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Techniques of Water-Resources Investigations
of the United States Geological Survey

Chapter C1

LABORATORY THEORY

AND METHODS

for

SEDIMENT ANALYSIS

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UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1969

PREFACE

This series of manuals on techniques describes procedures for planning and executing specialized work in water-resources investigations. The material is grouped under major subject headings called books and further subdivided into sections and chapters; Section C of Book 5 is on sediment analysis.

The unit of publication, the chapter, is limited to a narrow-field of subject matter. This format permits flexibility in revision and publication as the need arises.

Provisional drafts of chapters are distributed to field offices of the U.S. Geological Survey for their use. These drafts are subject to revision because of experience in use or because of advancement in knowledge, techniques, or equipment. After the technique described in a chapter is sufficiently developed, the chapter is published and is sold by the U.S. Geological Survey, 1200 South Eads Street, Arlington, VA 22202 (authorized agent of Superintendent of Documents, Government Printing Office).

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LABORATORY THEORY AND METHODS FOR SEDIMENT ANALYSIS

By Harold P. Guy

Abstract

The diverse character of fluvial sediments makes the choice of laboratory analysis somewhat arbitrary and the processing of sediment samples difficult. This report presents some theories and methods used by the Water Resources Division for analysis of fluvial sediments to determine the concentration of suspended-sediment samples and the particle-size distribution of both suspended-sediment and bed-material samples. Other analyses related to these determinations may include particle shape, mineral content, and specific gravity, the organic matter and dissolved solids of samples, and the specific weight of soils.

The merits and techniques of both the evaporation and filtration methods for concentration analysis are discussed. Methods used for particle-size analysis of suspended-sediment samples may include the sieve-pipet, the VA tube-pipet, or the BW tube-VA tube depending on the equipment available, the concentration and approximate size of sediment in the sample, and the settling medium used. The choice of method for most bed-material samples is usually limited to procedures suitable for sand or to some type of visual analysis for large sizes.

Several tested forms are presented to help insure a well-ordered system in the laboratory to handle the samples, to help determine the kind of analysis required for each, to conduct the required processes, and to assist in the required computations. Use of the manual should further "standardize" methods of fluvial sediment analysis among the many laboratories and thereby help to achieve uniformity and precision of the data.

Introduction

Acknowledgments

The writer has attempted to document the "special" procedures developed and routinely used by many scientists and laboratory technicians for sediment analysis. These procedures are not individually acknowledged because they have usually evolved as a result of the many sediment conditions encountered in the many kinds of streams in the United States and because the scientists and technicians who have developed these highly efficient systems did so in close association with fellow workers. It is regrettable that the writer cannot document all these procedures in great detail because it is difficult to obtain complete information and because there is need for standardization. Sedimentation theories, however, are better acknowledged; but again, many contributions have evolved from individuals or groups and are not fully documented.

Among the many who have contributed to this chapter, as well as the earlier 1960 draft, special appreciation is extended to C. D. Albert, F. C. Ames, B. C. Colby, B. R. Colby, C. R. Collier, R. K. Flint, J. C. Mundorff, G. Porterfield, and R. B. Vice.

Functions of a sediment laboratory

A sediment laboratory in the Water Resources Division of the U.S. Geological Survey has two principal functions: (1) the determination of suspended-sediment concentration of samples collected from streams and (2) the determination of particle-size distribution of suspended sediment, streambed material, and reservoir deposits. Other kinds of analyses, usually associated with these two functions, may include quantitative determination and (or) removal of organic matter and dissolved solids, the specific

gravity of sediment particles, the specific weight of soils and sediment deposits, particle shape determinations, and mineral analyses.

Data from the concentration and particle-size determinations are used to make computations of suspended-sediment discharge, computations of total sediment discharge, and computations of the probable volume and specific weight of exposed and submerged reservoir deposits. These are but a few of the many uses made of concentration and particle-size data of fluvial sediment. The reliability of these computations and the utility of the data are dependent on the accuracy and reliability of the laboratory analyses. This discussion of the functions of a sediment laboratory is given to provide insight into some of the problems encountered in sediment analyses and to help guide the field technician in the collection of samples that are suitable for the desired analysis.

In the determination of suspended-sediment concentration, the quantity and characteristics of the sediment, and the chemical quality of water from the stream (native water) must be considered in the processing of the sample. Too small a quantity of sediment tends to magnify errors inherent in determining the weight of dry sediment, or in the transfer of material from one container to another. On the other hand, too large a quantity of sediment may cause problems with respect to splitting, drying, and weighing the sample. Samples collected with certain types of mineralized water and (or) containing colloidal clay result in difficult separation of sediment from the native water. A weight correction based on the quantity of dissolved solids is often necessary when the evaporation method is used to determine suspended-sediment concentration. These and other aspects of suspended-sediment concentration determinations are discussed later in this chapter.

The determination of the sediment particle-size distribution in a sample of streamflow offers several challenges in addition to those encountered in determining concentration. As discussed later, the sieve-pipet method or the visual-accumulation tube-pipet method is recommended in order to obtain maximum information regarding fall velocity. Since each kind of analysis requires a rather narrow range of sediment quantity, the much larger range normally found in sediment samples is likely to be a problem. Compositing or grouping of the sediment from several samples into one may be necessary when the stream concentration is low; or, a sample from a stream having a high concentration may need to be split so that an optimum smaller quantity of sediment may be analyzed. For example, the quantity of sand to be analyzed in the visual-accumulation tube can range from 0.05 to 0.8 g (gram) for the smallest tube to about 5 to 15 g for the largest tube; or in the case of the pipet, the quantity of silt and clay must be just sufficient to yield a concentration between 2,000 and 5,000 ppm (parts per million) in the sedimentation tube. Each kind of analysis has its own range of sediment quantity necessary to obtain optimum results.

In addition to the problem of determining the kind of analysis to use, it is necessary to keep in mind the need to determine the concentration of sediment in the samples for which particle-size distribution is determined. Provision should, therefore, be made to obtain the weights of all increments of sediment in the analysis as well as portions not used in the analysis. The sample must be kept wet until the particle-size analysis is complete to prevent the formation of aggregates that resist redispersion. Division of a combined sample into separate portions for separate concentration and particle-size analysis should be avoided unless the sample can be divided into two samples each representing the streamflow at the given time. Splitting may introduce quantitative and qualitative errors that will affect the concentration and (or) particle-size results. Procedures for

determining particle-size distribution of fluvial sediment by sieve and sedimentation methods are discussed in sections to follow. The frequency of sampling for analysis and the need for special analytical procedures for both native and dispersed settling media are also discussed.

The determination of particle-size distribution of bed-material samples is different from the determination of particle-size distribution of suspended-sediment samples because the quantity of material is usually large, the samples are usually sand with a considerably larger median size and most samples will be in a room-dry condition. Unlike suspended-sediment samples, which often have very limited quantities of material available for analysis, the larger bed-material samples with proper splitting allow the use of optimum quantities of material for all size ranges.

