UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

WATER RESOURCES DIVISION

FALLING-STREAM TURBIDIMETER AS A MEANS OF MEASURING SEDIMENT CONCENTRATIONS IN STREAMS

By

Harold P. Guy and Richard C. Olson

Open-file report

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ABSTRACT

An optical (photocell) sensing device was used to measure the relative transparency characteristics of sediment suspensions with a view toward improving our ability to measure the temporal variations of suspended-sediment concentration moving in streams. The instrument used was a commercial "falling stream" turbidimeter that measured the relative transparency of a gravity induced smooth flat sample stream formed as the flow drops vertically from an orifice.

Output results were recorded on a strip-chart recorder as a function of concentration, up to about 100,000 mg/ℓ, for a range of particle sizes and for three kinds of sediment--a fine sand, a silty alluvial soil, and a clayey residual soil. The sensitivity range was improved by use of both the 1/8- and 1/16-inch thick orifices. The use of the two orifice or nozzle sizes provided data useful in evaluation of the effect of particle size and type of sediment at different concentrations. The unique relative transparency-concentration relationships were more linear for coarse than for fine sediments of a given kind. It was concluded that curvature in this relationship resulted from light reflections from the surface of the particles and (or) the fact that some particles moved through the system while in the "shadow" of other particles closer to the light source.

The ratio of suspended-sediment concentration to the square root of the median particle size of sand-sized sediments was found to be a useful parameter for elimination of the effect of particle size in the relative transparency-concentration relationships. Thus it was possible to evaluate the effect of the different type of sediment on the relative transparency independent of particle size. The use of this parameter to eliminate the effect of particle size was unsuccessful for finer sediments.

INTRODUCTION

Sediment suspended in natural waters must be measured more frequently and effectively if environmental problems are to be properly evaluated. Present techniques for measurement of water discharge permit more accurate and complete hydrologic and hydraulic analysis of streams than is possible for the sedimentologic aspects. In addition to problems of environmental degradation, partial or complete failure of water-use systems frequently has resulted from inadequate evaluation of stream sediment, especially its suspended-sediment concentration. The problem of inadequate sediment evaluation is further intensified by the ever increasing number of manmade alterations to the environment, which, in turn, affects the sediment charge to streams and the regime of streams. Man's increasing activity and water use is likely to make more accurate and more timely measurement of sediment even more urgent in the future than now.

Sediment concentration and movement at a given stream location basically result from when and how sediment is introduced to the stream and the way it is transported. Even without the effects of man's activities, stream sediments vary greatly, both in time and location, as a result of climatic, hydrologic, and physical variations in the drainage basin. With the effects of man's activities, the physical variations are frequently amplified, and it is necessary to make more frequent measurements. Conventional manual sediment measurement techniques, developed mainly for rivers, are far from adequate in smaller streams, especially in or adjacent to construction areas, where the concentration of sediment moved to the streams changes rapidly. Additional insight concerning the intensity and character of sediment yield from basins and the manner of sediment transport in streams can be obtained from Colby (1963), Colby (1964), Einstein (1950), Guy (1964), Guy (1965), Guy (1970), Rainwater (1962), and Wischmeier and Smith (1965).

This paper presents the results of tests made with a commercially available turbidimeter designed to sense the relative amount of light passing through a falling stream of water-sediment mixture. The data and their analysis are presented in terms of the relative transparency characteristics of different water-sediment suspensions for three kinds of sediments. These relative transparency characteristics may then be used to indicate the possible ability of the instrument to sense the suspended-sediment concentration of streams.

The falling-stream turbidimeter is different from any of the three basic types of turbidimeters though it most nearly resembles the transmissometer (Hach, 1968), (Jones, written communication, 1971). The <u>absorbtometer</u> measures the difference between the light energy of the ray that has passed through a turbid medium and the energy of an identical ray that has passed through a reference medium. The <u>transmissometer</u> measures the light energy of a ray that has passed through a turbid medium. The nephelometer measures the light energy scattered from a turbid medium. By measurement of the amount of light blocked and thereby indirectly the amount of light passing through the medium, the falling stream turbidimeter closely resembles a transmissometer. It is hypothesized that the relationship between the light passed through the medium (relative transparency) and concentration of sediment in the medium would be curvilinear, as indicated in figure 1.

It has previously been suggested that sediment sensing must be based on some form of energy attenuation and scattering--such as light, sound, x-ray, or radioisotope emanations (Guy, 1965, p. 403). Most of these systems have been under study for several years by the Federal Inter-Agency Sedimentation Project of the Water Resources Council (Reports 1-14 and Reports A-T). Grassy (1943) and Benedict (1945) attempted to use a turbidimeter for determining the suspended-sediment concentration of natural streams, but found the results generally unsatisfactory. Recently, Kunkle and Comer (1971) in a study on the Sleeper River in northern Vermont concluded that the turbidimeter (Hach, model 1860) could be a valuable tool where approximate values of sediment concentration are needed for large numbers of watersheds.

It seems likely that much of the difficulty with the classical use of "turbidity" as a measure of sediment concentration is that the equipment originally was designed to aid in classifying the

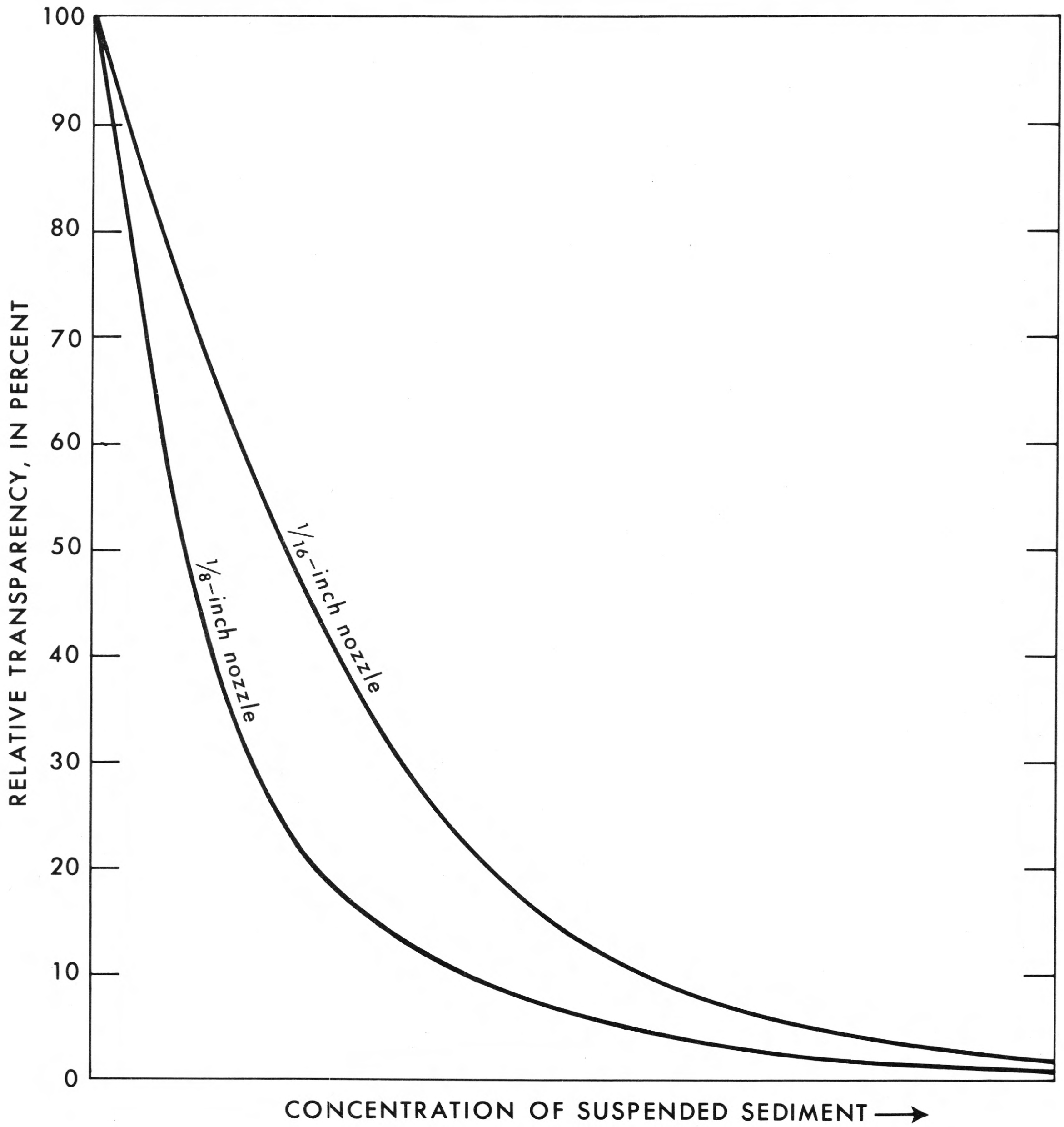


Figure 1.--Idealized curves showing the effect of nozzle size on the relative transparency-sediment concentration relationship.

presence, in relative terms, of very fine easily suspended particles. However, sediment concentration in a dynamic stream also must reflect the amount of coarser particles in suspension, even sand. Therefore, lacking a better commonly understood term for these kinds of measurements, turbidity will be used herein to refer to a relative measure of the concentration of particles suspended in a sample or the stream.

The unit of turbidity measurement usually is based on results from the Jackson candle turbidimeter. This consists of a special candle and a flat bottomed glass tube graduated in JTU (Jackson turbidity units). The sample is poured into the tube until the image of the candle, observed from the top, disappears into a uniform glow. The JTU scale on the side of the tube, as originally derived, represents parts per million of suspended silica. Although the candle turbidimeter has been modified in many ways, the accuracy of the results in terms of weight of suspended matter depends on the size, shape, color, transparency, and gloss of the particles.

DESCRIPTION OF EQUIPMENT

A simplified diagram of the "falling-stream" turbidimeter, used for the experiments reported herein, appears in figure 2. This shows the relationship of the major functional elements to each other. The instrument (Hach Model CR 1031)[1/] measures the relative amount of light passing through the stream as the flow drops vertically from an orifice. This turbidimeter differs from others in that no part of the physical optics, i.e., glass, is in contact with the sample stream. Thus, the problem of contamination of the optic system encountered by Fleming (1969) and investigators using other turbidimeters is eliminated.

The schematic diagram and photograph shown in figure 3 illustrate the equipment used for the experiments. At 100 percent relative transparency (presumed for distilled water), the photocell produced approximately 2.5 millivolts. When sediment was added to the flow, the light energy reaching the photocell decreased, and the resulting signal was indicated by the voltmeter. Instead of reading the results from the instrument dial, a strip-chart recorder was connected to the terminals inside the turbidimeter to record the results for later reference.

The relationship between the turbidimeter photocell output (the only physical output variable) and "Optical Density," as observed on the Hach meter, is represented graphically in figure 4.

1/ Trade names are used solely to provide specific information. Mention in no way consitutes an endorsement of the product by the Federal government.

