSC and TSS sample pairs were collected at 3 streamflow-gaging stations on streams in the Lake Michigan watershed, Wisconsin, as part of an evaluation of the differences in results of water-quality monitoring caused by differences in sample-collection methods (Kammerer and others, 1998). Low-flow samples were collected in August and October 1993, and high-flow samples were collected in April-July 1994. The SSC samples were collected using techniques described by Edwards and Glysson (1999). The TSS samples were collected concurrently with the SSC samples by the Wisconsin Department of Natural Resources using an open bottle. Subsamples for SSC and TSS analyses were obtained using a cone splitter. SSC samples were analyzed by the USGS sediment laboratory in Iowa City, Iowa. TSS samples were analyzed by a Wisconsin State laboratory (Herbert S. Garn, U.S. Geological Survey, written commun., 1999).

Quality-Control Data. The SSC and TSS natural-water data used in this evaluation were augmented by analytical results of quality-control samples from a cooperating labora-

tory. Known amounts of water and sediment were used to constitute quality-control samples as part of the USGS National Sediment Laboratory Quality Assurance Program. The National Sediment Laboratory Quality Assurance Program is designed as an interlaboratory-comparison evaluation to provide a measure of bias and variance of suspended-sediment data analyzed by laboratories operated or used by the USGS. The quality-control samples received by the participating laboratories were identified as such.

The quality-control samples were submitted in five batches to a cooperating laboratory during 1997-99. Of the quality-control samples, the first 35 were shipped as batch numbers 1997-1, 1997-2, and 1998-1 and were analyzed for TSS. Eighteen quality-control samples were shipped as batch numbers 1998-2 and 1999-1 and analyzed for SSC using the evaporation method (Kenneth Pearsall, U.S. Geological Survey, 1999, oral commun.).

COMPARABILITY OF SUSPENDED-SEDIMENT CONCENTRATION AND TOTAL SUSPENDED SOLIDS DATA

Natural-Water Data

The relation between SSC and TSS data was evaluated by comparing all available paired SSC and TSS natural-water data, and subsets of those data for each State. The number of paired SSC and TSS values for selected SSC concentration ranges with and without particle-size data are shown in figure 1.

Of the 3,235 natural-water SSC samples used in this study,

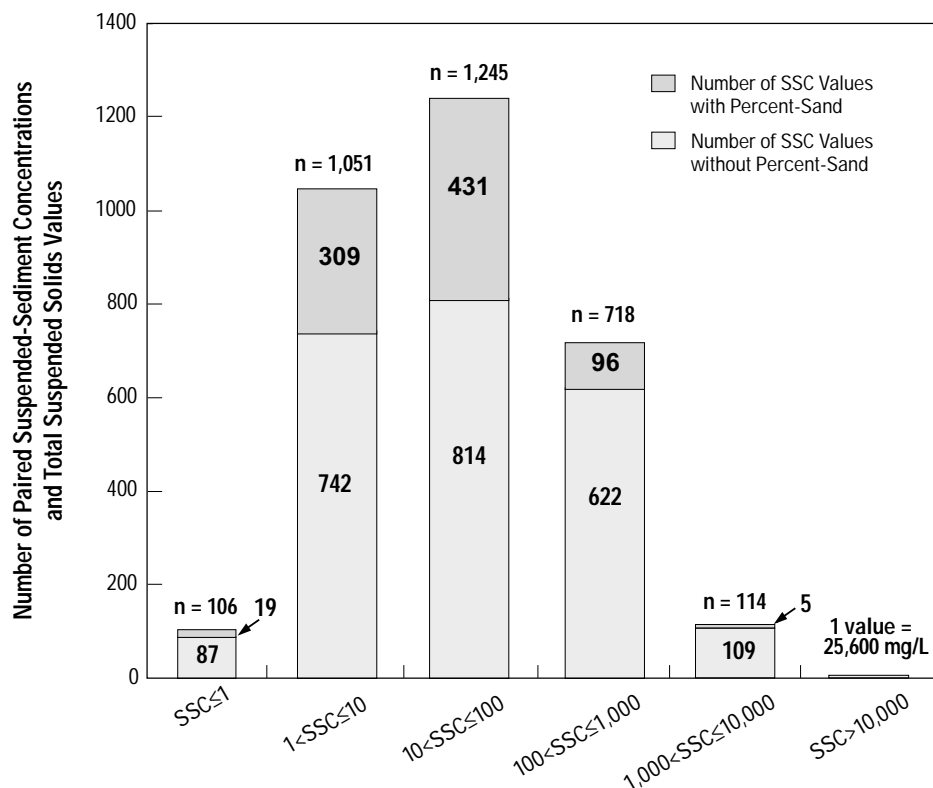


Figure 1. Number of paired suspended-sediment concentration (SSC) values and total suspended solids (TSS) values of the 3,235 data pairs for selected suspended-sediment concentration ranges, in milligrams per liter.