Sieves are used to determine particle-size distribution of material ≥ 2.0 mm (millimeter), whereas the VA tube (visual-accumulation tube) is used most frequently to determine particle-size distribution of material from 0.062 to 2.0 mm. However, the sieve can be, and sometimes is, used for the entire range of sand and gravel sizes. Particle size determined by the VA tube is referred to as sedimentation diameter and the relationship between sieve size and sedimentation diameter is well known for quartz spheres. It is usually assumed that the particles have a specific gravity of 2.65 unless the material in the sample appears to contain significant quantities of minerals other than quartz. Both specific gravity and particle shape vary depending on the geologic and hydrologic characteristics of any given stream and drainage basin. It may be useful to check the specific gravity and shape characteristics of sediment for a specific stream in order to convert the fall diameter of sediment determined by the VA tube to standard fall velocity or actual particle size.

Units of measurement and definitions

The methods used for collecting sediment samples are described in a chapter of this series entitled "Field Methods for Fluvial Sediment Measurement." Though it is possible to determine many kinds of sediment concentration such as the temporal mean or the average along a line, over an area, and throughout a specified volume, the sampling and compositing procedures are usually designed to give a time-integrated, velocity-weighted, cross-sectional average value of concentration or size distribution.

The common unit for expressing suspended-sediment concentration is milligrams per liter (mg/l) and is computed as one million times the ratio of the dry weight of sediment in grams to the volume of water-sediment mixture in cubic centimeters. Other units, such as percent or parts per million (ppm), have been used to express suspended-sediment concentration but are not recommended. In the laboratory it is more convenient to obtain the weight of the water-sediment mixture than to obtain its volume. Therefore, the following formula involving parts per million is used

$$\text{mg/l} = C \ (\text{ppm}) = C\left[\frac{\text{weight of sediment} \times 1{,}000{,}000}{\text{weight of water-sediment mixture}}\right]$$

where C is given in table 1. Total sediment concentration has, in some cases, been expressed on a volume basis, especially for sands and other coarse material. Such volume measurements are generally not reliable because variation due to particle characteristics and compaction makes the assumption of a specific weight for the conversion of volume into weight difficult.

Table 1.—Factors C for computation of sediment concentration in milligrams per liter when used with parts per million or the ratio (times 10⁶) of the weight of sediment to the weight of the water-sediment mixture

[The factors are based on the assumption that the density of water is 1.000, plus or minus 0.005, the range of temperature is 0°-29°C, the specific gravity of sediment is 2.65, and the dissolved solids concentration is less than 10,000 parts per million]

Ratio	C	Ratio	C	Ratio	C
0- 15, 900	1. 00	234, 000-256, 000	1. 18	417, 000-434, 000	1. 36
16, 000- 47, 000	1. 02	257, 000-279, 000	1. 20	435, 000-451, 000	1. 38
47, 000- 76, 000	1. 04	280, 000-300, 000	1. 22	452, 000-467, 000	1. 40
77, 000-105, 000	1. 06	301, 000-321, 000	1. 24	468, 000-483, 000	1. 42
106, 000-132, 000	1. 08	322, 000-341, 000	1. 26	484, 000-498, 000	1. 44
133, 000-159, 000	1. 10	342, 000-361, 000	1. 28	499, 000-513, 000	1. 46
160, 000-184, 000	1. 12	362, 000-380, 000	1. 30	514, 000-528, 000	1. 48
185, 000-209, 000	1. 14	381, 000-398, 000	1. 32	529, 000-542, 000	1. 50
210, 000-233, 000	1. 16	399, 000-416, 000	1. 34		

Several measures of particle size should be defined as the basis for simple, accurate, and practical determination and expression of sediment sizes. Some measures of particle size are difficult to evaluate and are seldom determined; others are determined only approximately. Before the basic concepts of these measurements are discussed, several definitions relating to particle size [1] are quoted essentially as reported in (U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1957b, p. 11):

The *nominal diameter* of a particle is the diameter of a sphere that has the same volume as the particle.

The *sieve diameter* of a particle is the diameter of a sphere equal to the length of the side of a square sieve opening through which the given particle will just pass.

The *standard fall velocity* of a particle is the average rate of fall that the particle would attain if falling alone in quiescent, distilled water of infinite extent and at a temperature of 24°C.

The *standard fall diameter*, or simply *fall diameter*, of a particle is the diameter of a sphere that has a

specific gravity of 2.65 and has the same standard fall velocity as the particle.

The *sedimentation diameter* of a particle is the diameter of a sphere that has the same specific gravity and terminal uniform settling velocity as the given particle in the same sedimentation fluid.

The *standard sedimentation diameter* of a particle is the diameter of a sphere that has the same specific gravity and has the same standard fall velocity as the given particle.

Size distribution, or simply *distribution*, when applied in relation to any of the size concepts, refers to distribution of material by percentages or proportions by weight.

Fall velocity and *settling velocity* are generally terms which may apply to any rate of fall or settling as distinguished from standard fall velocity.

The basic concept of "size" of a sediment particle is expressed in terms of volume (the nominal diameter as defined above). When consideration of the density or mass of the particle is necessary, specific gravity is used. It is recognized that sieves, frequently used for the separation of sediments into "size" grades, do not grade particles entirely by size but by shape as well. Ideally, sieving should show relative quantities of the sample in terms of square openings; but in reality, many irregular particles that have nominal diameters much greater than the stated sieve openings will pass through a given sieve.

The above definition of sieve diameter means that the sieve diameter of the particle is the length of the side of the smallest square opening through which the particle could pass. Thus, it is assumed that the nominal and sieve diameters of a sphere are always equal. It should be mentioned further that the nominal diameter of a sieved fraction may be larger than the indicated sieve diameter if the sieve is badly worn

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[1] The meaning of the term "particle" is often rather ambiguous. Consider any given sample of soil which contains a considerable number of relatively large aggregates; these aggregates are "particles," and many properties of soil depend on their size and stability. The aggregates in turn consist of grains which are also "particles" and which are commonly referred to as the "ultimate particles" of soil. The size of the ultimate particles also determines many soil properties. These so-called ultimate particles may also be considered as not truly ultimate because the grains may be composed of two or more crystals of the same or different minerals.

Obviously, it is important to be aware of the kinds of particles to be measured. In sediment investigations, the ultimate particle size should be used unless otherwise specified. Ultimate particle size in fluvial sediment can be defined for practical purposes as the particle size obtained by standard methods of preparation and dispersion of sediment samples. Standard methods of preparation and analysis in native water usually results in floccules of particles, especially in the clay sizes.

or if some openings have been stretched out of their "square" shape.

One of the dynamic properties necessary for sediment transport studies is the velocity of fall of the individual particles in quiet water. Terms, such as "settling velocity," "fall velocity," "velocity of settling," or "velocity of fall," have been applied to this fundamental characteristic. *Standard fall velocity* allows various investigators to compare their data directly. This fall-velocity concept is simple and logical; however, a size concept is so thoroughly embedded in the concepts relative to the field of sedimentation that an expression or measure of diameter is needed. Hence, *fall diameter* is related to fall velocity in that a given particle has only one fall diameter which is independent of the type of material, the concentration of analysis, or the method of analysis.