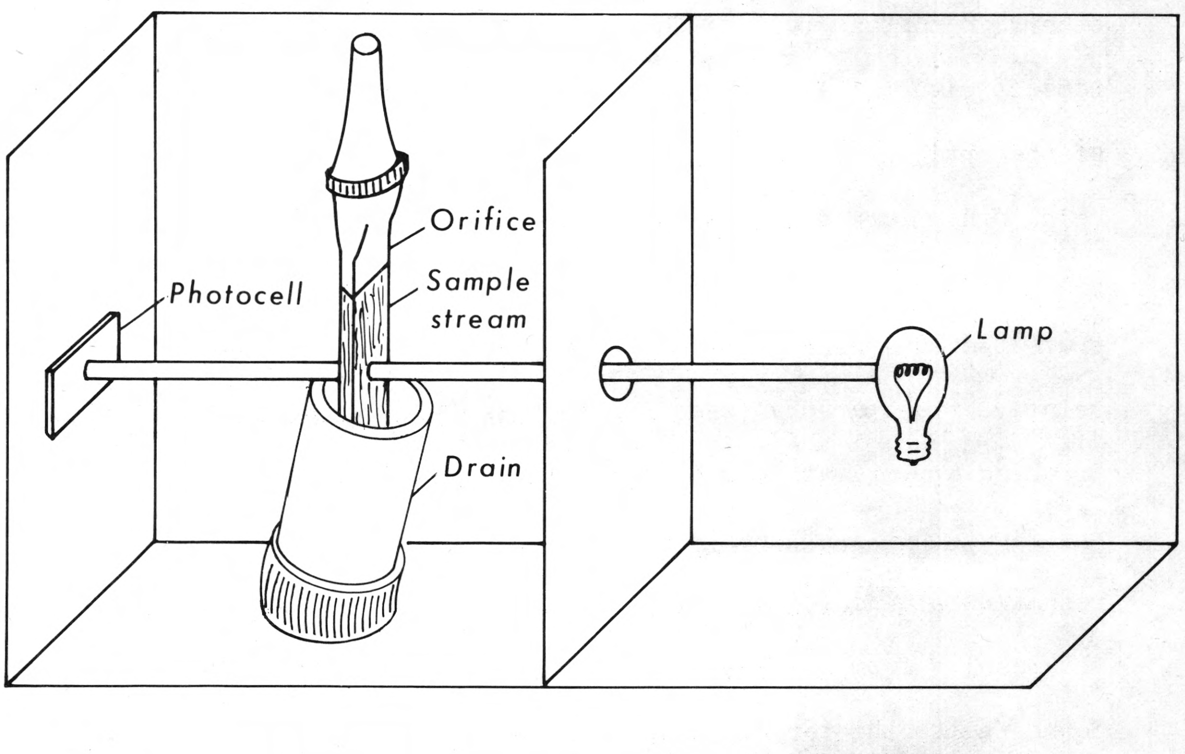
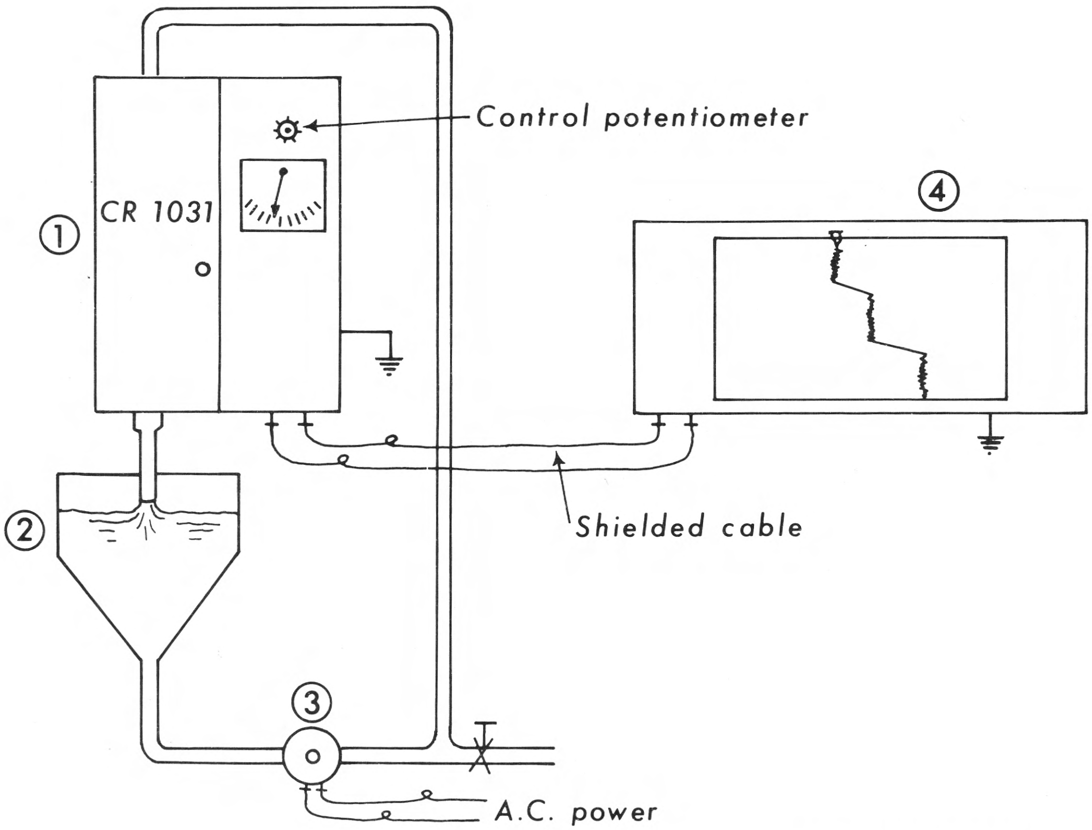
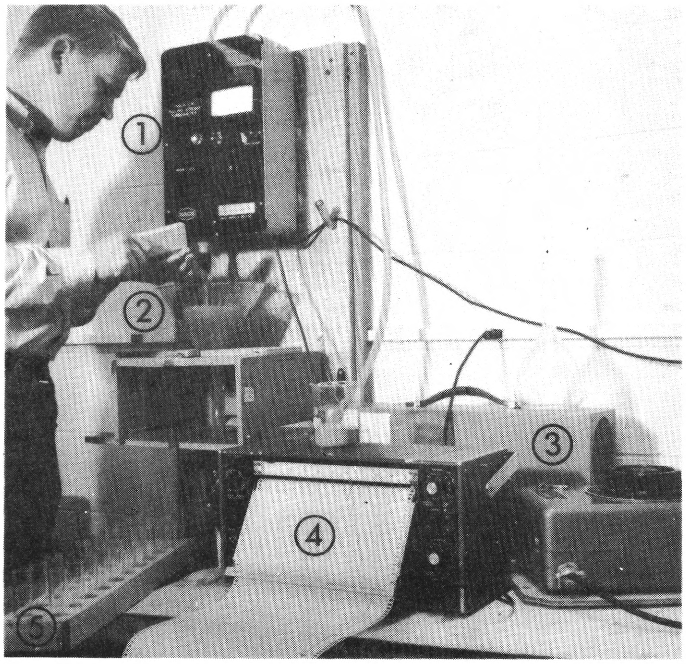


Figure 2.--Schematic diagram relating the functional elements of the "Falling Stream" Turbidimeter.





EXPLANATION

1. Turbidimeter
2. Mixing and bubble release reservoir
3. Small propylene magnetic-driven impeller pump (behind recorder on photo)
4. 10-inch chart recorder
5. Preweighed vials of sediment

Figure 3.--Diagram and photograph of equipment used in experiments.

This also shows the relationship of photocell output to the reported relative transparency and the complimentary relative opacity.

Simply stated, the RT (relative transparency) equals $\frac{100}{2.5}$ x photocell output, or 40 x photocell output in millivolts; and, furthermore, RO (relative opacity) = 100 - RT.

The manufacturer provided three sizes of orfice nozzles (nominally 1/4-, 1/8-, and 1/16-inch) to improve sensitivity of the instrument. For suspensions that block but little light--low concentrations and (or) large particles--a relatively thick orifice would logically be needed. Conversely, for suspensions that block much light--high concentrations and (or) fine particles--a relatively thin orfice would be needed. Thus, provision was made to increase the sensivity over that obtainable if only a 1/8-inch nozzle were provided.

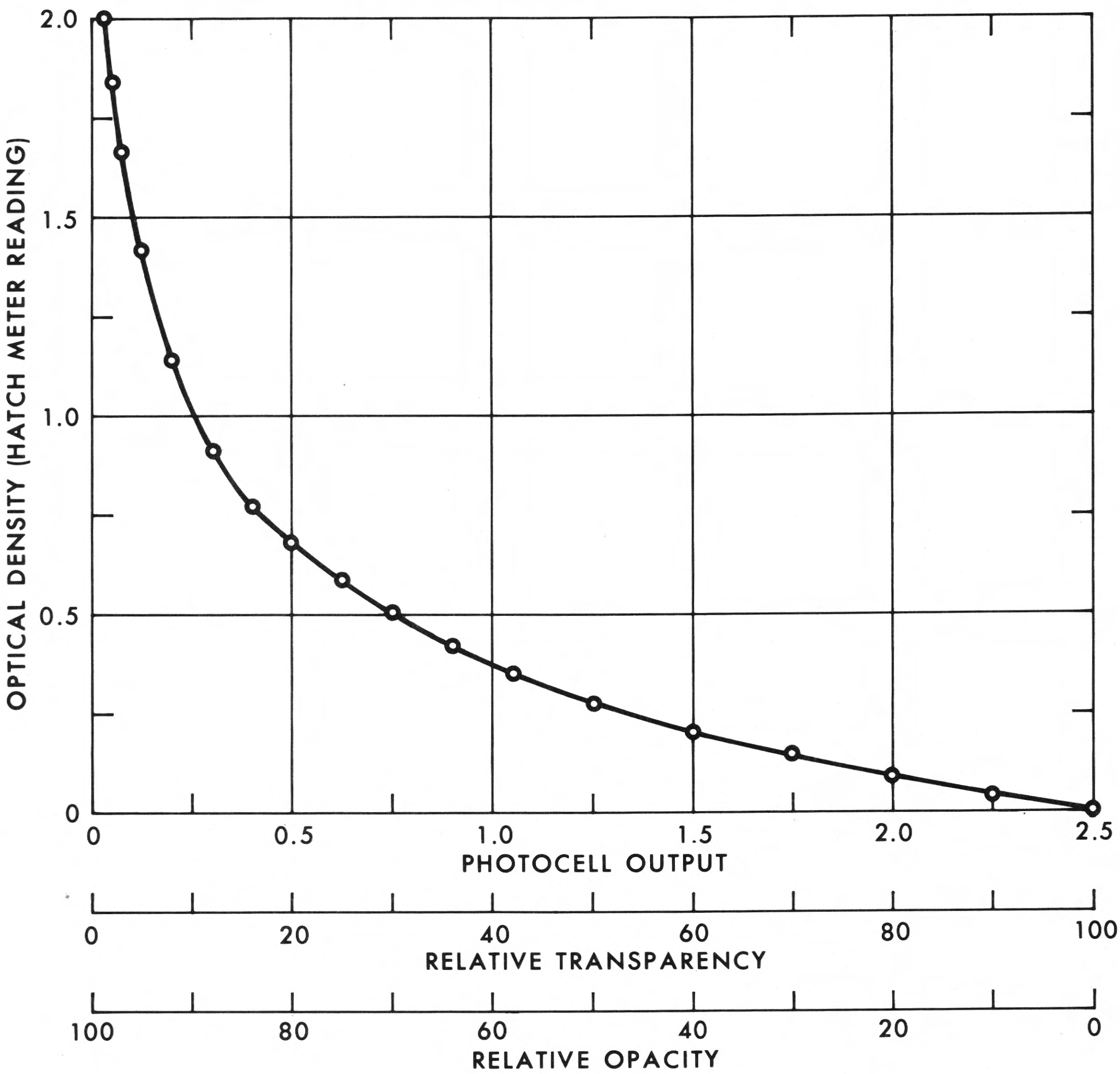


Figure 4.--Graph showing the relationship of optical density to photocell output, relative transparency, and relative opacity.