Table 2. Statistical characteristics of paired suspended-sediment concentration (SSC) and total suspended solids (TSS) data for each of eight States, and for the combined data from all States [mg/L, milligrams per liter; >, greater than]

Source of SSC and TSS Paired Data	SSC Values		SSC Minus TSS				
	Number of values	3rd Quartile mg/L	Number of values >0 mg/L	Percentage of values >0 mg/L for all paired data	Number of values when SSC value is > 3rd Quartile value	Number of values >0 mg/L when SSC value is > 3rd Quartile value	Percentage of values >0 mg/L when SSC value is > 3rd Quartile value
Arizona	122	153.25	93	76%	31	30	97%
Hawaii	13	353.0	13	100%	3	3	100%
Illinois	223	48.5	111	50%	56	34	61%
Kentucky	95	10.2	28	29%	24	9	38%
Maryland	1,561	324.0	1,071	69%	390	328	84%
Virginia	188	16.0	105	56%	44	40	91%
Washington	817	30.0	518	63%	203	179	88%
Wisconsin	216	80.25	184	85%	54	54	100%
All Paired Data ¹	3,235	108.0	2,123	66%	809	672	83%

¹ Based on statistics using all 3,235 paired data; some values vary slightly from those calculated using summary statistics from the eight States.

74 percent had values less than or equal to 100 mg/L; only one value (25,600 mg/L) exceeded 10,000 mg/L (figure 1).

Statistical characteristics of SSC and TSS paired data for each State and for all paired data are given in table 2. Sixty-six percent of all TSS values are smaller than their corresponding paired SSC values. Eighty-three percent of all TSS values are smaller than their paired SSC value when SSC values exceed the 3rd quartile value. For each State except Kentucky (38 percent for 24 paired samples), 61 to 100 percent of the TSS values are smaller than their paired SSC value when SSC values exceed the 3rd quartile value. To summarize, SSC values tend to exceed their corresponding paired TSS values. This tendency becomes stronger at larger values of SSC.

Relations between all 3,235 paired TSS and SSC measurements are shown in figures 2 and 3. According to Glysson and others (2000), there is no simple, straightforward way to adjust TSS data to estimate SSC if paired samples are not available. Relations identified herein are not recommended for use in adjusting TSS data unless supported by additional research.

The data shown in figure 2 are plotted without transformation and include the two ordinary least squares regression lines obtained by regressing TSS

on SSC (the lower line) and SSC on TSS (the upper line). Because of measurement errors associated with the collection processing, and analysis of the data, neither line can be interpreted as an unbiased estimate of the true relation

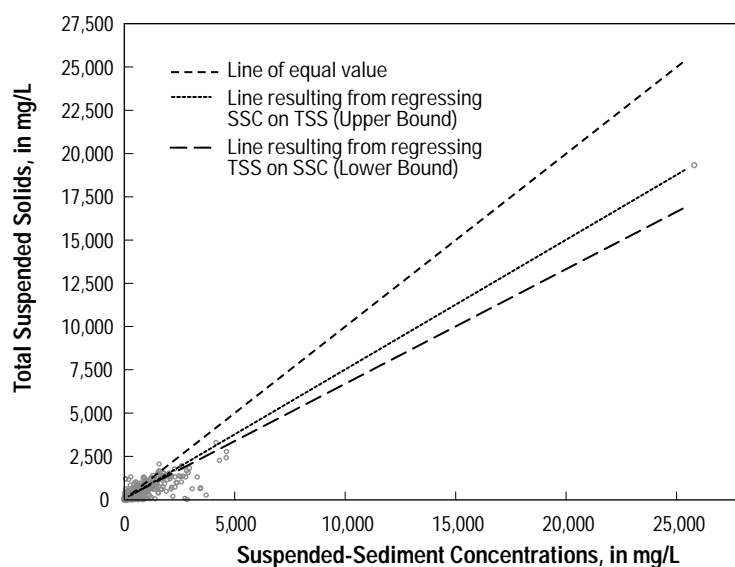


Figure 2. Relation between untransformed values of suspended-sediment concentration and total suspended solids for 3,235 data points.

between the two measurement methods. In fact, the existence of measurement error implies the system of equations describing the two measurements is insufficiently identified, making estimation of an unbiased relation impossible without additional information on the variance of the measurement error for at least one of the measurements (Klepper and Leamer, 1984). However, the two least squares regression lines can be used to bound the true slope and intercept coefficients (Frisch, 1934). In the case of TSS and SSC, the least squares intercepts are very small relative to the range of the data. Consequently, the two regression lines effectively form consistent upper and lower bounds on the true relation between TSS and SSC. These bounds imply that TSS is biased downward relative to SSC by a proportionate amount of 25 to 34 percent. Given the large skew apparent in the data, this finding is tentative and requires confirmation using a statistical or functional transformation yielding homoscedastic residuals.

The relation between SSC and TSS for all 3,235 pairs of transformed data using the base-10 logarithm and the line of equal value are shown in figure 3; the relations for each State and lines of equal value are shown in figure 4. Trends in the scattergrams plotted for all data compared to those with data that were segregated by State show some similarities, including a tendency for the data to plot to the right of the line of equal value, particularly at larger values of SSC.

As described previously, at least two factors associated with the TSS analysis can result in subsamples obtained by pipette or by pouring that are deficient in sand-size material. Rapidly falling sand-size material can be difficult to withdraw representatively, particularly if pipette subsamples are obtained from near the surface and (or) if the subsample is not withdrawn immediately after mixing. Also, coarser sand particles may plug the pipette intake, precluding withdrawal of a representative mixture. Subsamples obtained by

pouring are also unlikely to contain representative amounts of sand-size material. In contrast, the amount or percentage of sand-size material in a SSC sample has no effect in bias because all sediment in the original sample is used in the SSC analysis.