Studies have shown that a particle settling as one of several surrounding particles generally falls with a velocity different from that for the particle settling alone. The fall-diameter distribution of a sample may be described as the distribution determined as though each particle were dropped separately and a summation made of the fall diameters of the particles. This distribution is based on weight and fall diameter and is believed to be the most basic and desirable expression for the sedimentation analysis of a sample.

The definition of *sedimentation diameter* does not restrict the conditions under which the settling velocity may be determined. The relation of diameter to settling velocity depends only on the specific gravity of the particle. Any of the various settling velocities, depending on the nature of the sample, the concentration, the fluid, and the apparatus, must be used with a determination or estimate of specific gravity to establish sedimentation diameter. It is apparent from the definition previously given that the *standard sedimentation diameter* of a particle depends only on the volume and shape of the particle, and that the relationship of nominal diameter to standard sedimentation diameter becomes a measure of the effect of shape and roughness on the settling velocity of the particle in water at 24°C.

The physical size of particles, especially for gravel and larger particles, may be expressed on the basis of the length of three diameters of the particle (a, b, and c) which are mutually perpendicular (Inter-Agency Report 12, p. 12). The axes are differentiated as $a=$ the longest axis of the particle, $b=$ the intermediate axis of the particle, and $c=$ the shortest axis of the particle. The harmonic mean diameter (Krumbein and Pettijohn, 1938, p. 128) is defined as $d_h=3\ abc/(ab+bc+ac)$ and is considered to be closely related to diameters calculated on the basis of Stokes law. In addition to the harmonic mean, the arithmetic mean $d_a=(a+b+c)/3$ and the geometric mean diameters $d_g=\sqrt[3]{abc}$ have been used by various investigators to express size. The important value of these physical measurements is in the expression of a particle shape factor.

The shape factor $sf=c/\sqrt{ab}$ is useful in relating nominal diameters to fall velocity or fall diameter. Figure 1 shows the relation of naturally worn quartz particles to their fall velocity for shape factors of 0.5, 0.7, and 0.9 and at temperatures of 0°, 10°, 20°, 30°, and 40° C. The shape factor of 0.7 is about average for natural sediments.

The usefulness of shape factors is limited in routine sedimentation studies, for even if the sieve, nominal, and axis length diameters are known, the fall diameter may be determined more easily and accurately through fall velocity data than by the shape factor. In summary, the factor of shape may be kept in proper perspective by remembering that for smooth quartz spheres all four diameters, nominal, sieve, axis length, and fall are the same; that the relative effect of shape varies with size; and that the effect of shape is more significant with sieve than with the sedimentation type of analyses, at least for the smaller sizes.

With respect to methods of particle-size analyses, the following distinction is made between a dispersed system and a stratified system as reported in (U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1957b, p. 13):

A *dispersed system* is one in which particles begin to settle from an initial uniform dispersion and in which particles of sedimentation sizes settle together. Size distribution may be determined by measuring the
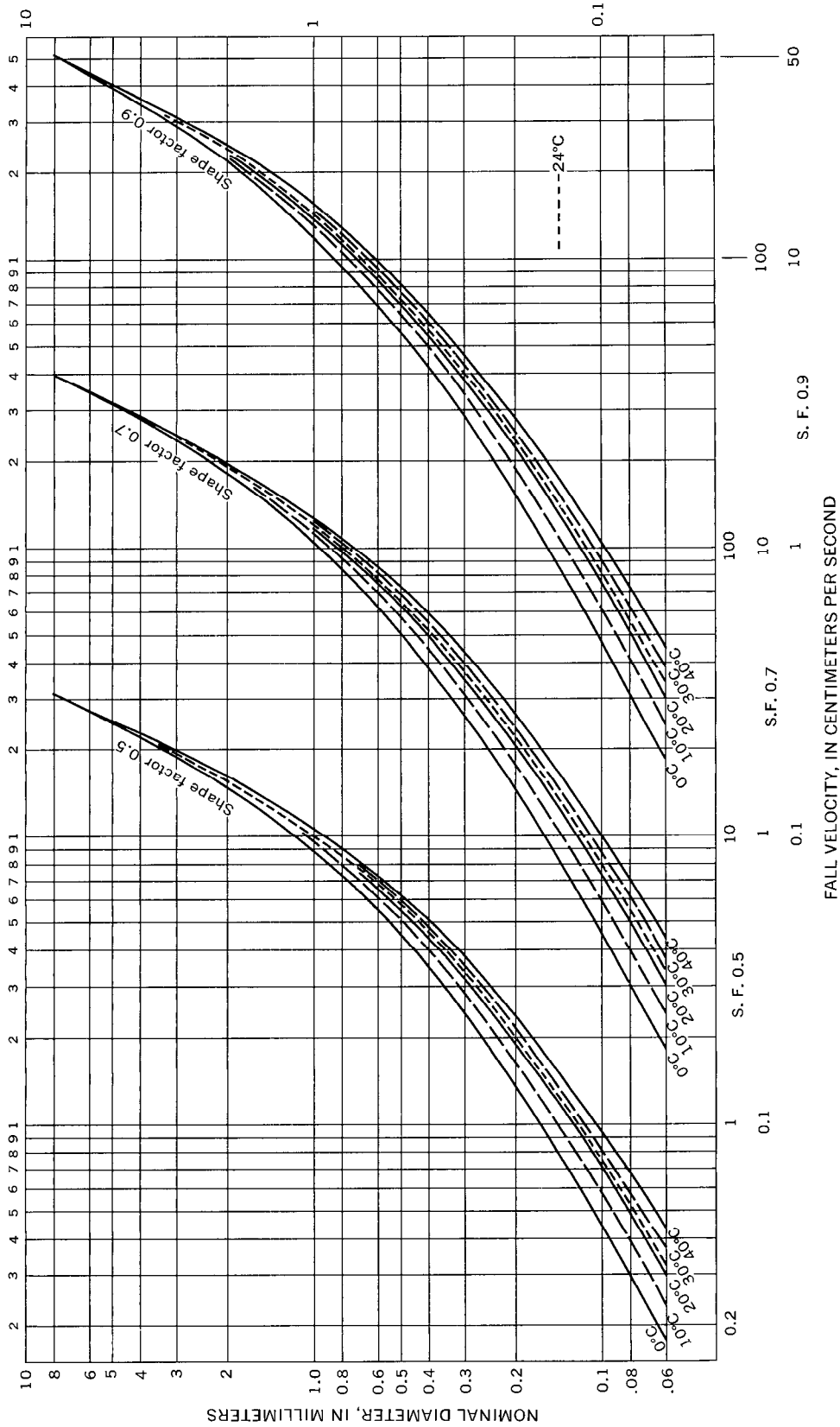
Figure 1.—Relation of nominal diameter and fall velocity for naturally worn quartz particles with shape factors (s.f.) of 0.5, 0.7, and 0.9 (From figure 2 in Inter-Agency Report No. 12 (U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1957a).)

concentration of sediment at given intervals of depth and settling time, as in the pipet method, or the distribution may be obtained from the quantity of sediment remaining in the suspension after various settling times, as in the bottom-withdrawal-tube method.

A *stratified system* is one in which the particles start falling from a common source and become stratified according to settling velocities, as in the visual-accumulation-tube method. At any given instant, the particles coming to rest at the bottom of the tube are of one sedimentation size only and are finer than the particles that have previously settled out and are coarser than those remaining in suspension * * *.