EXPERIMENTAL TECHNIQUE

The relative transparency of a wide range of sediment suspensions pumped through the turbidimeter was determined by relating the voltage output (light passing) to the concentration. Concentration is defined as the weight of particles per unit volume of water (Guy, 1969, p. 3). Light passing through the sample stream decreases with increasing concentration of suspended particles. This relationship should be affected by the size, shape, opacity, and color of the particles; hence, there should be differences for sediments from different drainage basins, aside from the effect of particle size.

Procedure

As indicated in figure 2, the experimental work on optical density of suspended sediments was centered around the sensing of a continuously falling stream of a suspension carrying known amounts of one of the specific sediments, as described later.

The calculation of sediment concentration (mg/ℓ, milligrams per liter) in circulation at any one time was simplified by use of 1.000 ℓ of distilled water in the circulating system. The distilled water was added at $30^{\circ} \pm 1^{\circ}$ C (Celsius) to insure a reasonably constant temperature of operation at about 2° C above room temperature. This insured dissipation of heat input from mechanical energy imparted to the system. With distilled water circulating through the system, the meter of the instrument was then adjusted to read zero, and the chart recording relative photocell output was adjusted to a full scale reading of 100. This procedure compensated for any differences in "block-box effects" or optical differences, if any, in the distilled water.

While the water was circulated through the instrument, known weights of sediment were added in increments to the mixing reservoir, resulting in easily computed increases in sediment concentration. After about 1 minute of circulation with the pump, the incremental mixture became uniform, and a notation of the concentration was made on the strip chart. The sequence was repeated for 12 to 20 increments, each increasing the concentration toward a maximum concentration of 100,000 mg/ℓ or a total of 100 grams of sediment in 1.00 ℓ of water. Figure 5 shows the recorder chart resulting from this procedure for a typical run.

For the purpose of comparing the results obtained using the falling-stream turbidimeter to the classical turbidity measuring system of Jackson standard turbidity units, tests were performed using a reference suspension. The suspension used was Formazin, as described in a manual prepared by Hach and based on the works of Brown, Skougstad, and Fishman (1970, p. 157). Suspensions of known turbidity by the Jackson Standard were introduced into the falling stream meter, and the results were recorded for the 1/8- and 1/16-inch nozzles for the various suspensions. Figure 6 indicates the relationship found to exist between Jackson Standard turbidity and relative transparency. Note that time permited only the use of the 1/8- and 1/16-inch nozzles in the sediment suspension tests.

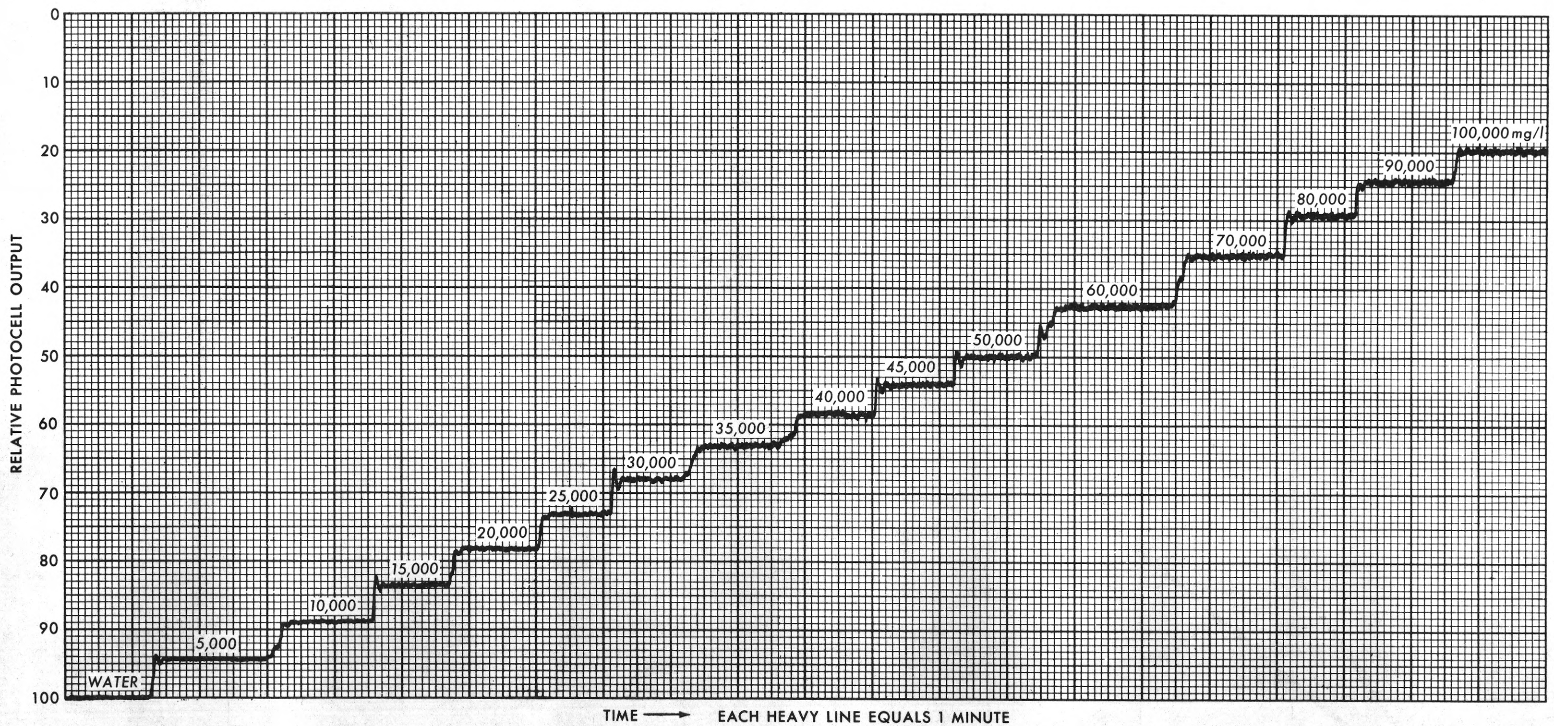


Figure 5.--Recorder chart (reduced from 10 inches wide) showing relative photocell output for suspensions of 0.063 - 0.088 mm Carter Lake sediment using 1/8-inch nozzle (Run G2).

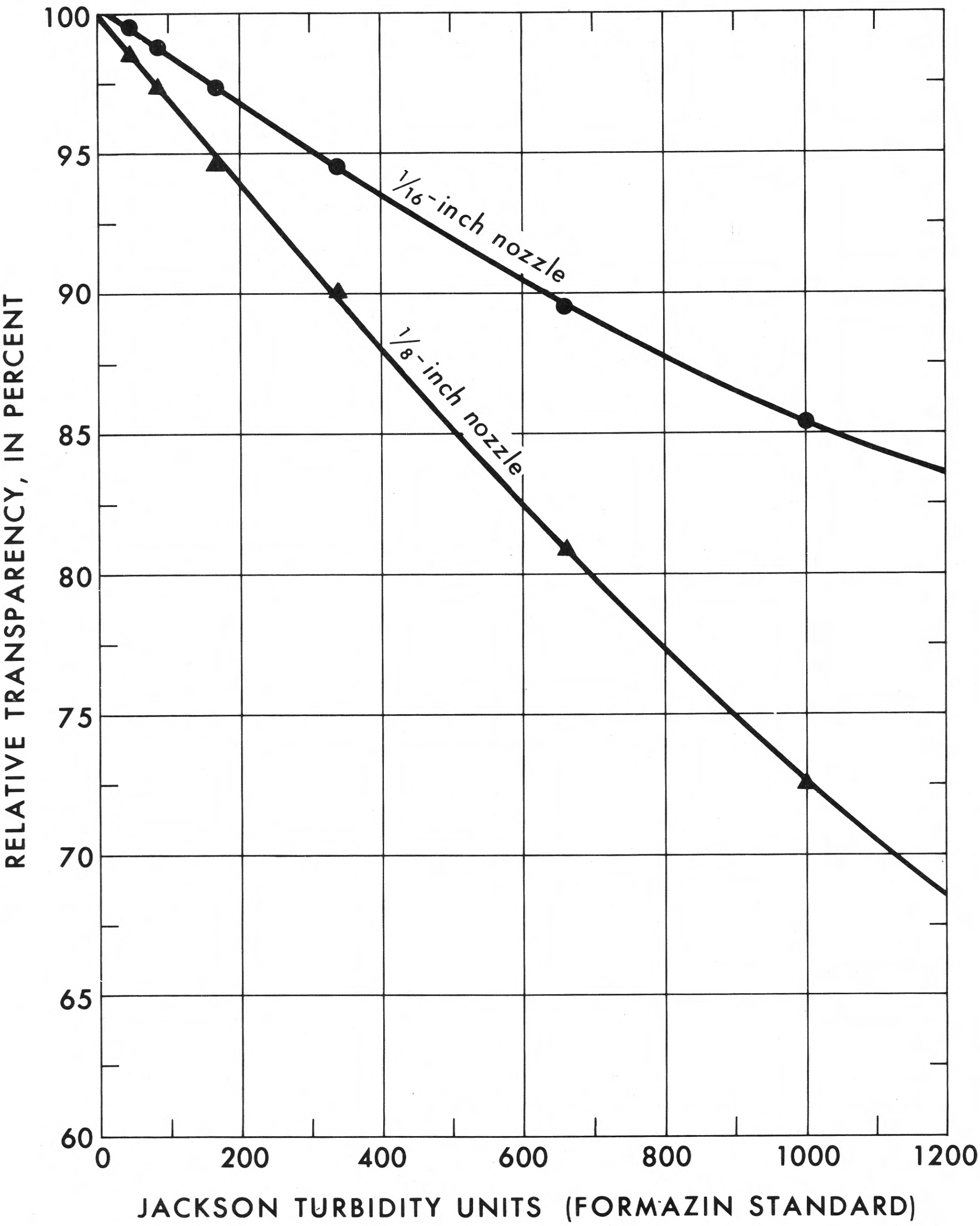


Figure 6.--Graph showing relationship of Jackson turbidity units to relative transparency.

Sediments

The three sediments used in the study were: (1) A rather well rounded quartz sand previously used for flume experiments, having a median size of 0.19 mm (millimeters) (Guy, Simons, and Richardson, 1966, p. 4), (2) a silty soil from the flood plain of Boxelder Creek in Larimer County, Colo., and (3) a clayey soil obtained from a steep east slope near Carter Lake, Larimer County, Colo. These sediments are hereafter referred to as (1) Lab Sand, (2) Boxelder, and (3) Carter Lake sediments, respectively. The particle-size distribution curves for these three sediments are shown in figure 7. Preliminary runs of each composit (non-graded) sediment were made with only that Lab Sand and Carter Lake sediment that passed the 0.250 mm sieve and only the Boxelder sediment that passed the 0.177 mm sieve; final runs for the composit Lab Sand and Carter Lake sediments could not be made for lack of time.

In order to evaluate the effect of particle size on the relative transparency of suspensions, each of the sediments was separated by series ($2^{\frac{1}{2}}$) sieves having 0.250, 0.177, 0.125, 0.088, and 0.062 mm mesh diameter. Each of the size classes was used to determine relative transparency-concentration relationships in the same manner as the composit samples.