The relation between sand-size material and TSS bias was examined using the 860 paired SSC and TSS values for which the amounts of material coarser and finer than 0.062 mm in the SSC sample are known. Percent sand-size material, percent finer material, and the total mass of sand-size material were included in the analysis. All but one of the paired data associated with particle sizes are for streams in Illinois, Virginia, and Washington.

The relation between percent sand-size material associated with the SSC sample, and the SSC minus TSS remainder is shown in figure 5. No bias is apparent when sand-size material composes less than about a quarter of the sample's sediment mass. Above about a third sand-size material, the large majority of the SSC values exceed their paired TSS values. The increase in bias at larger SSC values as percent sand-size values increase is consistent with the observation that splitting original samples that contain a substantial percentage of sand-size material will rarely produce subsamples with a SSC or particle-size distribution similar to those of the original.

Splitting samples that contain small percentages of sand-size material are more likely to produce subsamples with concentrations and particle-size distributions similar to the original. The relation between TSS and the concentration of material finer than 0.062 mm for 860 of the paired SSC and TSS data with associated particle-size distribution data is shown in figure 6. The concentration of fine material was calculated as follows:

$$C_{<0.062\text{mm}} = \text{SSC} [1 - (\text{Percent}_{\geq 0.062\text{mm}}/100)]$$

$C_{<0.062\text{mm}}$ is the concentration of material finer than 0.062 mm in diameter,

SSC is suspended-sediment concentration, and
Percent $\geq 0.062\text{mm}$ is percent sand-size material associated with the SSC value.

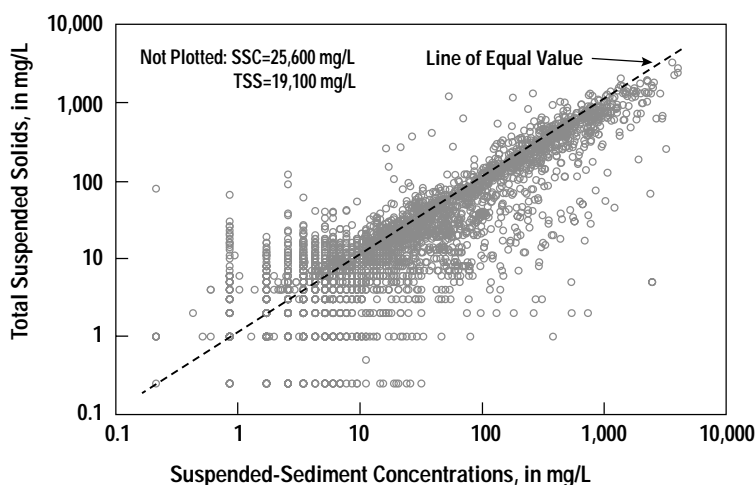


Figure 3. Relation between the base-10 logarithms of suspended-sediment concentration (SSC) and total suspended solids (TSS) for 3,235 data pairs in the scattergrams plotted. All SSC and TSS values less than 0.25 mg/L were set equal to 0.25 mg/L to enable plotting the data on logarithmic coordinates.

At TSS values that exceed about 5 mg/L of fine material, the SSC and TSS data are more or less evenly distributed around the line of equal value (figure 6). This suggests that the TSS method can provide relatively unbiased results when the large majority of material in a sample is finer than 0.062 mm.

The importance of bias in the relation between SSC and TSS characterized in figure 3 can be magnified when TSS data are used to compute sediment discharges. Sediment discharges increase when the product of water discharge and SSC increases (Porterfield, 1972). Additionally, the mobility of coarse material tends to increase with larger flow velocities. Because of the strong tendency for SSC to exceed TSS at larger values of SSC (see figures 3 and 4), calculating discharges of TSS will usually result in underestimates of