The size-gradation scale, or the distribution of the size classes, is a descriptive function which serves to place nomenclature and terminology on a uniform basis. A grade scale has been defined by Krumbein and Pettijohn (1938, p. 76) "* * * as an arbitrary division of a continuous scale of sizes, such that each scale unit or grade may serve as a convenient class interval for conducting the analysis * * *." In such a scale of sizes, it is recognized that a natural sediment has a continuous size distribution without implication of natural grouping. The Wentworth grade scale is favored in

America. This scale has a fixed geometric interval with each grade one-half as large as the preceding, as suggested by Udden in 1898. Grade scales are, without exception, based on unequal class intervals as a result of the large range of sizes for most sediment. If equal intervals were chosen to give full significance to the smaller sizes, then an excessive number of classes would be necessary with the result of virtually no significance between classes for the larger sizes. The unequal class intervals may make the application of certain statistical analyses to the data more difficult. Table 2 gives the number for Tyler and U.S. Standard sieves and the size limits for each class name of the recommended gradation scale.

The phi scale shown in column 6, derived by Krumbein (1934), is a logarithmic transformation that has integers for the class limits that increase with decreasing grain size. This scale was developed to make it easier to directly apply conventional statistical practices to sediment-size data.

Specific gravity is the ratio of the weight of a substance to the weight of an equal volume

Table 2.—Recommended scale of sizes by classes for sediment analysis

[After Lane and others (1947)]

Tyler sieve No. (1)	U.S. standard sieve No.[1] (2)	Class name (3)	Metric units (millimeters) (4)		Metric units (micrometers) (5)		Phi value [1] (φ) (6)	English units (feet) (7)	
----	----	Boulders	>256		----		----	>0. 840	
(2)	(2)	Large cobbles	256	−128	----		−8	0. 840	−0. 420
(2)	(2)	Small cobbles	128	− 64	----		−7	0. 420	−0. 210
(2)	(2)	Very coarse gravel	64	− 32	----		−6	0. 210	−0. 105
(2)	(2)	Coarse gravel	32	− 16	----		−5	0. 105	−0. 0525
(2)	(2)	Medium gravel	16	− 8. 0	----		−4	0. 0525	−0. 0262
2. 5	(2)	Fine gravel	8. 0	− 4. 0	----		−3	0. 0262	−0. 0131
5	5	Very fine gravel	4. 0	− 2. 0	----		−2	0. 0131	−0. 00656
9	10	Very coarse sand	2. 0	− 1. 0	2000	−1000	−1	0. 00656	−0. 00328
16	18	Coarse sand	1. 0	− 0. 50	1000	− 500	0	0. 00328	−0. 00164
32	35	Medium sand	0. 50	− 0. 25	500	− 250	+1	0. 00164	−0. 000820
60	60	Fine sand	0. 25	− 0. 125	250	− 125	+2	0. 000820	−0. 000410
115	120	Very fine sand	0. 125	− 0. 062	125	− 62	+3	0. 000410	−0. 000205
250	230	Coarse silt	0. 062	− 0. 031	62	− 31	+4	0. 000205	−0. 000103
----	----	Medium silt	0. 031	− 0. 016	31	− 16	+5	0. 000103	−0. 0000512
----	----	Fine silt	0. 016	− 0. 008	16	− 8	+6	0. 0000512	−0. 0000256
----	----	Very fine silt	0. 008	− 0. 004	8	− 4	+7	0. 0000256	−0. 0000128
----	----	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	----	

[1] For maximum size of the given class.
[2] Sieve openings are marked in inches and millimeters.

of water at 4°C. The measurement is then dimensionless. It should not be confused with *specific weight* which is defined as the weight per unit volume; for example, water has a specific weight of 62.4 pounds per cubic foot and a specific gravity of 1.0.

Theory of particles falling in a fluid

Table 3 illustrates the relative position of the finer particles commonly present in sediment samples with respect to the general subdivisions of particulate matter. The table also contains a list of the properties for a given size range as well as related information such as the limit of the microscope and the diameter of pores of various types of filtering materials. Ordinarily, sediment-size analyses are made only for material down to about 0.002 mm in the coarse-suspensions category. Further separations would require excessive time and lack practical value in hydraulic engineering work; however, in many scientific fields a knowledge of the size distribution of material finer than 0.002 mm can be useful.

The settling medium

Most methods of determining particle-size distribution gradation are based upon the action, size, and concentration of particles in fluids. The milling, ceramic, cement, abrasive, and paint industries usually accomplish the separation into size classes in a rising column of air. In the fields of geology, soils, and river hydraulics, quiet water is the most common settling medium. Whatever the medium, the principle involved measures the tendency for particles of similar specific gravity to fall at a rate that is related to the size and shape of the particles. Several laws or mathematical expressions have been developed for expressing the relation of particle size to settling velocity. These laws, especially Stokes law, serve as a basis for many size-separation techniques for particles in the silt and clay classes. Particularly important for the discussion to follow are the pipet and BW tube (bottom-withdrawal-tube) methods. For most particle-size analysis, either sieves or the VA tube are used for 0.062 mm and larger sizes. The latter has the advantage of being a hydraulic method and helps to insure continuity among the size classes representing the range from the fine to the coarse particles. In the following discussion, the settling medium is assumed to be water because it is the universal environment of fluvial sediment and has most of the desirable physical characteristics for analytical use.

Table 3.—The subdivision of matter and the resulting properties

[From table 1, U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1941]

SIZE CHARACTERISTICS				
Millimeters............mm..	1–0.001	0.001–0.0001	0.0001–0.00001	0.00001–0.000001
Micrometers............μ..	1,000–1	1–0.1	0.1–0.001	0.001–0.0001
Nanometers............nm..	1,000,000–1,000	1,000–100	100–1	1–0.1
Relative number of particles......	1–10 ^{9}	10 ^{6}–10 ^{12}	10 ^{12}–10 ^{18}	10 ^{18}–10 ^{21}
Relative surface of particles.......	1–10 ^{3}	10 ^{3}–10 ^{4}	10 ^{4}–10 ^{6}	10 ^{6}–10 ^{7}

QUALITIES STUDIED	COARSE SUSPENSIONS	COLLOIDAL SUSPENSIONS	COLLOIDAL SOLUTIONS	MOLECULAR SOLUTIONS
Appearance in water..............	Very cloudy............	Turbid..................	Clear....................	Clear.
Particles observed................	With naked eye..........	With microscope........	With ultra-microscope..	Cannot be observed.
Rate of settling..................	Quickly or overnight....	Slowly or not at all......	Do not settle............	Do not settle.
Particles separated from water....	With filter paper........	With clay filters.........	With ultra-filter..........	Not by filtration.
Determination of particle sizes....	Sieves, microscope, gravity, or centrifugal settling.	Microscope, centrifugal settling, absorption or dispersion of light.	Ultra-microscope, ultra-centriuge.	Ultra-centrifuge.
Form after evaporation..........	Loose powders.........	Powders and gels........	Gels....................	Crystals.
Soil separates...................	Sand, silt, and (or) clay..	Suspended clay..........	Ultra clay..............	Soil solution.