The individual size classes of the sediments determined from the sieves also were analyzed by the VA tube-pipet method (Guy, 1969, p. 30-38) to determine the "fall diameter" size distribution within

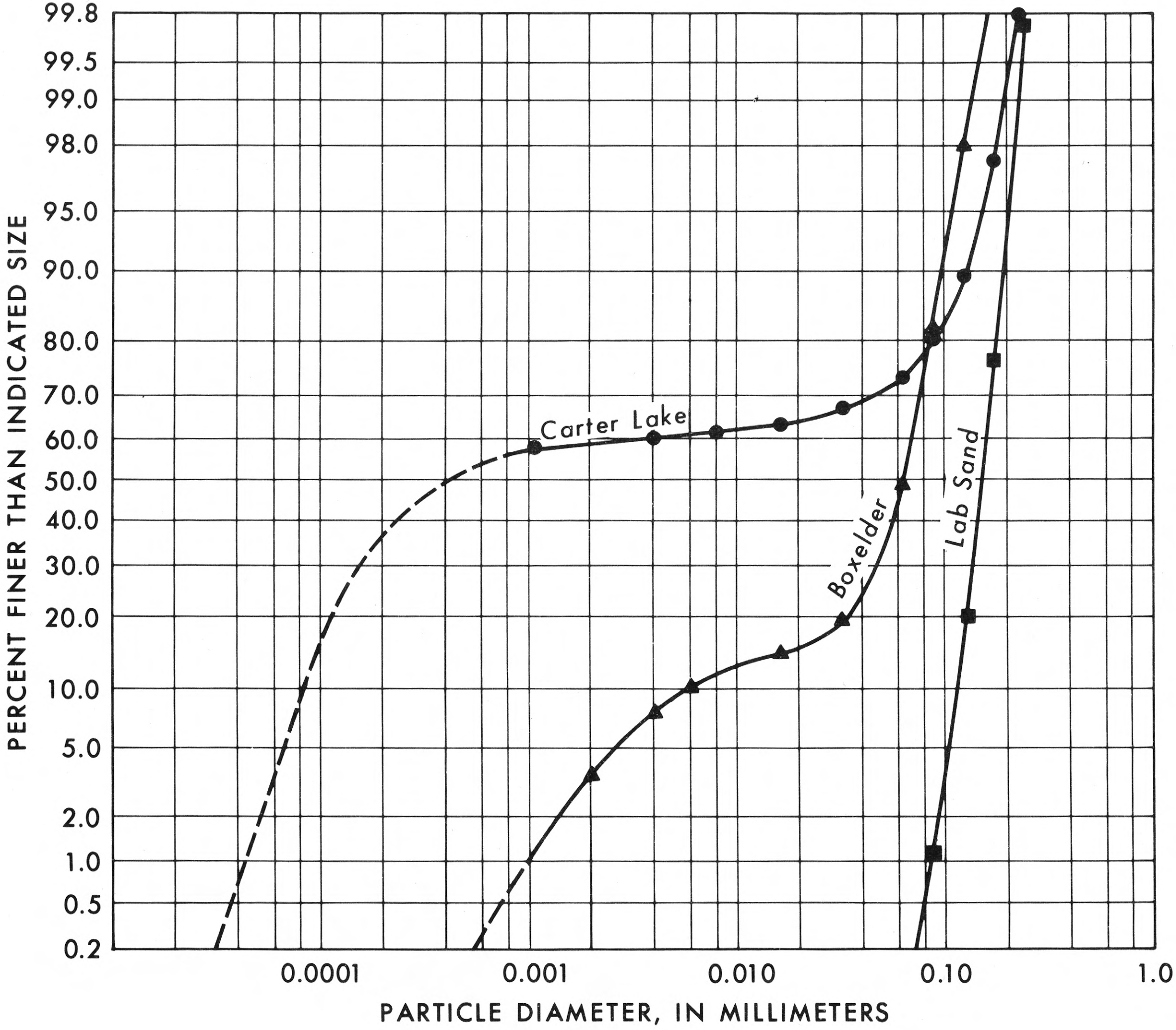


Figure 7.--Composite particle-size-distribution curves for Lab Sand, Boxelder, and Carter Lake sediments

the class for possible correlation with relative transparency. The particle-size-distribution curves for each sand fraction of these three sediments is shown in figure 8. The portion that passed the 0.062 mm sieve for the Boxelder and Carter Lake sediments is graphed in figure 9. The relative amounts of the Carter Lake sediment finer than 1, 0.5, 0.2, and 0.1 micron was determined by Ruth Deike of Arlington, Va., by a centrifuging technique.

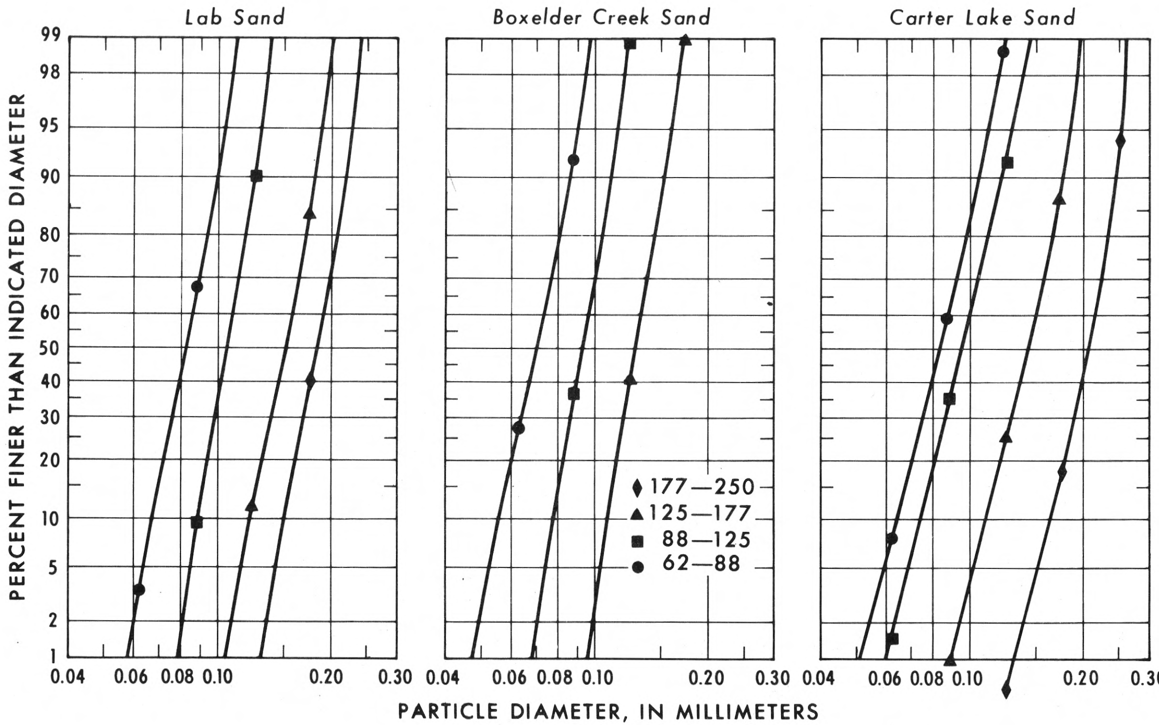


Figure 8.--Fall diameter particle-size-distribution curves of the sand fractions for Lab Sand, Boxelder, and Carter Lake sediments.

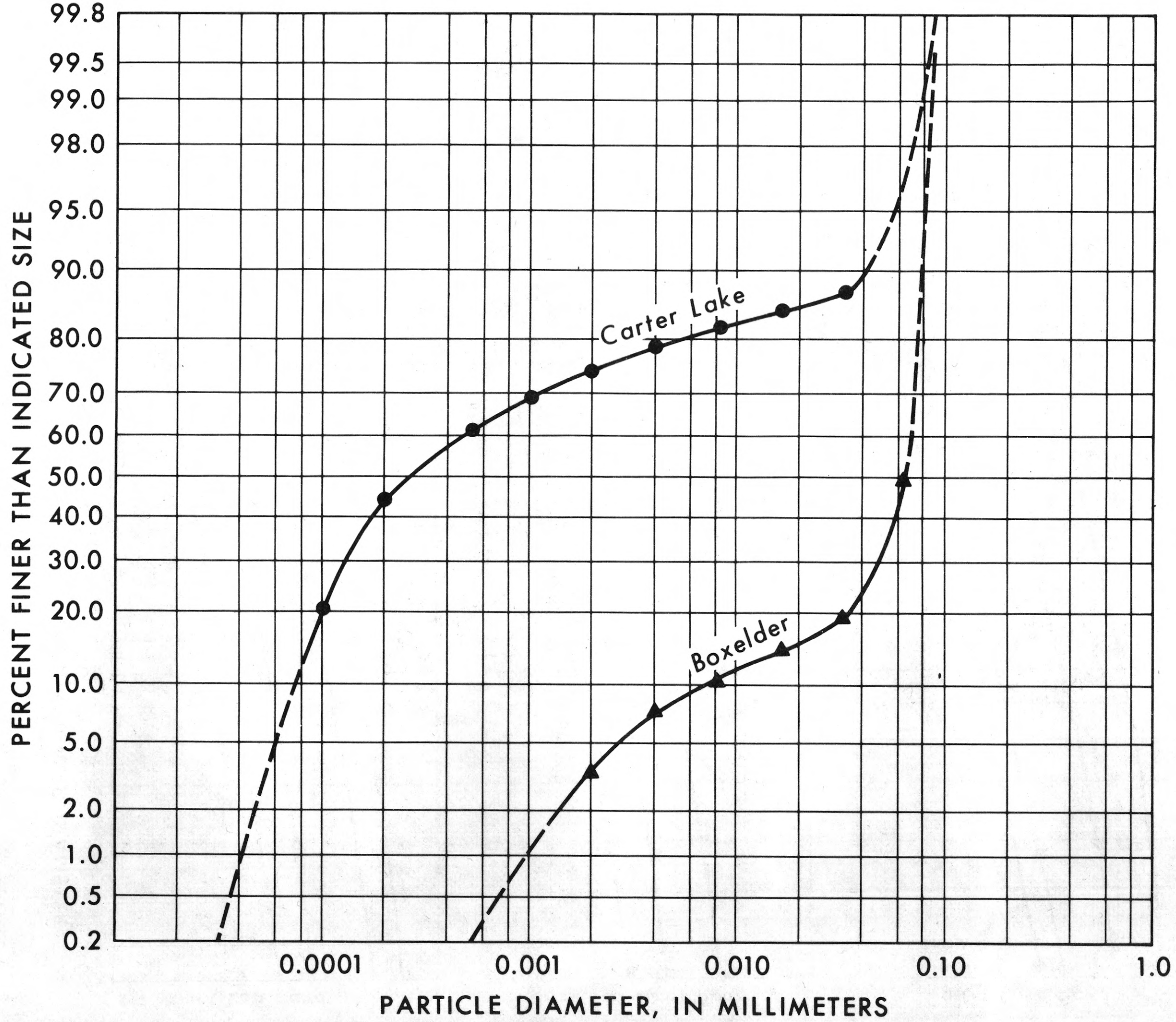


Figure 9.--Particle-size-distribution curves for the fine portion (passed 0.062 mm sieve) for the Boxelder and Carter Lake sediments

DATA AND RESULTS

For the purpose of providing some insight into what follows, the results will be briefly summarized before they are presented in detail so that the relationships determined by the various test runs may be more fully comprehended.