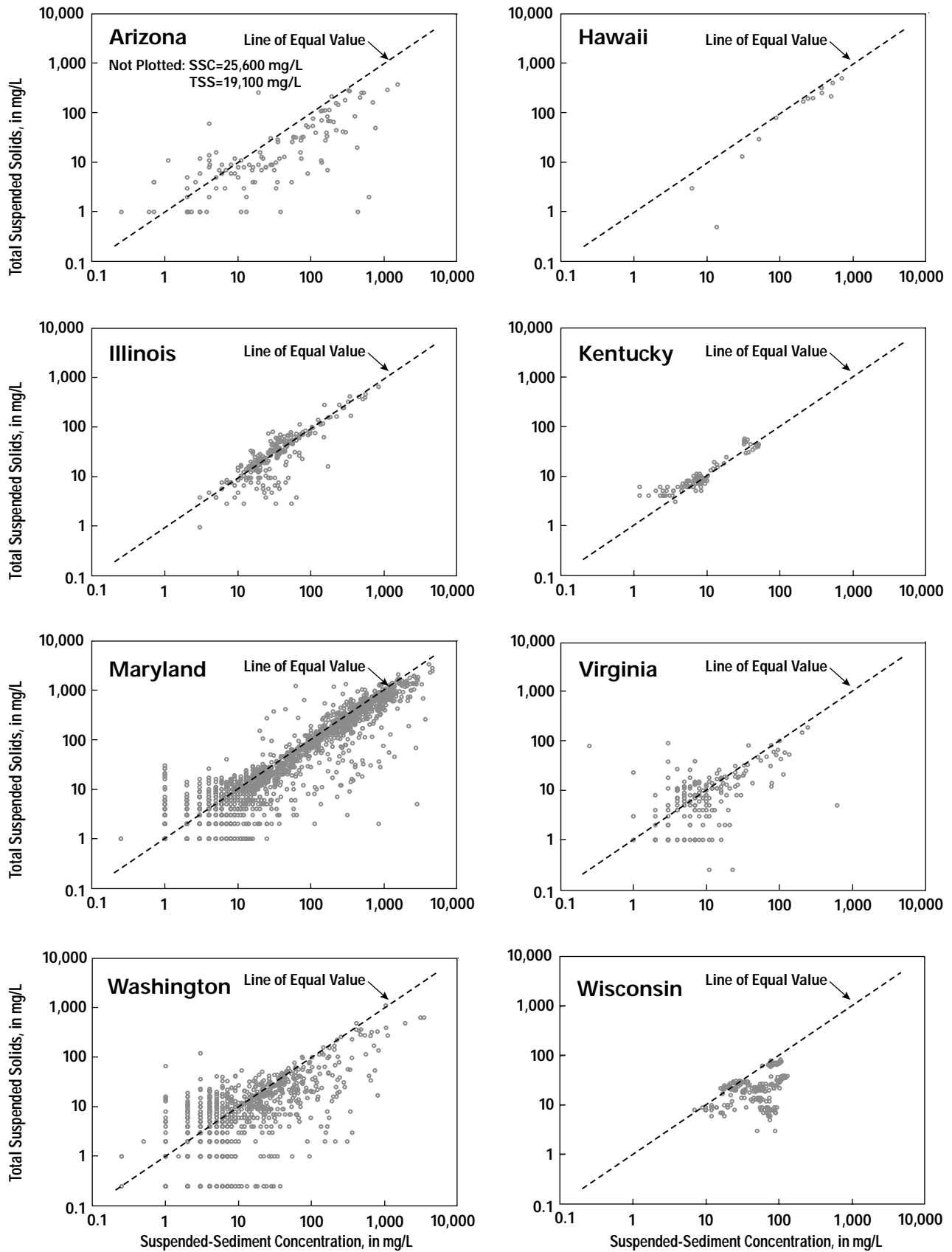


Figure 4. Relation between the base-10 logarithms of suspended-sediment concentration (SSC) and total suspended solids (TSS) for the data pairs from each State used in the analysis. All SSC and TSS values less than 0.25 mg/L were set equal to 0.25 mg/L to enable plotting the data on logarithmic coordinates.

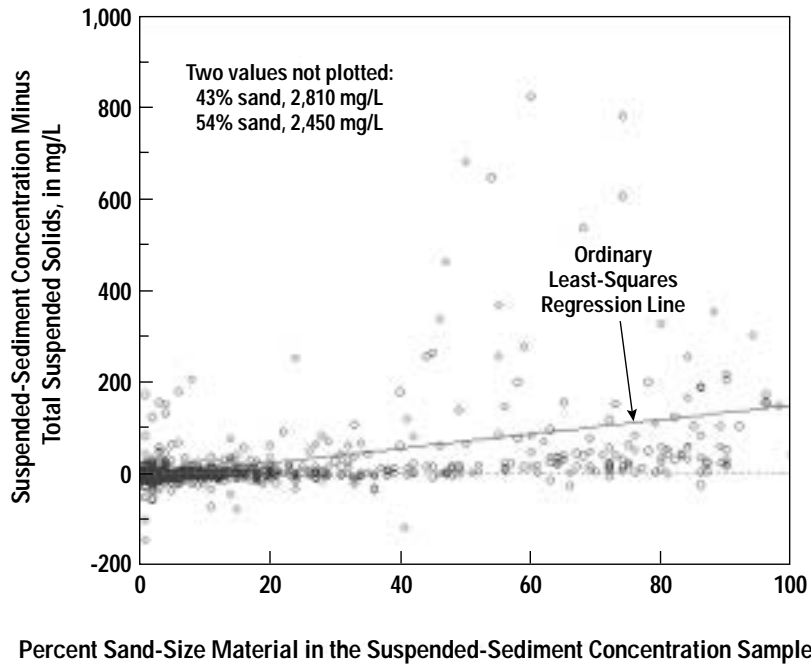


Figure 5. Relation between percent sand-size material in the sample analyzed for suspended-sediment concentration and the remainder of suspended-sediment concentration minus total suspended solids.