NOTE.—Limits of size measurements of microscopes and filtering materials:
Limit of microscope (ultra violet light)_____ 100μ
Limit of ultramicroscope_____ 10μ
Limit of ultrafilter_____ 1μ
Brownian movement starts at about_____ 5μ
Diameter pores of hardened filter paper_____ 1.5μ–2.2μ
Diameter pores of Chamberland filter_____ 0.2μ–0.4μ
Diameter of bacteria_____ 0.5μ–1.2μ
Diameter of 200-mesh particles_____ 74μ

Stokes law for small particles

The nature of particle movement in a settling medium depends on a balance of the accelerating and retarding forces which, in turn, depend on the size, shape, and density of the particle and the viscosity and (or) turbulence induced in the fluid. The resistance to motion can be any one of three types of drag (Rouse, 1938; U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1941, p. 24):(1) deformation, (2) surface, or (3) form, depending on the interrelation of the characteristics of the particle and fluid. The deformation drag is the resistance due entirely to the viscosity of the fluid as the relative movement of the fluid extends a considerable distance away from the particle. Stokes law expresses the viscous fall of particles under such conditions, usually for quartz sediment particles finer than 0.062 mm. If the fall velocity of a particle is somewhat faster than that normal for the Stokes law range, then the inertial effects of the fluid reduce the viscous influence to a thin layer around the particle which produces the effect of surface drag. For the larger sizes of particles, the inertial effects of the fluid become increasingly important in the flow around a particle, and therefore the form type of resistance dominates. Such flow causes a wake or low pressure area behind the particle, and eddies are formed; the net result is a force opposing motion.

Stokes law, as developed in 1851, states that the viscous resistance to fall of a particle in a fluid is equal to the net downward force of the particles. Remembering that the net downward force is the force of gravity on the spherical particle minus the buoyant force of the liquid, or

$$4/3 \ (\pi r^3 \ \rho_s g) - 4/3 \ (\pi r^3 \ \rho_f g),$$

then these forces can be stated as

$$6\pi r \mu v = 4/3 \pi r^3 g (\rho_s - \rho_f),$$

where

r = radius of sphere in centimeters,
μ = dynamic viscosity of the fluid in dyne-seconds per centimeter,
v = velocity of fall in centimeters per second,

g = acceleration due to gravity (980 centimeters per second,
ρ_s = density of sphere in grams per centimeter,
ρ_f = density of fluid in grams per centimeter.

The fall velocity as defined by Stokes law is

$$v = 2/9 \frac{(\rho_s - \rho_f) g r^2}{\mu}.$$

Assuming that the specific gravity of the particles is 2.65 and that water is the settling medium, the fall velocity is

$$v = \frac{0.8983 \ d^2}{\mu} \text{ or } d = \frac{\sqrt{\mu v}}{0.9487}$$

where d = diameter of particle in millimeters. Figure 2 gives a graphical solution to the Stokes equation for a water temperature of 20°C. Viscosity correction factors for use with the graph when temperatures other than 20°C are used are tabulated in table 4.

Basic assumptions in the application of Stokes law are (1) that the particles be of sufficient size to overcome Brownian movement, or be sufficiently large for the fluid to be considered homogeneous in relation to the particle size, (2) that the particle be smooth and rigid and of near spherical shape, and (3) that the particle be falling at a uniform velocity as it would in a fluid of unlimited extent with the resistance of the fall due only to the viscosity of the fluid. These assumptions are in general not difficult to satisfy (U.S. Inter-Agency Committee on Water Resources, Subcommittee on Sedimentation, 1941, p. 33–36).

Greatest consideration must be given to the effect of the proximity of particles to each other whereby the deformation effects extend into the path of nearby particles. It is also conceivable that a group of particles creating a region of high concentration may cause a localized area of higher density than the settling medium and thus settle as a unit at an abnormally high rate. The sphericity of the particle is of no great concern since the particle velocity is compared with sedimentation or nominal diameter for most investigations. From a practical viewpoint, a consideration of the shape of these

fine particles for the purpose of relating settling velocity to physical size would be nearly an insurmountable task, hence, the use of the sedimentation diameter concept.
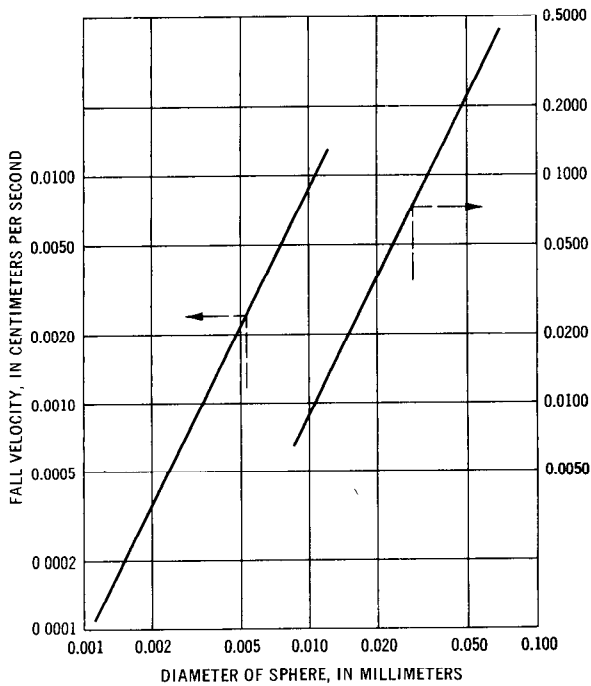

Figure 2.—Relation between fall velocity and diameter (Stokes law) for quartz spheres in water at 20°C.

Table 4.—Fall velocity correction factors for use with figure 2 when temperatures are different from 20°C.

Temperature (°C)	Correction factor $\left(\frac{\mu_T}{\mu_{20}}\right)$	Temperature (°C)	Correction factor $\left(\frac{\mu_T}{\mu_{20}}\right)$
18	1. 051	29	0. 811
19	1. 027	30	. 794
20	1. 000	31	. 776
21	. 976	32	. 760
22	. 953	33	. 746
23	. 930	34	. 729
24	. 908	35	. 714
25	. 887	36	. 700
26	. 867	38	. 673
27	. 848	40	. 648
28	. 829		

Drag-Reynolds number

Stokes law is not applicable for quartz particles larger than about 0.060 mm falling in water because the inertial effects of the fluid reduce the viscous influence. The Reynolds number, **R,** indicates the ratio of inertial forces to viscous forces and, therefore, the character of the resistance to fall. For spherical particles falling in a fluid, **R** is a dimensionless quantity defined as $vd\rho_s/\mu$. The resistance to fall of these larger particles is $C_D A v^2 \rho_s/2$. where C_D is the coefficient of resistance and A is the projected cross-section area of the particle. This resistance is equated to the net downward force as previously shown in deriving Stokes law.

$$\tfrac{1}{2} C_D A v^2 \rho_s = \tfrac{4}{3} \pi r^3 g (\rho_s - \rho_f).$$

The relationship between C_D and **R** has been established empirically for spheres and for some other shapes (Inter-Agency Report No. 4, p. 39, and Inter-Agency Report No. 12, p. 21 and 51). The data indicate that Stokes law is applicable up to **R**=0.1 and sometimes up to 0.4. The relationship between C_D and **R** is of academic interest only because methods of analysis using sedimentation methods must be calibrated in terms of some definite, easily understood, and readily reproducible unit of sediment size. *Standard fall velocity* and *fall diameter* provide a simple foundation for the expression of the size distribution of samples. Particle size for these larger sizes is based on a comparison with actual samples from which the individual particle fall velocities have been determined.