Transmission of light through the orifice flow would not be expected to be linear with changing concentrations because sediment particles are not necessarily opaque and, furthermore, tend to reflect some light from their surfaces, thus, defusing the light beam. Figure 1 showed idealized curves of the relationship between relative transparency (RT) and sediment concentration (C) for 1/8- and 1/16-inch nozzles. For a given sediment, it may be reasonable to assume that the RT - C relationship would be linear at low concentrations where the effect of internal reflections would be a minimum. Thus, RT for the 1/8-inch nozzle should be approximately half that for the 1/16-inch nozzle in the upper part of the curve. At higher concentrations, it would be expected that increasing numbers of particles would move through the light path in the shadow of particles close to the light source. This would cause the RT - C curve to approach the abcisia tangently at very high sediment concentrations.

The relative photocell output recorded on the charts during each run was transformed to relative transparency (fig. 4) and tabulated along with the sediment concentration, as in table 1.

TABLE 1.--Values of relative transparency in percent for given type of sediment, particle size, and nozzle size at varying concentrations.

Concentration mg/ℓ	Boxelder <0.177 1/8	Boxelder <0.177 1/16	Carter Lake <0.062 1/8	Boxelder <0.062 1/8	Carter Lake <0.062 1/16	Boxelder <0.062 1/16
100					98.9	99.4
200					97.8	98.8
300					96.7	98.2
500					94.6	97.3
700					92.8	96.2
1000			82.0	90.2	90.0	95.0
1500					85.8	92.8
2000					81.7	90.4
2500						88.2
3000			55.4	72.9	74.1	85.9
4000						81.4
5000	74.4	90.5	37.8	57.2	60.7	77.0
7000					49.7	68.6
10000	54.6	82.3	16.7	31.6	37.5	57.2
15000	39.8	73.0	10.4	19.2	23.9	42.1
20000	29.4	63.9	6.8	12.7	15.7	31.6
25000	21.0	55.5			11.3	
30000	14.8	47.5	3.4	6.6	8.8	19.4
35000	11.2	40.2				
40000	10.1	34.1	1.8	3.6	5.5	12.7
45000	6.8	28.9				
50000	5.3	24.3	.90	2.0	3.55	8.8
60000	3.4	18.4	.45	1.1		6.5
70000	2.28	14.1	.30		1.65	
80000	1.44	10.3	.10	.40		3.6
90000	.95	8.5			.77	
100000	.72	6.7		.20	.45	1.9
120000						1.1
140000						.9

These data were then plotted on arithmetic coordinate paper, as in figure 10, with the relative transparency on the vertical and the sediment concentration on the horizontal scale. Specifically, figure 10 shows the differences in the relationship of relative transparency and concentration for the part of Boxelder and Carter sediments <0.062 mm and Lab Sand 0.088 - 0.125 mm using both the 1/16- and 1/8-inch nozzle. As already mentioned, there were no data collected using the 1/4-inch nozzle.

Figure 10 was used to derive table 2, showing the suspension concentrations that yield 90, 50, and 10 percent relative transparency for these sediments. This table shows (1) that a very much higher concentration of sand is required to yield a given relative transparency than is required for fine sediment, (2) that the difference between Carter Lake and Boxelder fine sediments is striking, probably because one is mostly silt (<.062 mm - >.002 mm) and the other is mostly clay (<.002 mm), and (3) the ratio between the respective values for the two nozzles is not consistently 2.0. Thus, it is apparent that the instrument cannot be reliably calibrated for field use at a specific site without considerable correlation with the sediment moving in the stream.

The effect of particle size is more clearly indicated for the three different sediments by the relative transparency-concentration relationships given in figures 11-13, for the 1/16-inch nozzle (table 3) and for the 1/8-inch nozzle (table 4). As indicated

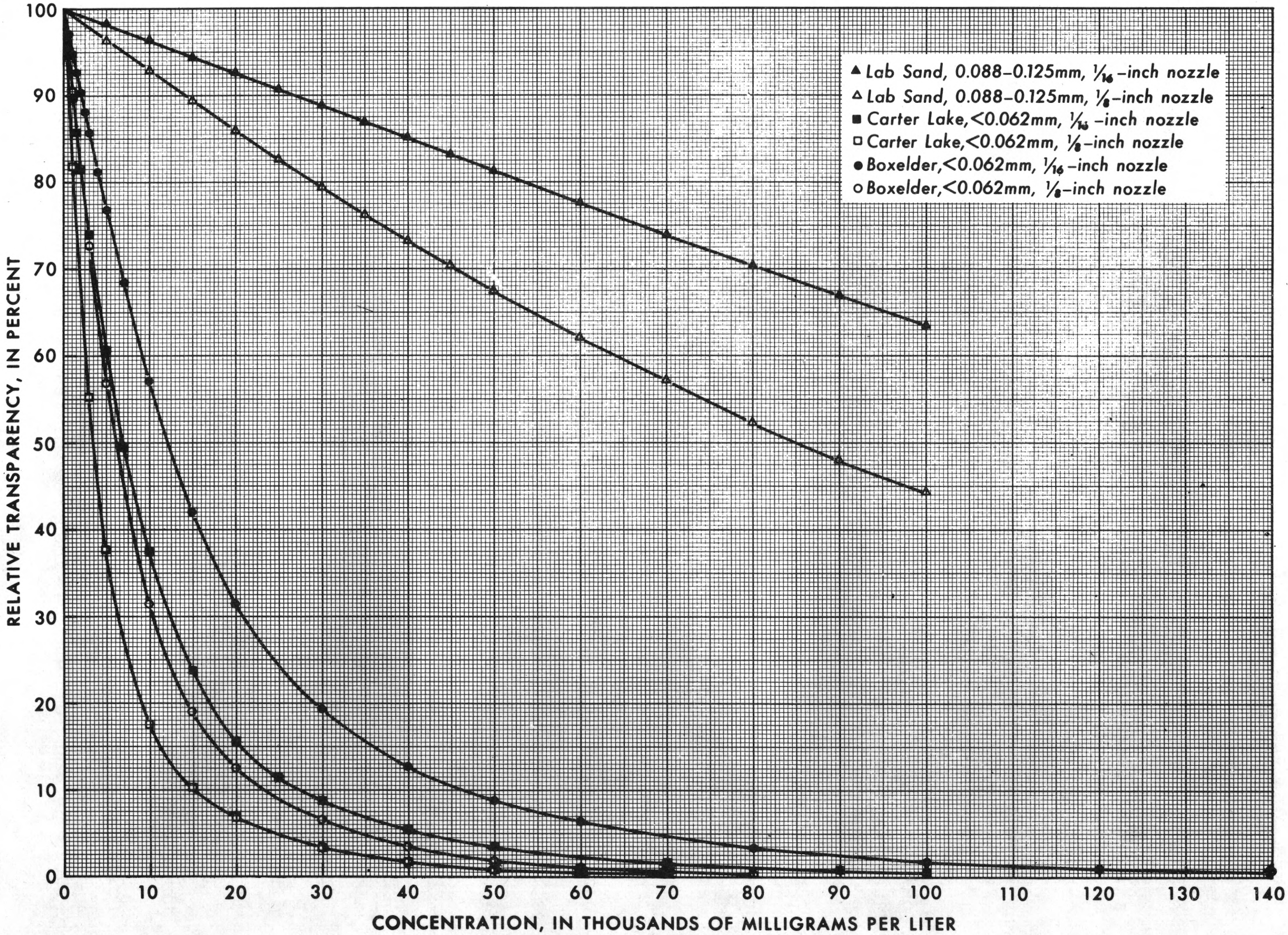


Figure 10.--Relationship of relative transparency to sediment concentration for 0.088 - 0.125 mm Lab Sand and fines <0.062 mm for Carter Lake and Boxelder.

TABLE 2.--Suspension concentrations yielding 90, 50, and 10 percent relative transparency for the 0.088 - 0.125 mm Lab Sand, the <0.062 Carter Lake, and the <0.062 mm Boxelder sediment using the 1/16- and 1/8-inch nozzles.

Relative transparency (percent)	Sediment concentration (1000 mg/ℓ)					
	Lab Sand		Carter Lake		Boxelder	
	1/16	1/8	1/16	1/8	1/16	1/8
90	27.2	14.4	1.2	0.6	2.1	1.1
50	>100	96.0	7.0	3.5	12.3	6.2
10	>100	>100	27.6	15.2	46.5	23.3

TABLE 3. -- Values of relative transparency in percent for given particle size class and type of sediment using 1/16-inch nozzle.

CONCENTRATION (mg/ℓ)	0.177 - 0.250			0.125 - 0.177			0.088 - 0.125			0.062 - 0.088		
	LAB	CARTER	BOX	LAB	CARTER	BOX	LAB	CARTER	BOX	LAB	CARTER	BOX
5,000	98.9	98.9	---	98.6	98.6	98.1	98.4	98.2	97.9	97.7	97.5	97.3
10,000	97.7	97.5	---	96.8	96.9	96.0	96.5	96.1	95.7	95.6	94.8	94.6
15,000	96.4	96.0	---	95.2	95.3	93.9	94.6	94.2	93.5	---	92.3	92.0
20,000	95.0	94.6	---	93.5	93.6	91.8	92.8	92.0	01.3	91.1	89.7	89.5
25,000	93.6	92.9	---	91.4	91.9	89.7	90.8	90.1	89.1	----	87.1	86.9
30,000	92.2	91.3	---	90.3	90.0	87.2	88.9	88.0	86.8	86.7	84.6	84.4
35,000	90.8	89.7	---	88.8	88.5	85.3	87.1	86.0	84.4	---	82.0	81.8
40,000	89.5	88.4	---	87.2	86.7	83.1	85.3	83.9	82.1	82.5	79.5	79.1
45,000	88.2	---	---	85.6	85.1	80.7	83.2	81.8	79.7	---	77.0	76.5
50,000	86.8	---	---	84.0	83.4	78.6	81.4	79.8	77.7	---	74.6	74.0
60,000	83.9	---	---	80.7	80.1	74.4	77.8	75.9	73.0	74.0	69.9	69.3
70,000	81.2	---	---	77.5	76.9	70.2	74.1	71.9	68.6	---	65.2	64.6
80,000	78.5	---	---	74.4	---	66.3	70.6	67.8	64.1	66.1	61.0	60.1
90,000	75.5	---	---	71.0	---	62.5	67.2	64.3	59.8	---	56.8	55.8
100,000	72.6	---	---	68.0	---	58.4	63.7	60.7	55.8	59.5	52.8	51.5

TABLE 4. - Values of relative transparency in percent for given particle size class and type of sediment using 1/8-inch nozzle.