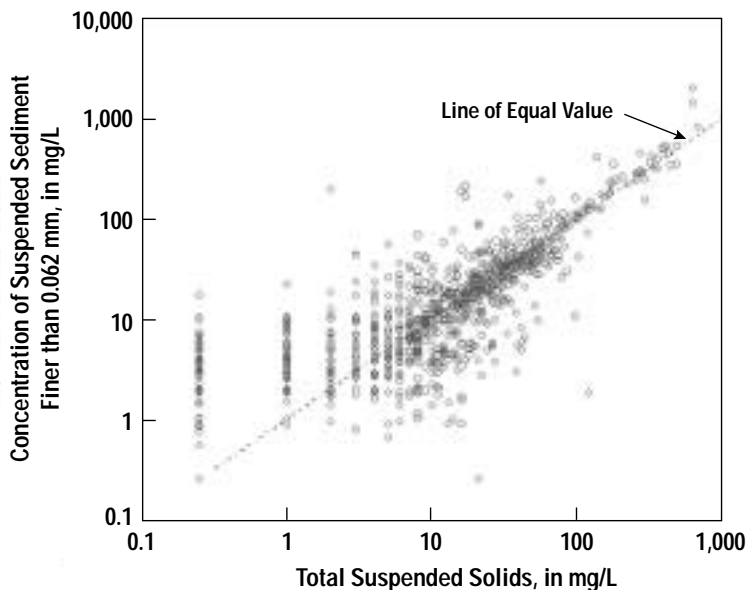


Figure 6. Relationship between total suspended solids and the concentration of suspended sediments finer than 0.062mm in paired suspended-sediment concentration samples. All SSC and TSS values less than 0.25 mg/L were set equal to 0.25 mg/L to enable plotting the data on logarithmic coordinates.

the suspended solid-phase discharges compared to those estimates that are computed from SSC data. TSS discharge underestimates may be negligible for streams conveying a predominantly fine material load over the range of discharges. Substantial underestimates of TSS discharges can be expected for streams conveying sediment loads that exceed

about a third sand-size material in composition, and with percentages and concentrations of sand-size material that increase with discharge.

Figure 7 shows an example of the influence of bias resulting from using TSS data to calculate instantaneous sediment discharges for a stream in the north-eastern United States. All the TSS and SSC samples used to compute sediment discharges from October 15 through December 24, 1998 were collected by a cooperating agency using an open bottle and analyzed by the cooperator's laboratory. The apparent order-of-magnitude change in sediment discharges between November and December 1998 was not related to any in-stream change in solid-phase transport, but to a change in analytical procedures (Henry Zajd, Jr., U.S. Geological Survey, oral commun., 2000). TSS analyses were performed on all samples collected in October and November 1998, and SSC analyses were used to produce subsequent data. The USGS did not publish daily sediment discharges for the pre-December period shown in figure 7 because the TSS data used in the computations were considered unreliable.

Quality-Control Data

Box plots that show the results of quality-control samples analyzed for SSC and TSS by a cooperating laboratory participating in the USGS National Sediment Laboratory Quality Assurance Program are shown in figure 8. The samples were analyzed in five sample sets. Box plots for sample sets 1997-1, 1997-2, and 1998-1 represent TSS analytical results. Box plots for study sample sets 1998-2 and 1999-1 represent SSC analytical results. This figure illustrates two important characteristics related to sediment-data quality.

First, both the SSC and TSS data tend to be negatively biased. The combined data for all samples analyzed as part of the Sediment Laboratory Quality Assurance Program from 1996 through September 2000 have a median concentration bias of -1.83 percent; the 25th percentile is -4.39 percent; and the 75th percentile is 0.00 percent. The bias primarily reflects a loss of some sediment, such as through a filter, or an inability to weigh accurately very small amounts of fine material in the SSC analytical procedure. The SSC median percent bias values for both study sets are about -2 and -4 percent of the known sediment mass. In contrast, TSS median percent bias values for the three study sets range from -6 to -23 percent from the known sediment mass; the mean difference in TSS median percent bias from the known sediment mass is -16 percent. Only for sample set 1997-2 does any quartile include the

TSS value for the known sediment mass. The median percent bias in TSS sample set 1997-1 and in 1998-1 exceeds three F-pseudosigmas² from the mean value of all measured sediment mass measurements reported in the USGS National

²The F-pseudosigma is a nonparametric statistic analogous to the standard deviation that is calculated by using the 25th and 75th percentiles in a data set. It is resistant to the effect of extreme outliers.

Sediment Laboratory Quality Assurance Program. The analytical method used by the laboratory for determination of TSS in natural-water samples was deemed unacceptable by the U.S. Geological Survey (USGS, 1999b).

Second, the variances associated with the TSS quality-control data are large compared to those for SSC data (figure 8). The least variable data – those from sample set 1997-1 – range from -18 to -32 percent of the known value, and the difference between the 1st and 3rd quartile values is 9 percent. In comparison, the most variable SSC data – those from sample set 1999-1 – range from 0 to -5 percent; the difference in the 1st and 3rd quartile values is 4 percent.

In terms of bias and variance, the TSS results from two of the first three sample sets – 1997-1 and 1998-1 – were considered unacceptable by the U.S. Geological Survey (U.S. Geological Survey, 1998; 1999a). The SSC results from study sample sets 1998-2 and 1999-1, which were produced by the same laboratory, are considered among the most accurate of all laboratories that participated in the USGS National Sediment Laboratory Quality Assurance Program (John Gordon, U.S. Geological Survey, oral commun., 2000).