Significant figures for reporting results

The number of significant figures to be used in recording data from analysis in the sediment laboratory is the product of compromises between the need for uniformity in the final tables of data, precision of measurement, and also the degree of precision necessary for the use of the data.

For concentration of sediment in a sample, it is practical and desirable to report to the nearest 1 mg/l up to 999 mg/l and then for higher values to use three significant figures. Often the third significant figure in the series 500 to 999, 5010 to 9990, and so forth, has very weak significance, but is justified on the basis of uniformity. Again, in some instances it may be desirable to use

the nearest 0.1 mg/l up to 9.9 mg/l, especially between 0.1 and 0.9 mg/l. These recommendations are based on the assumption that the net sediment can be weighed to the nearest 0.0001 g and the water-sediment mixture can be weighed to the nearest 1 g.

With respect to size gradation, the goal should be to publish the percentage of material in each fraction to the nearest whole percent. In some analyses, where fractions may contain 2 percent or less, it may be useful to report to the nearest 0.1 percent. Whenever practicable, the net quantity of sediment in a given fraction should be weighed to the nearest three significant figures. With balances weighing to the nearest 0.0001 g, the significant figures must be reduced to two when the quantity is less than 0.0100 g.

Procedure for Determining Suspended-Sediment Concentration

The best methods for making determinations of concentrations and particle-size distributions from suspended-sediment samples must be selected from numerous possible procedures. The samples may contain only minute quantities of sediment of very small particle size or may contain large quantities of sediment with a wide range of particle size. Samples with such extremes usually require the use of special procedures. Samples for particle-size analysis always require special processing and computational procedures to insure the determination of the concentration as well as the particle-size distribution with only one drying of the sediment.

Each of the several methods for determining concentration has advantages and disadvantages. The two most commonly used methods are evaporation and filtration. The filtration method may be somewhat faster than the evaporation method for samples of low concentration. However, larger quantities of sediment tend to clog the filters and inhibit the use of this method for the higher concentrations. The evaporation method requires an adjustment for dissolved solids if the dissolved solids content is high, especially for samples having low sedi-

ment concentration. Thus, the filtration method may best be used on samples ranging up to about 10,000 mg/l of sediment that is mostly sand and about 200 mg/l of sediment that is mostly clay. The evaporation method may be best used when the concentration is more than these limits.

Evaporation method

The evaporation method consists of allowing the sediment to settle to the bottom of the sample bottle, decanting the supernatant liquid, washing the sediment into an evaporating dish, and drying it in an oven. The main advantage of the method over the filtration method is the simplicity of equipment and technique. The method works well if the sediment readily settles to the bottom of the sample container because of its coarseness or because of the natural flocculation of the suspended clay. Conversely, with suspensions of naturally dispersed clay, the settling time may make the method impractical unless special procedures are used.

NOTE A.—Special procedures to handle unsettled samples involve the use of (1) a filter tube, in which case, it may be just as easy to adopt the complete filtration method, or (2) a flocculating additive to reduce the settling time. In the first procedure, the sample is allowed to settle as much as practical and then, by use of a Berkefeld filter tube (or a similar device) and a vacuum apparatus, most of the native water is removed from each bottle. The sediment in suspension adheres to the outside of the filter tube and the water passes through the walls. The material on the outside of the tube is removed by back flushing with native water from the sample and can be treated in the same manner as the dissolved solids content.

A second special procedure is to use a flocculating agent to reduce the settling time of the naturally dispersed clays. This method will require the use of a correction factor to be applied to the weight of dried sediment. Such a factor is likely to be more of an estimate than an exact value because of the difficulty in determining the amount of flocculant incorporated in the final weight and the amount of dissolved material precipitated. Hence, a flocculant should not be used unless necessary and then only a minimum amount. As the samples decrease in concentration, the opportunity for significant error increases because of the estimated correction. Dilute HCl or $CaCl_2$ are the flocculants commonly used. The one most effective will depend on the nature of the sediment and the dissolved minerals in the water. Extreme care is necessary in

using either dilute HCl or CaCl₂ as a flocculant. Carbonate minerals are readily decomposed in acid solutions and many other minerals are slightly soluble in weak acid solutions; therefore, the use of hydrochloric acid is not recommended. Calcium chloride is highly hygroscopic; therefore, if the sample has been treated with calcium chloride, the use of closed weighing bottles is recommended instead of open evaporating dishes for the determination of concentration.

The supernatant liquid is carefully decanted from the sample so that the sediment in the bottom of the container will not be disturbed nor removed. A small quantity of the supernatant liquid is therefore left with the sediment. A specified amount of such liquid should be left with each sample, usually about 20 to 50±2 ml (milliliters). This specified amount is especially significant if a correction for dissolved solids is necessary. Distilled water is used to wash the sediment and remaining liquid into the evaporating dish. The contents of the dish are then dried in an oven at a temperature that is slightly below the boiling point. If the boiling point is reached, then sediment may be lost from the dish. After all visible moisture has evaporated, the temperature should be raised to 110°C for at least 1 hour.

The weight of natural dissolved solids in the supernatant water is included in the weight of dry material obtained by the evaporation method and must be subtracted to determine the weight of sediment. The following may be used as a guide to determine if a correction for the weight of the dissolved solids is necessary. A 5 percent or more improvement in the results of the sediment determination will be realized when the dissolved solids concentration is equal to or greater than the sediment concentration, assuming that an aliquot of 20 ml of native water is used in the evaporation, and that 400 g of water-sediment mixture is contained in the original sample. For example, a dissolved-solids correction should be made when the dissolved solids concentration is 200 mg/l or higher and the sediment content is 200 mg/l or less. Similarly, a 2 percent improvement will result if the dissolved solids concentration is 40 percent or more of the sediment concentration. The weight of the dissolved-solids correction for different aliquots and a range of concentrations can be obtained from figure 3.
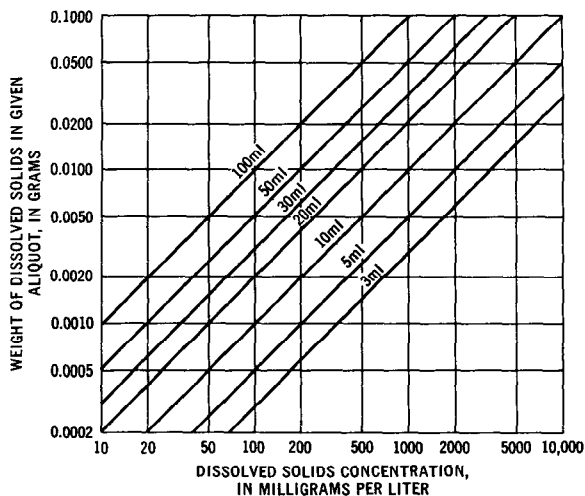
Figure 3.—Weight of dissolved solids for given size of aliquot and given concentration.