CONCEN TRATION (mg/ℓ)	0.177 - 0.250			0.125 - 0.177			0.088 - 0.125			0.062 - 0.088		
	LAB	CARTER	BOX	LAB	CARTER	BOX	LAB	CARTER	BOX	LAB	CARTER	BOX
5,000	97.7	97.8	---	97.1	97.0	96.5	96.5	96.4	96.0	95.9	95.4	94.5
10,000	95.3	95.3	---	94.0	93.8	92.8	93.0	92.8	91.9	92.0	90.8	89.5
15,000	---	92.8	---	91.2	90.7	89.2	89.6	89.4	87.9	88.3	86.4	84.6
20,000	90.5	90.2	---	88.3	87.6	85.6	86.2	85.9	84.0	84.3	81.9	79.9
25,000	---	87.7	---	85.8	84.5	82.0	83.8	82.2	80.1	80.5	77.6	75.1
30,000	85.7	85.2	---	83.0	81.6	78.5	79.7	79.1	76.3	76.8	73.4	70.4
35,000	---	82.6	---	80.2	78.5	75.1	76.5	75.8	72.4	73.2	69.3	66.2
40,000	81.0	80.0	---	77.5	75.7	71.6	73.5	72.6	68.8	69.7	65.2	61.9
45,000	---	77.4	---	74.8	73.0	68.3	70.7	69.5	65.3	66.4	61.5	57.8
50,000	---	75.0	---	72.1	70.4	65.3	67.7	66.5	61.7	63.2	57.9	53.7
60,000	71.5	70.4	---	67.0	65.0	59.1	62.4	60.8	55.0	57.2	51.1	46.7
70,000	---	65.6	---	62.2	60.0	53.5	57.4	55.7	48.9	51.5	45.2	40.6
80,000	62.5	61.4	---	57.6	55.4	48.0	52.6	50.7	43.2	46.6	39.9	35.2
90,000	---	57.0	---	53.2	50.9	42.8	48.3	46.3	37.8	42.0	35.2	30.3
100,000	53.1	53.0	---	49.4	46.6	38.3	44.5	42.2	33.0	38.0	31.4	26.3

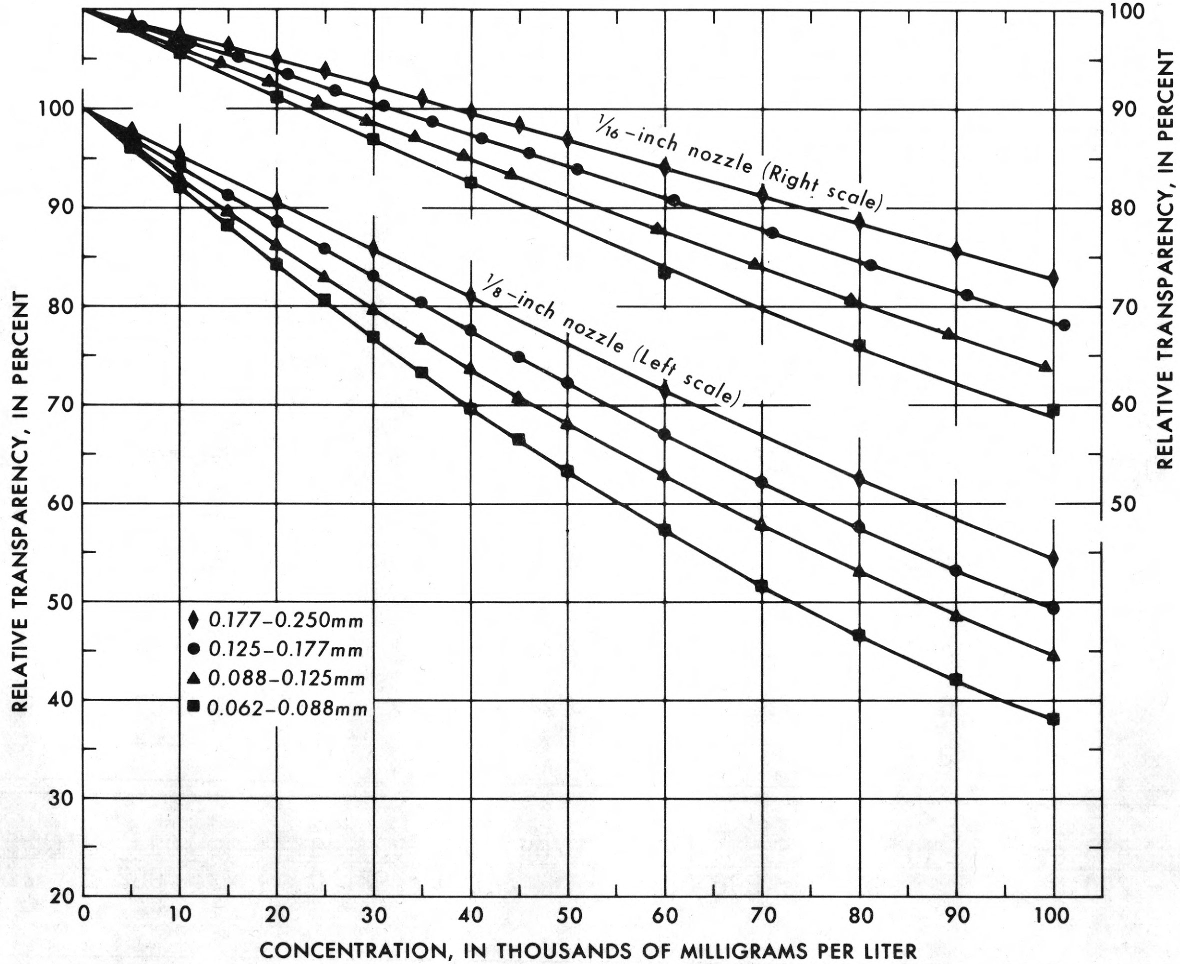


Figure 11.--Relationship of relative transparency to sediment concentration for Lab Sand.

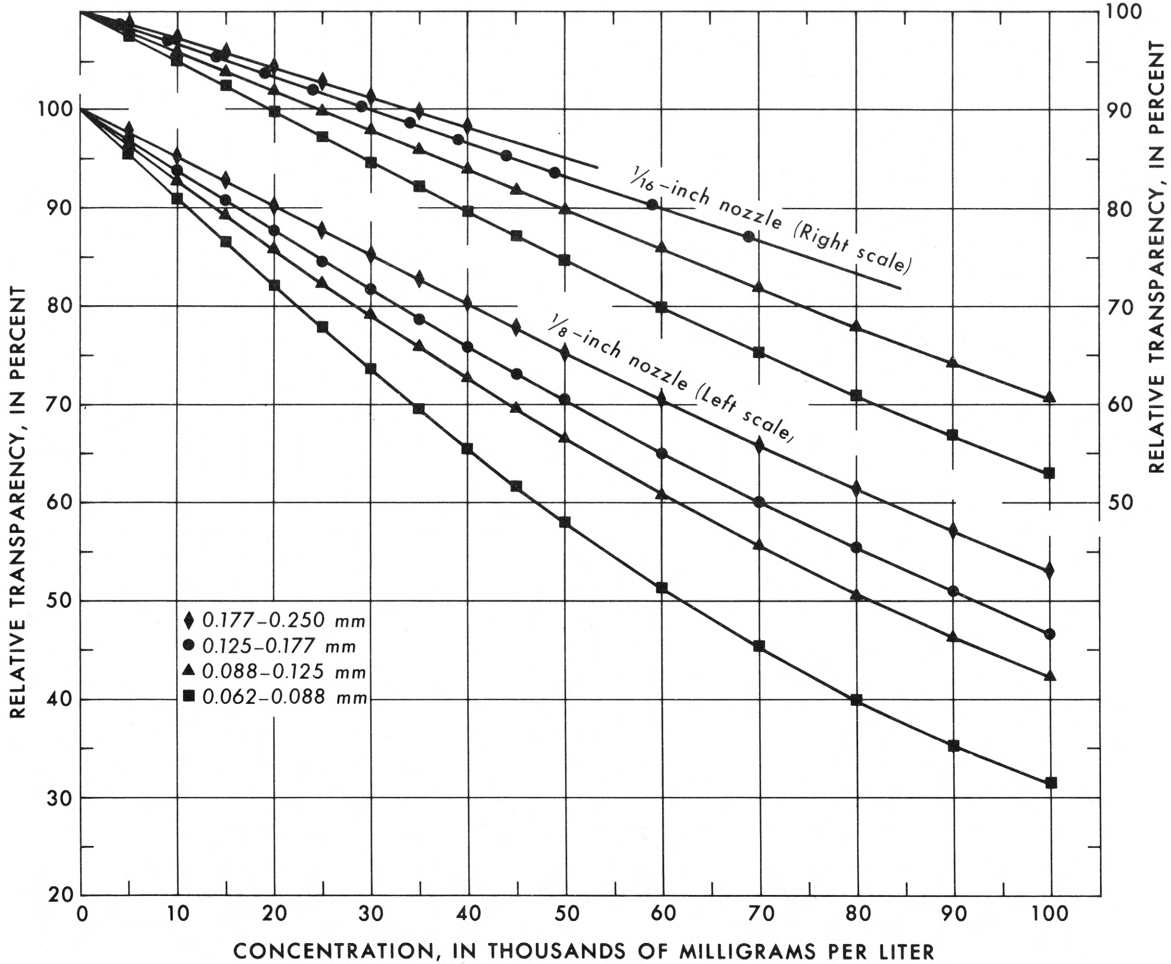


Figure 12.--Relationship of relative transparency to sediment concentration for Carter Lake sands.

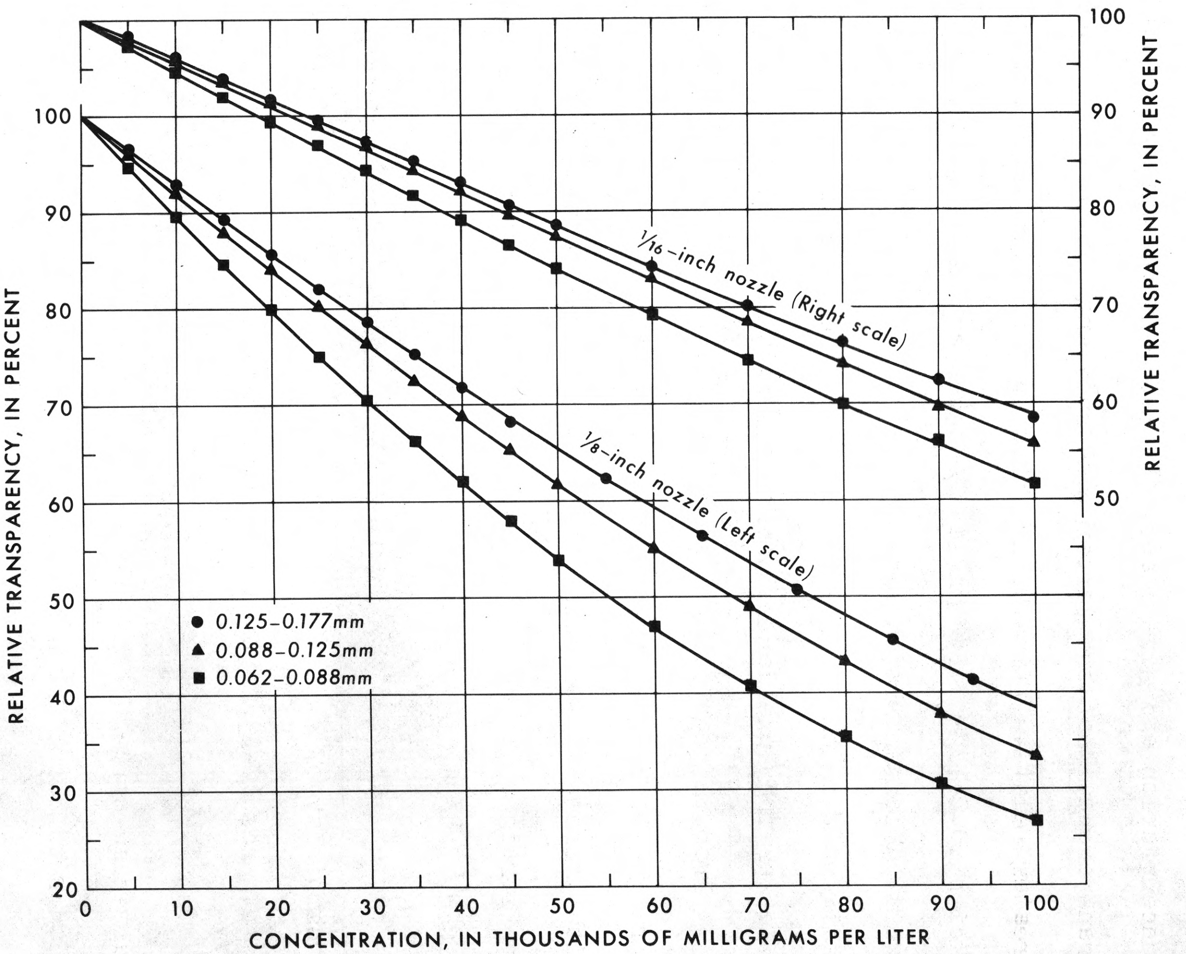


Figure 13.--Relationship of relative transparency to sediment concentration for Boxelder sands.

previously, the nominal size classes were based on the square-root-of-two series, and the fall diameter gradation of these size classes for each sediment is indicated in figure 8. For a given concentration and size class, the Lab Sand has greater relative transparency than the Carter Lake sediment, which, in turn, has greater relative transparency than the Boxelder sediment. Insufficient 0.0177 - 0.250 mm sediment was available to continue the run at a concentration greater than 40,000 mg/ℓ for the Carter Lake sediment with the 1/16-inch nozzle. Also this size was not available for the Boxelder sediment for use with either nozzle.