CONCLUSIONS

Of the two analytical methods examined for measuring the mass of solid-phase material in natural-water samples – suspended-sediment concentrations (SSC), and total suspended solids (TSS), – data produced by the SSC technique are the more reliable. This is particularly true when the amount of sand in a sample exceeds about a quarter of the dry sediment mass. This conclusion is based on the following observations:

1. The SSC analytical

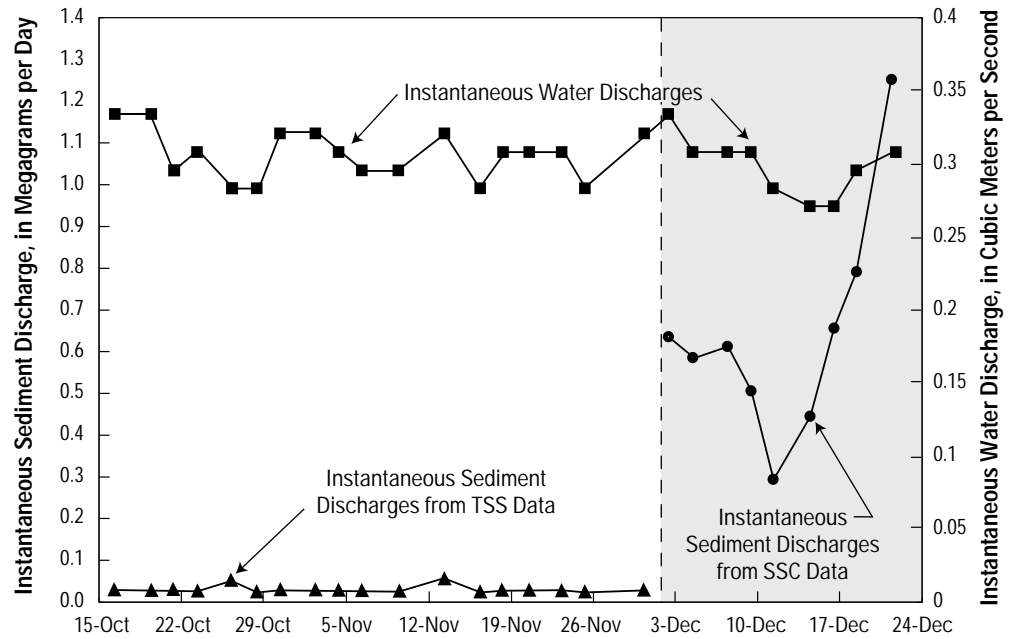


Figure 7. Instantaneous water discharges, and sediment discharges computed from total suspended solids (TSS) and suspended-sediment concentration (SSC) data for a stream in the northeastern United States, 1998.

procedure entails measurement of the entire mass of sediment and the net weight for the entire sample. In contrast, only a part of the water-sediment mixture is typically used in the TSS analysis. Difficulties in, and variations for methods associated with obtaining TSS subsamples can result in determinations of solid-phase characteristics that are substantially different from those of the original sample.

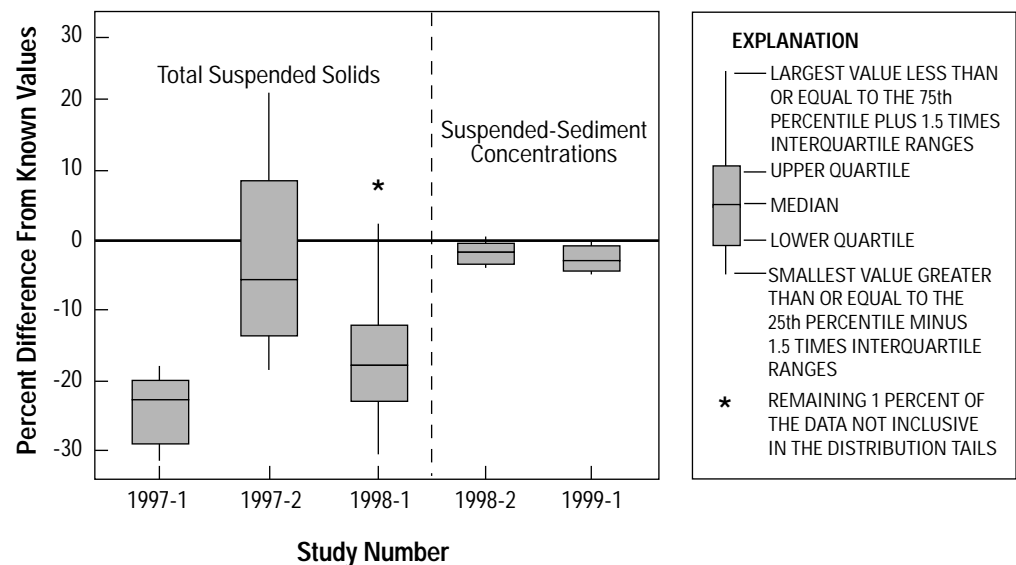


Figure 8. Variability in results of suspended-sediment concentrations and total suspended solids analytical methods in quality-control water samples analyzed by a co-operator laboratory. (John D. Gordon, U.S. Geological Survey, written commun., 2000).

2. Subsampling by pipette or by pouring from an open container will generally result in production of a sediment-deficient subsample. An analysis of 3,235 paired SSC and TSS natural-water samples from eight States showed that SSC values tend to exceed their paired TSS values, particularly at larger values of SSC. This is consistent with the assumption that most subsamples used to determine the TSS data were obtained by pipette or by pouring from an open container.

3. An analysis of 860 paired SSC and TSS natural-water samples for which relative amounts of sand-size and finer material are known for the SSC sample were used to determine the effect of sand-size particles on the TSS analysis. SSC values tend to be larger than their paired TSS values as the percentage of sand-size material exceeds about a quarter of the mass of sediment in the sample. Additionally, a relation between values of TSS and the paired SSC material finer than 0.062 mm showed that for samples with TSS values exceeding about 5 mg/L, the paired SSC and TSS data are more or less evenly distributed around the line of equal value. Sand-size material is more difficult to subsample than finer material due to the large fall velocity of sand-size material as described by Stokes' Law.