Filtration method

The filtration method for the determination of suspended-sediment concentration has obvious advantages over the evaporation method and should be used whenever it is practical to do so. The method usually utilizes a Gooch crucible in conjunction with various types of filter material. The Gooch crucible is a small porcelain cup of approximately 25 ml capacity with a perforated bottom. The crucible is easily adapted to an aspirator system and vacuum filtration; it is lighter in weight and consumes less oven and desiccator space than the evaporating dishes; its tare weight is less likely to change during the weighing because less surface is exposed to sorption by moisture; and dissolved material passes through the crucibles and thus eliminates the need for a dissolved-solids correction.

In most laboratories the Corning # 32960 Pyrex fritted glass crucible and glass-fiber filter disks, # 934–AH or similar specifications, have proven satisfactory for filtration of most types of sediment samples. These filter disks show no weight loss during filtration, save considerable preparation time, result in more uniform filtration, and make cleaning of the crucible easier than do other types of filters. However, the filter disks become clogged rather rapidly when some types of fine sediment are filtered.

Better filtration results have been obtained for these fine-grained sediment samples by using a glass-fiber filter disk in conjunction with an asbestos mat. The crucible with this extra asbestos mat is prepared by placing the glass-fiber filter disk in the crucible while vacuum is applied and then pouring an asbestos slurry on top of the disk also while vacuum is applied. (See the next paragraph concerning the preparation of asbestos mats.) During the filtration process, the somewhat coarse asbestos mat retains much of the sediment that would ordinarily clog the glass-fiber disk. The glass-fiber disk prevents loss of asbestos or loss of very fine sediment that would pass through the asbestos mat. This filter is recommended if inaccuracy or inconvenience results from the use of a single type of filter because little additional time is required for the preparation of the double glass-fiber asbestos-type filter.

If glass-fiber filters are not available, asbestos is considered satisfactory because of its inertness, resistance to heat, and low hygroscopicity. The asbestos filter mats can be prepared in two ways. The simplest and most convenient way is to prepare a slurry of shredded asbestos and distilled water, and pour a small volume of this slurry into the crucible while vacuum is applied. A uniform mat of asbestos is thus formed in the bottom of the crucible. The mat should be rinsed with distilled water while vacuum is still applied; the crucible is then oven dried, cooled in a desiccator, and the tare weight determined. Another method for preparation of the asbestos mat is to place a small portion of loose, uniform asbestos on the bottom of the crucible, and wet the asbestos with distilled water while vacuum is applied.

If the sediment sample contains extremely fine material, an actual loss of fine material through the filter may result in a turbid filtrate. This problem is treated in one of three ways: (1) add a known quantity of an adsorbing agent, such as activated carbon, which adsorbs the colloids as a result of the difference in electric charges, (2) impregnate the filter with sediment and then re-filter the filtrate, or (3) use a flocculating agent of the acid or salt type. In addition to preventing loss through the filter,

the adsorbing agent should reduce the settling time and prevent the rapid clogging of the filter. The main advantage of the adsorbing agent over the use of the flocculating agent is that a precise correction, instead of an estimated correction, can be made for the amount retained on the filter. Acids or salts are not usually recommended because undesirable reactions with the sediment are likely to occur. As already mentioned, the use of a fiber-glass filter disk in conjunction with an asbestos mat will eliminate most filter problems.

Sometimes it is possible to utilize another advantage of the filtration over the evaporation method when the concentration or the amount of sediment is small. Specifically, preparation time can be saved by using the same mat two or more times. When the crucible and mat are re-used, the gross weight of the prior use becomes the tare weight for the new use.

Laboratory forms

Figures 4, 5, and 6 show forms used in recording data and making computations for determination of suspended-sediment concentration. These forms (*Sediment Concentration Notes, Depth Integrated Samples [Short form]; Sediment Concentration Notes, Depth Integrated Samples [Comprehensive form]; Sediment Concentration Notes, Point Integrated Samples*) provide an orderly means of recording the sample information, the necessary weights, and the results of computations for the concentration of the sample. On the *Short form* for depth integrated samples (fig. 4), space is provided for 20 bottles or samples; the other two forms provide for only 10. The forms serve as a record of samples collected for each sampling site. Each bottle should be recorded in the chronological order of sampling at the time of sample weighing. Appropriate notes can be made on the form if one or more samples are later withdrawn or particle-size analysis or composited for concentration. If more space is needed for remarks, reference by number should be made to the back of the sheet; or, expanded notes can be retained on the front by using space ordinarily used for other bottles.

Form 9.265e (REV. 10-62)

UNITED STATES DEPARTMENT OF THE INTERIOR

Geological Survey-Water Resources Division

SEDIMENT CONCENTRATION NOTES, DEPTH INTEGRATED SAMPLES (Short form)

Stream and location _____

Computed by _____ Checked by _____

Date											
Time											
Gage height											
Sampling Sta.											
Temp. and Spec. Cond.											
Remarks											
WEIGHT OF SAMPLE — Gross											
WEIGHT OF SAMPLE — Tare											
WEIGHT OF SAMPLE — Net											
Container no.											
WEIGHT OF SEDIMENT — Gross											
WEIGHT OF SEDIMENT — Tare											
WEIGHT OF SEDIMENT — Net											
D.S. Corr.											
Net											
Conc. (ppm)											

Date											
Time											
Gage height											
Sampling Sta.											
Temp. and Spec. Cond.											
Remarks											
WEIGHT OF SAMPLE — Gross											
WEIGHT OF SAMPLE — Tare											
WEIGHT OF SAMPLE — Net											
Container no.											
WEIGHT OF SEDIMENT — Gross											
WEIGHT OF SEDIMENT — Tare											
WEIGHT OF SEDIMENT — Net											
D.S. Corr.											
Net											
Conc. (ppm)											

Figure 4.—Sample of laboratory form, Sediment Concentration Notes, Depth Integrated Samples (Short form)

Figure 5.—Sample of laboratory form, Sediment Concentration Notes, Depth Integrated Samples (Comprehensive form)

Form 9.265g (REV. 10-62)

UNITED STATES DEPARTMENT OF THE INTERIOR

Geological Survey-Water Resources Division

SEDIMENT CONCENTRATION NOTES, POINT INTEGRATED SAMPLES

Stream and location _____　　Computed by _____　　Checked by _____

Date																									
Time																									
Gage height																									
Discharge																									
Sampling Sta.																									
Temperature																									
Sampling depth, ft																									
Total depth, ft																									
Filling time, sec																									
WEIGHT OF SAMPLE — Gross																									
WEIGHT OF SAMPLE — Tare																									
WEIGHT OF SAMPLE — Net																									
Filling rate, cc/sec																									
Nozzle size																									
Velocity, ft/sec																									
Specific conductance																									
Container no.																									
WEIGHT OF SEDIMENT — Gross																									
WEIGHT OF SEDIMENT — Tare																									
WEIGHT OF SEDIMENT — Net																									
WEIGHT OF SEDIMENT — D.S. Corr.																									
WEIGHT OF SEDIMENT — Net																									
Concentration (ppm)																									