From the curves of figures 11-13, it is apparent that the straight-line relationship extended to a lower relative transparency with increasing sand size for a given nozzle size. For example, the straight linearity extended to 86 for 0.063 - 0.088, to 82 for 0.088 - 0.125, to 78 for 0.125 - 0.177, and to 75 for 0.177 - 0.250 mm Carter Lake sediments using the 1/8-inch nozzle. Aside from the possibility of some "black box" effects, the curvature exhibited in figures 10-13, may be attributed to (a) light reflections from the surfaces of the particles and (or) (b) to the movement of some particles through the system while in the shadow of other particles closer to the light source.

Effect of Nozzle Size

As already mentioned, the system suggests a simple hypothesis--that a given concentration of a given size and type of sediment will allow twice as much light to be transmitted with use of the 1/16-inch nozzle as with the use of the 1/8-inch nozzle. Though it was not used in these experiments, it would be expected that the use of the 1/4-inch nozzle would result in a proportionate decrease in transmitted light. It should be remembered that these are only "nominal" and not precise nozzle sizes. This simple hypothesis would be expected to hold best for very low concentrations of sediment, where the light would be reflected or absorbed by only single particles; that is, a situation that would avoid the likelihood of one particle moving in the shadow of another. However, for nearly opaque mixtures, where the relative transparency approaches zero, the results would theoretically be the same regardless of nozzle thickness. Logically, the best results can be obtained with the equipment, in the sense of true proportionate differences among the different nozzles, when the mixture is capable of transmitting considerable light.

Comparison of the results obtained with the 1/8-inch and 1/16-inch nozzles for the different sizes and types of sediment can best be made by converting the data from relative transparency to relative opacity. This is accomplished by subtracting the data in tables 2 and 3 from 100.0. The ratios listed in table 5 are then defined as

TABLE 5. -- Relative opacity ratios (1/8 to 1/16 inch nozzles) for given concentration, size (mm) and type of sediment. († estimate)

CON-CENTRATION (mg/ℓ)	Lab. Sand					Carter Lake					Boxelder					All sediments				Average all
	0.177–0.250	0.125–0.177	0.088–0.125	0.062–0.088	Aver.	0.177–0.250	0.125–0.177	0.088–0.125	0.062–0.088	Aver.	—	0.125–0.177	0.088–0.125	0.062–0.088	Aver.	0.177–0.250	0.125–0.177	0.088–0.125	0.062–0.088	
5,000	2.09	2.07	2.18	1.78	2.03	2.00	2.14	2.00	1.84	1.99	---	1.84	1.90	2.04	1.93	2.04	2.02	2.03	1.85	2.00
10,000	2.04	1.88	2.00	1.78	1.92	1.88	2.00	1.85	1.80	1.88	---	1.80	1.88	1.95	1.88	1.96	1.89	1.91	1.84	1.90
20,000	1.90	1.80	1.91	1.76	1.84	1.81	1.94	1.76	1.76	1.82	---	1.76	1.84	1.91	1.84	1.85	1.83	1.84	1.81	1.83
40,000	1.81	1.76	1.80	1.73	1.77	1.72	1.83	1.70	1.70	1.73	---	1.68	1.74	1.82	1.74	1.77	1.76	1.74	1.75	1.76
60,000	1.77	1.71	1.69	1.65	1.70	1.65†	1.76	1.63	1.63	1.67	---	1.60	1.67	1.74	1.67	1.71	1.69	1.66	1.67	1.68
80,000	1.74	1.65	1.61	1.57	1.64	1.61†	1.67†	1.53	1.54	1.59	---	1.54	1.58	1.62	1.58	1.67	1.62	1.57	1.57	1.61
100,000	1.66	1.58	1.53	1.53	1.57	1.56†	1.58†	1.47	1.45	1.52	---	1.48	1.52	1.52	1.51	1.61	1.55	1.50	1.50	1.54
Average	1.86	1.78	1.82	1.68	1.78	1.74	1.85	1.71	1.67	1.74	---	1.67	1.75	1.80	1.73	1.78	1.77	1.75	1.72	1.75

$$\text{Ratio} = \frac{100 - RT_8}{100 - RT_{16}} = \frac{RO_8}{RO_{16}}$$

where RT is the relative transparency, RO is the relative opacity, 8 refers to 1/8-inch nozzle, and 16 refers to 1/16-inch nozzle.

The merit of converting RT to RO can be illustrated by use of data from the run for Lab Sand 177-250. At a concentration of 20,000 mg/ℓ, the ratio of RT_8 to RT_{16} is 0.953, whereas the ratio of RO_8 to RO_{16} is 1.900. Thus RO is a better measure of the expected effect of nozzle size. Furthermore, a comparison of ratios at 20,000 mg/ℓ with the ratios at a concentration of 40,000 mg/ℓ (RT_8 to RT_{16} = 0.905 and RO_8 to RO_{16} = 1.810) shows that $\Delta RT = 0.048$, whereas $\Delta RO = 0.090$. Thus, the use of RO not only is a better measure of the expected effect of nozzle size, but also will accentuate variations caused by concentration differences and thus improve the efficiency of studies of the effects of sediment size and type.

Plots of the relative opacity ratios with concentration for different sizes and types of sediments are shown in figure 14. Although there is considerable deviation among the ratios for different sizes and types of sediments, the average at 5,000 mg/ℓ is 1.99 and decreases to 1.53 at 100,000 mg/ℓ. In other words, the values tend to decrease from the ideal value of 2.00 toward 1.00 as the relative opacity increases, which is in accordance with the hypothesis mentioned. The average ratio of the seven

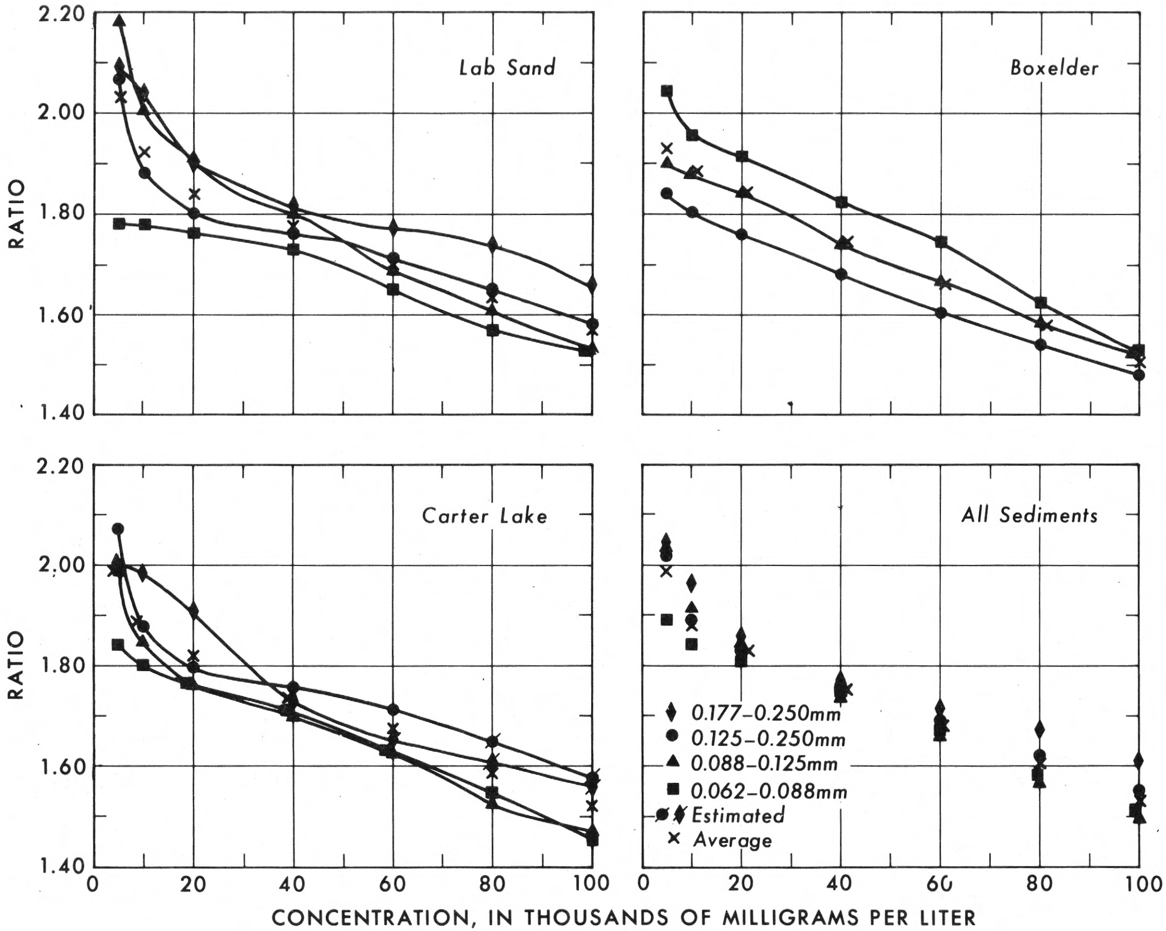


Figure 14.--Ratios of relative opacity for 1/8- to 1/16-inch nozzles for given concentration, size, and kind of sediment.

points of increasing concentration for all types of sediment along the curves is 1.78, 1.77, 1.76, and 1.80, in the order of decreasing size classes. The average for all sizes is 1.78, 1.74, and 1.73, in the order of Lab Sand, Carter Lake, and Boxelder sediments. The overall curves and these averages show that the ratios are somewhat higher for the Lab Sand than for Carter Lake or Boxelder sediments. This would be expected because of the higher relative transparency for the Lab Sand, as indicated by contrasting the curves in figure 11 with the curves in figures 12 and 13.