The tendency for SSC values to exceed their paired TSS values has important ramifications for computations of suspended solid-phase discharges; those computed using TSS data will often underestimate solid-phase discharges. This is particularly true for sites when the percentages of sand-size material in the water samples exceed about a third and where concentrations and percentages of sand-size material in transport increase with flow.

4. Fifty-three quality-control samples from a cooperator's laboratory — three sample sets totaling 35 TSS analyses of subsamples obtained by pouring from original samples, and two sample sets totaling 18 SSC analyses — were used to compare bias and variance introduced by use of the TSS and SSC analytical methods. Two of the three sample sets analyzed for TSS had unacceptably large mean negative bias. Variances associated with all three TSS sample sets were at least double those associated with the SSC quality-control results from the same laboratory. The two SSC sample sets analyzed by the same laboratory had small variances compared with those for the three TSS sample sets. The slight negative bias values associated with the SSC sample sets were consistent with data analyzed by most laboratories participating in the USGS National Sediment Laboratory Quality Assurance Program.

5. Review of the literature indicates that the TSS method originated as an analytical method for wastewater, presumably for samples collected after a settling step at a wastewater treatment facility. The results of this evaluation do not support use of the TSS method to produce reliable concentrations of solid-phase material in natural-water samples. The TSS method is being misapplied to samples from natural water.

Some SSC and TSS data may be comparable, particularly when the percentage or amount of sand-size material in

the sample is less than about 25 percent. TSS values from analyses of samples collected following a settling step for coarser sediments, such as those obtained for compliance purposes at sewage treatment plants and water treatment facilities, may be reliable. However, because relatively few TSS data are associated with the percent sand-size and finer material from SSC samples, it is usually impossible to identify which if any TSS data may be biased. Some of the TSS data may reflect the mass of suspended solids in natural-water samples, but there are currently no absolute means to identify those data, nor a generally reliable procedure to correct biased TSS data.

The TSS method, which was originally designed for analyses of wastewater samples, is shown to be fundamentally unreliable for the analysis of natural-water samples. In contrast, the SSC method produces relatively reliable results for samples of natural water, regardless of the amount or percentage of sand-size material in the samples. SSC and TSS data collected from natural water are not comparable and should not be used interchangeably. The accuracy and comparability of suspended solid-phase concentrations of the Nation's natural waters would be greatly enhanced if all these data were produced by the SSC analytical method.

REFERENCES CITED

- American Public Health Association and American Water Works Association, 1946, Standard methods for the examination of water and sewage (9th ed.): New York, American Public Health Association, 286 p.
- American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1971, Standard methods for the examination of water and wastewater (13th ed.): Washington, D.C., American Public Health Association, 874 p.
- American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1976, Standard methods for the examination of water and wastewater (14th ed.): Washington, D.C., American Public Health Association, 1,193 p.
- American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1985, Standard methods for the examination of water and wastewater (16th ed.): Washington, D.C., American Public Health Association, 1,268 p.
- American Public Health Association, American Water Works Association, and Water Pollution Control Federation, 1995, Standard methods for the examination of water and wastewater (19th ed.): Washington, D.C., American Public Health Association, variously paged.
- American Society for Testing and Materials (ASTM), 2000, Standard test methods for determining sediment concentration in water samples: D 3977-97, vol. 11.02, Water (II), 395-400.
- Buchanan, P.A., and Schoellhamer, D.H., 1998, Summary of suspended-solids concentration data, San Francisco Bay, California, Water Year 1996: U.S. Geological Sur-