Figure 6.—Sample of laboratory form, Sediment Concentration Notes, Point Integrated Samples

The entry for *D.S. Corr.* (dissolved solids) is used when the evaporation method is used and then only when the dissolved-solids content is relatively high, when an adsorbing or flocculating agent has been added to the sample, or when an adsorbing agent is used with the filtration method. Although details concering the principles of dissolved-solids determinations are discussed in the last section of this chapter, "Related water-quality analysis," it is appropriate to outline the essentials of the determinations here. The dissolved solids content of a stream usually does not change appreciably from day to day for normal flow, but usually diminishes rapidly with increasing storm runoff. Such periods may be determined by a study of the gage heights recorded on the samples and (or) by the increase of sediment content associated with storm runoff. A single dissolved-solids determination is usually adequate for several daily samples when the streamflow rate is relatively uniform. The composite determination is made from a sample prepared by withdrawing nearly equal volumes of the sediment-free water from each daily sediment sample. The sample, whether for a single day or a composite for several days, is evaporated to dryness, heated at 110° C for 1 hour, cooled in a desiccator, and weighed to obtain a unit weight. The dissolved solids correction to be applied to the dry weight of sediment solids in each evaporating dish is equal to the product of the unit volume correction and the volume of water evaporated from the dish. Also see page 12 and figure 4.

Procedure for concentration analysis

With the above information it is possible to compile the following step-by-step procedure for concentration analysis:

1. Inspect the general condition of the samples as they are received at the laboratory. Loose caps should be replaced and bottles with excessively dirty exteriors should be cleaned.
2. Store samples in a cool dark room to prevent excessive evaporation and growth of organisms.
3. Arrange the samples for a given location in chronological order while assembling them for transport to the sample weighing station.

4. At the sample weighing station, record the sample information from the sample labels on the appropriate concentration form. (See figs. 4, 5, and 6.)
5. Record the gross and tare weights to the nearest gram for each sample, assuming the net sample to weigh in excess of 200 g. It is often desirable to use a balance with a tare removing attachment and a procedure that will directly yield the net weight of the sample. This avoids copying and computation errors, but puts greater responsibility on the operator.
6. Store the weighed bottles on a convenient rack or table for several hours, or overnight, to assure that the sediment settles from suspension. In the event that the sediment does not settle, follow the procedure outlined in "Note A (p. 11)." Samples to be analyzed for particle-size distribution should be separated from those to be analyzed for concentration only.
7. Some laboratories at this point obtain and record the conductance of the supernatant water for each sample set. This is not published but is used as a control on the person taking the samples and as an aid in finding and correcting errors made in recording the field and lab data. In this case the comprehensive form (fig. 5) would be used.
8. Decant most of the sediment-free water using care not to disturb or remove sediment. If a dissolved-solids correction is necessary when using the evaporation method, then the amount of supernatant liquid left with the sediment should be approximately equal to one of the aliquots indicated in figure 3.
9. Use distilled water to wash the remainder into a previously weighed evaporating dish or filtration crucible, depending on the method used. Check to be certain that the container number on the form *Sediment Concentration Notes* corresponds with the given sample or samples.
10. The sample bottles must be thoroughly cleaned, air dried, recapped and packed in carrying cases for reuse.
11. Dry the evaporating dishes or crucibles and, after loss of all visible water, heat at about 110° C for 1 hour. The evaporating dishes must be dried at a temperature low enough to prevent "spattering" of sediment from the dishes by boiling action.
12. Cool the containers in a desiccator at room temperature.
13. Weigh the containers to the nearest 0.0001 g on an analytical balance. The tare weight of the evaporating dish should be obtained before each use because of the loss of weight caused by small chips, frequent washing, and slight differences in washing or cleaning methods. The tare weight of the crucible must be obtained before each use

because of differences in weights of the filtering mats, especially when the asbestos mats are used. If sediment concentrations are greater than 1,000 mg/l, then it may not be necessary to obtain a new tare weight each time a crucible with a glass-fiber filter mat is used.

14. Compute the net weight of sediment in the container and deduct, if necessary, the dissolved-solid correction.

15. Compute the concentration of the sample in parts per million determined on the basis of one million times the ratio of the net weight of sediment to the net weight of the water-sediment mixture. The computed parts per million can then be expressed in the common units of milligrams per liter by application of the conversion factor given in table 1. It is convenient to make the conversion from parts per million to milligrams per liter when the data are transferred from the form *Sediment Concentration Notes* to other uses. Usually concentrations are less than 16,000 parts per million in which case parts per million equals milligrams per liter. However, when the concentration does exceed 16,000 ppm the appropriate conversion factor should be penciled plainly below the concentration on the form as a reminder to the data user that milligrams per liter is different from parts per million.

Determination of Particle-Size Distribution of Suspended Sediments

Complete definition of the variations of particle-size distribution for a stream throughout the ranges of discharge and with time is presently not economically feasible. It is feasible, however, to analyze a sufficient number of samples to provide representative data for a range of the many conditions occurring throughout the year.

Particle-size data have many uses. One use is to compute the probable specific weight of sediment as it will deposit in reservoirs. This computation requires plotting the median particle size against sediment load in tons per day. Information concerning the behavior of sediment particles in different environments may be studied and, therefore, requires analyses for particle-size distribution of fine particles in both native and dispersed settling media. The size distribution of both suspended and bed material has an important use in the computations of total (measured plus unmeasured) sediment discharge. The frequency and kind of particle-size analyses should be adequate to describe the pertinent characteristics of sediment particles so that satisfactory comparisons can be made between sediments collected from different places or from the same place at different times.

Recommended frequency of analyses

The following recommendations are for the determinations of ultimate sizes by use of a distilled-water settling medium and a chemical dispersant for the silt and clay fractions. The recommended frequency of native-water analysis is discussed in the section "Native water settling medium" in respect to the theories, problems, and methods of such analysis. Each sample should be depth integrated and represent the true size distribution in the cross section at the time of sampling. Thus, for most streams, samples must be collected by the ETR (equal-transit-rate) method or by sampling at an adequate number of the centroids of equal discharge. If the "daily" samples collected at one vertical near midstream are representative of the sediment characteristics in the entire cross section, the selection should normally be adequate to cover a wide range of flow conditions.

Judgment concerning the selection of samples will be enhanced by a study of the conditions for which particle-size samples of past records for the given station were selected, if available; and (or) by a study of the sample information recorded on the form *Sediment Concentration Notes* (fig. 4) for the current water year. For many streams, information on sediment characteristics is usually lacking during the first year of sampling on a given stream; therefore, some samples, particularly from high-stage flows, should be set aside to be analyzed at a later time either for particle size or concentration at the end of the water year when the facts are known concerning the range and other conditions of the year's flow. These extra samples should, of course, be tightly sealed, tared and stored in a dark place.

Size analyses of suspended sediment for the so-called daily station should be made on a minimum of five or six samples per year if selected to represent various flow conditions and range of concentrations. Additional samples, up to a