- vey Open-File Report 98-175, 59 p.
- Capel, P.D., Nacionales, F.C., and Larson, S.J., 1995, Precision of a splitting device for water samples: U.S. Geological Survey Open-File Report 95-293, 6 p.
- Capel, P.D., and Larson, S.J., 1996, Evaluation of selected information on splitting devices for water samples: U.S. Geological Survey Water-Resources Investigations Report 95-4141, 103 p.
- Edwards, T.K., and Glysson, G.D., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p.
- Federal Interagency Sedimentation Project, 1941, Methods of analyzing sediment samples: Iowa City, Iowa University Hydraulics Laboratory, Inter-Agency Report 4, 203 p.
- Folk, Robert L., 1980, Petrology of sedimentary rocks: Austin, Texas, Hemphill Publishing Co., 182 p.
- Frisch, R., 1934, Statistical confluence analysis by means of complete regression systems: Oslo, Norway, University Institute of Economics.
- Glysson G.D., and Gray, J.R., 1997, Coordination and standardization of federal sedimentation activities: Expanding sediment research capabilities in today's USGS, accessed July 6, 1999, at URL <http://water.usgs.gov/osw/techniques/workshop>
- Glysson, G.D., Gray, J.R., and Conge, L.M., 2000, Adjustment of total suspended solids data for use in sediment studies: Proceedings, ASCE's 2000 Joint Conference on Water Resources Engineering and Water-Resources Planning and Management, July 31-August 2, 2000, Minneapolis, Minn., 10 p.
- Gordon, J.D., Newland, C.A., and Gagliardi, S.T., 2000, Laboratory performance in the Sediment Laboratory Quality-Assurance Project, 1996-98: U.S. Geological Survey Water-Resources Investigations Report 99-4184, 69 p.
- Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p.
- Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: Elsevier, Studies in environmental science 49, 522 p.
- Hill, B.R. 1996, Streamflow and suspended-sediment loads before and during highway construction, North Halawa, Haiku, and Kamooalii drainage basins, Oahu, Hawaii: U.S. Geological Survey Water-Resources Investigations Report 96-4259, 34 p.
- James, R.B., Senior Consultant, 1999, Solids in storm water runoff: Water Resources Management, accessed April 17, 1999, at URL <http://stormwater-resources.com/library.htm>
- Kammerer, P.A., Jr., Garn, H.S., Rasmussen, P.W., and Ball, J.R., 1998, A comparison of water-quality sample collection methods used by the U.S. Geological Survey and the Wisconsin Department of Natural Resources—Proceedings of the National Water-Quality Monitoring Council National Conference on Monitoring—Critical foundations to protect our waters: Reno, Nevada. U.S. Environmental Protection Agency, Washington, D.C., p. III-259-269.
- Kimble-Contes, Inc., accessed May 1, 2000, at URL <http://www.kimble-kontes.com/html/pg-37005.html> and URL <http://www.kimble-kontes.com/html/pg-37034B.html>.
- Klepper, Steven, and Leamer, Edward E., 1984, Consistent sets of estimates for regressions with errors in all variables: *Econometrica*, v. 52, no. 1, p. 163-183.
- Knott, J.M., Sholar, C.J., and Matthes, W.J., 1992, Quality assurance guidelines for the analysis of sediment concentration by U.S. Geological Survey Sediment Laboratories: U.S. Geological Survey Open-File Report 92-33, 30 p.
- Knott, J.M., Glysson, G.D., Malo, B.A., and Schroder, L.J., 1993, Quality assurance plan for the collection and processing of sediment data by the U.S. Geological Survey, Water Resources Division: U.S. Geological Survey Open-File Report 92-499, 18 p.
- Matthes, W.J., Jr, Sholar, C.J., and George, J.R., 1991, A quality-assurance plan for the analysis of fluvial sediment by laboratories of the U.S. Geological Survey: U.S. Geological Survey Open-File Report 91-467, 31 p.
- Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C3, 66 p.
- Preston, S.D., and Summers, R.M., 1997, Estimation of nutrient and suspended-sediment loads in the Patuxent River Basin, Maryland, water years 1986-90: U.S. Geological Survey Water-Resources Investigations Report 96-4175, 69 p.
- Sullivan, D.J., and Blanchard, S.F., 1994, Surface-water-quality assessment of the Upper Illinois River Basin in Illinois, Indiana, and Wisconsin—Fixed-station network and selected water-quality data for April 1987-August 1990: U.S. Geological Survey Open-File Report 91-175, 213 p.
- Ward, J.R., and Haar, C.A., 1990, Methods for collection and processing of surface-water and bed-material samples for physical and chemical analyses: U.S. Geological Survey Open-File Report 90-140, 71 p.
- Wilde, F.D., Radtke, D.B., Gibs, Jacob, and Iwatsubo, R.T., eds., 1999, Processing of water samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chap. A5, 125 p.
- U.S. Environmental Protection Agency, 1998, Report of the Federal Advisory Committee on the Total Maximum Daily Load (TMDL) Program: The National Advisory Council for Environmental Policy and Technology, EPA 100-R-98-006, 97 p., 7 appendixes.
- U.S. Geological Survey, 1997, Comparison of the suspended-sediment splitting capabilities of the churn and cone splitters: U.S. Geological Survey, Office of Water Quality Memorandum No. 97.06, accessed Oc-

- tober 23, 1999, at URL <http://www.woper.er.usgs.gov/memos/97/qw97.06—correction.txt>.
- U.S. Geological Survey, 1998, A national quality assurance program for sediment laboratories operated or used by the Water Resources Division: U.S. Geological Survey, Office of Surface Water Technical Memorandum No. 98.05 accessed July 6, 1999, at URL <http://www.woper.er.usgs.gov/memos/98/sw98.05.txt>.
- U.S. Geological Survey, 1999a, Guidelines from the 1998 sediment laboratory chiefs workshop: U.S. Geological Survey Office of Surface Water Technical Memorandum 99.04 accessed July 6, 1999 at <http://www.woper.er.usgs.gov/memos/99/sw99.04.txt>.
- U.S. Geological Survey, 1999b, Sediment laboratory quality assurance project: U.S. Geological Survey, Office of Water Quality, Branch of Quality Systems, accessed January 27, 2000 at URL <http://sedserv.cr.usgs.gov/>.
- U.S. Geological Survey, 2000a, Chesapeake Bay river input monitoring program: Accessed January 27, 2000 at URL: <http://va.water.usgs.gov/chesbay/RIMP/index.html>.
- U.S. Geological Survey, 2000b, U.S. Geological Survey quality assurance project for sediment analysis: U.S. Geological Survey Fact Sheet No. FS 031-00, 4 p.

U.S. Geological Survey, Reston, Virginia
 John R. Gray, Hydrologist/Sediment Specialist
 U.S. Geological Survey, Office of Surface Water
 415 National Center, 12201 Sunrise Valley Drive
 Reston, VA 20192
 703/648-5318, FAX 648-5295, jrgray@usgs.gov