The erratic results indicated by some of the curves in figure 14, for the low-concentration observations may be attributed to minor errors in reading the results from the strip chart (fig. 5). For example, the indicated relative transparency for the Lab Sand at 5,000 mg/ℓ is 95.9 for the 1/8-inch nozzle and 97.7 for the 1/16-inch nozzle. The computed ratio then would be

$$\frac{100 - 95.9}{100 - 97.7} = \frac{4.1}{2.3} = 1.78.$$

Thus, in this instance an error of 0.1 in reading RT_8 would result in an error of 0.04 for the ratio, an error of 0.1 in reading RT_{16} would result in an error of 0.08, and an error of 0.1 in reading both RT_8 and RT_{16} could result in an error of as much as 0.13 for the ratio.

Effect of Sediment Size

The data presented in tables 2 and 3 and figures 11 - 13 support the hypothesis that the relative transparency decreases as the particle size decreases for a given concentration and type of sediment. The manner in which this decrease takes place was investigated by a study of the relative opacity ratios among the different size classes for given concentrations and types of sediment. These ratios are presented in tables 6 and 7 for the 1/8-inch and 1/16-inch nozzles, respectively. Each ratio was computed with the data for the 0.062 - 0.088 size class as the denominator, and, thus, all values are greater than 1.00.

As expected, the greater the sediment size with respect to the 0.062 - 0.088 mm size, the higher the ratio is for a given concentration and type of sediment. Also, as expected, the ratios decrease with increasing concentration or opacity of water-sediment mixture. Comparison of the ratios between the 1/8-inch nozzle (table 6) and the 1/16-inch nozzle (table 7) for all sediments show somewhat higher ratios for the 1/16-inch nozzles.

Effect of Sediment Type

The effect of sediment type on the relative transparency for a given concentration could be examined more easily if the effect of particle size on the transparency for a given sediment could be eliminated. This would also make it possible to extrapolate the data to other particle sizes.

TABLE 6. -- Relative opacity ratios among different size classes for given concentrations and type of sediment using 1/8-inch nozzle.

CON-CENTRA-TION (mg/ℓ)	Lab. Sand				Carter Lake				Boxelder			All sediments		
	0.062/0.088	0.062/0.125	0.062/0.177	Aver.	0.062/0.088	0.062/0.125	0.062/0.177	Aver.	0.062/0.088	0.062/0.125	0.062/0.177	0.062/0.088	0.062/0.125	0.062/0.177
5,000	1.17	1.41	1.78	1.46	1.28	1.53	2.09	1.63	1.38	1.57	--	1.28	1.50	1.93
10,000	1.14	1.34	1.70	1.39	1.28	1.48	1.96	1.57	1.30	1.46	--	1.23	1.42	1.83
20,000	1.14	1.34	1.65	1.37	1.28	1.46	1.85	1.53	1.26	1.40	--	1.21	1.40	1.75
40,000	1.14	1.33	1.59	1.35	1.27	1.43	1.74	1.48	1.22	1.34	--	1.21	1.37	1.66
60,000	1.14	1.30	1.50	1.31	1.25	1.40	1.65	1.43	1.19	1.30	--	1.19	1.33	1.58
80,000	1.13	1.26	1.42	1.27	1.22	1.35	1.55	1.37	1.14	1.25	--	1.16	1.28	1.48
100,000	1.12	1.22	1.36	1.23	1.18	1.28	1.46	1.30	1.10	1.19	--	1.13	1.23	1.41
Average	1.13	1.32	1.57	1.31	1.25	1.42	1.76	1.47	1.23	1.36		1.20	1.36	1.66

TABLE 7. -- Relative opacity ratios among different size classes for given concentrations and type of sediment using 1/16-inch nozzle. († estimate).

CONCENTRATION (mg/ℓ)	Lab. Sand				Carter Lake				Boxelder			All sediments		
	0.062/0.088	0.062/0.125	0.062/0.177	Aver.	0.062/0.088	0.062/0.125	0.062/0.177	Aver.	0.062/0.088	0.062/0.125	0.062/0.177	0.062/0.088	0.062/0.125	0.062/0.177
5,000	1.44	1.64	2.09	1.72	1.39	1.78	2.27	1.81	1.28	1.42	--	1.37	1.61	2.18
10,000	1.29	1.39	1.96	1.55	1.31	1.64	2.04	1.66	1.25	1.35	--	1.28	1.44	2.00
20,000	1.24	1.39	1.78	1.47	1.29	1.61	1.91	1.60	1.21	1.28	--	1.25	1.43	1.84
40,000	1.19	1.37	1.67	1.41	1.27	1.54	1.77	1.53	1.17	1.24	--	1.21	1.39	1.70
60,000	1.17	1.35	1.62	1.38	1.25	1.51	1.68†	1.48	1.14	1.20	--	1.19	1.35	1.65
80,000	1.15	1.32	1.58	1.35	1.21	1.46†	1.63†	1.43	1.11	1.18	--	1.15	1.32	1.60
100,000	1.12	1.26	1.48	1.28	1.20	1.40†	1.57†	1.39	1.10	1.16	--	1.14	1.27	1.52
Average	1.23	1.39	1.74	1.45	1.27	1.56	1.84	1.54	1.18	1.26	-	1.23	1.40	1.77

Glover, Bhattacharya, and Kennedy (1969) used a minature "electro-optical system" for measurement of suspended-sediment concentrations. In their instrument, they found the output voltage to be a linear function of the concentration of sediment for each grain size. The voltage output also decreased with decreasing particle size for a given concentration. When sediment concentration was divided by particle size, the family of curves could be collapsed by a single straight line representing the relation between the ratio of concentration to diameter and the output voltage or turbidity. They concluded that the light attenuation for their instrument resulted mostly from light scattering at the particle surfaces, the magnitude of which was inversly proportional to the particle diameter for a given concentration.

In this investigation, an attempt was made to collapse the data for the four size classes of Lab Sands and three classes of Boxelder sands considering the 1/8-inch nozzle (figs. 11 and 13, table 4) by plotting the ratio of concentration to D_{50} (median particle size as determined by fall diameter measurements) against relative transparency as in figure 15. The plot indicates that each sand is different (the lines do not collapse) even in the range from 0 to 30 thousand used by Glover, Bhattacharya, and Kennedy (1969), and that the values of D_{50} have too large a range to be represented by a single relation.

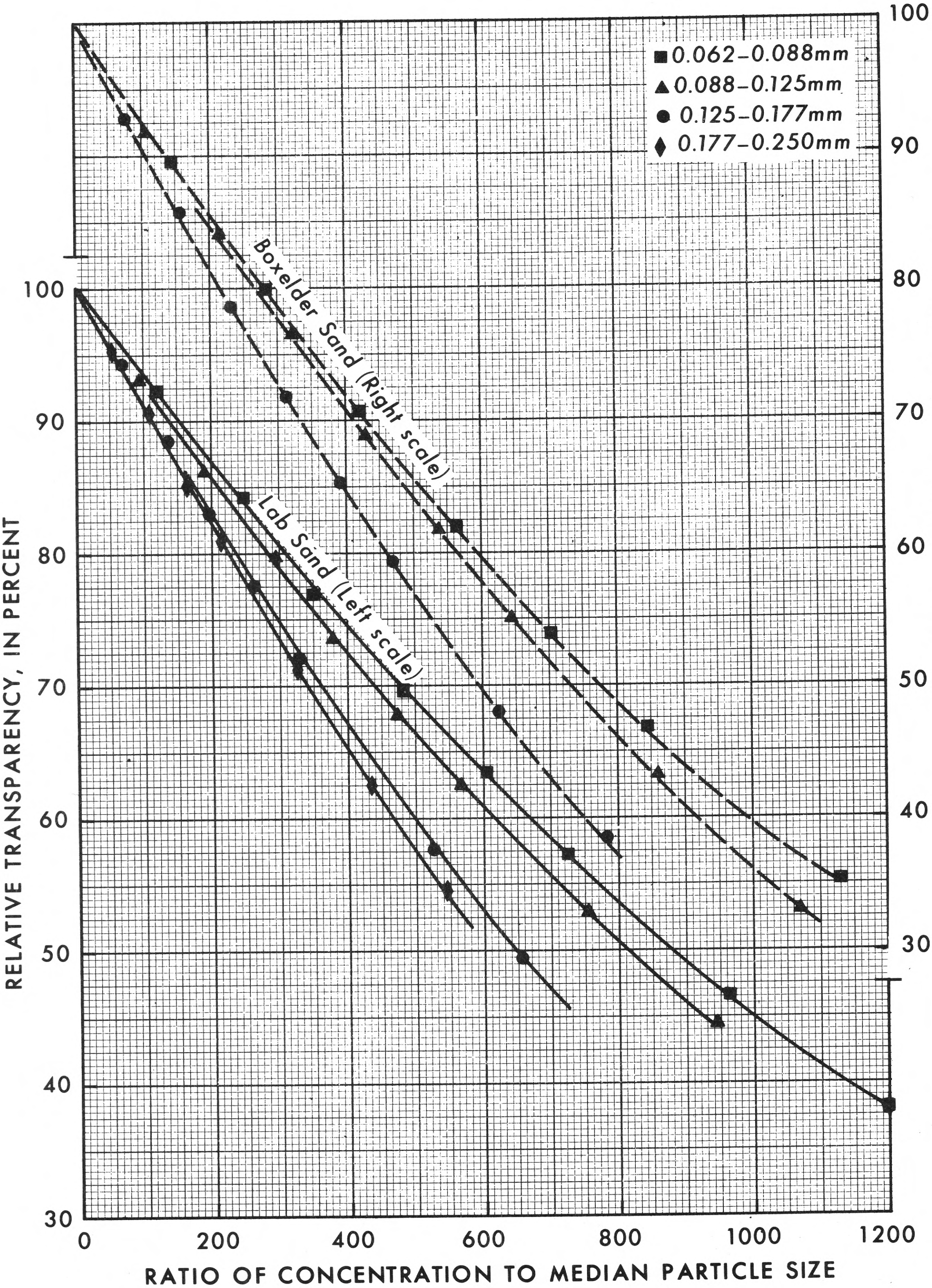


Figure 15.--Relative transparency for Lab Sand and Boxelder using 1/8-inch nozzle as a function of the ratio of concentration to median fall diameter particle size.

By trial and error, values of the ratio of the square root of D_{50} to concentration were found to collapse the lines reasonably well. Figure 16 shows the relation of this ratio to relative transparency for the sand separates of all three sediments for both nozzle sizes. Within the range of concentrations used by Glover, Bhattacharya, and Kennedy (1969), the plots for the different sediments could be considered to be straight lines, and the data deviate but little from the lines. However, for concentrations above about 30,000 mg/ℓ, the data for each sand size deviate considerable from the mean line for a given sediment for as yet unexplained reasons.

The scatter of the ratios plotted in figure 16 may be partly the result of possible errors in measuring the particle size D_{50}. Note, in figure 8, that the particle-size distribution curves are not quite parallel and are not spaced uniformily, as would theoretically be expected for the various size classes. Theoretical, D_{50_T}, for the 0.062 - 0.088, 0.088 - 0.125, 0.125 - 0.177 and 0.177 - 0.250 mm sieve size classes would be 0.074, 0.105, 0.149, and 0.210 mm compared with a measured fall diameter of 0.083, 0.106, 0.152, and 0.184 mm, respectively, for Lab Sand. For a given size class, D_{50_T} would be the same for all three sediments. The difference between D_{50} and D_{50_T} are relatively small, and a trial plot of $C/D_{50_T}^{0.5}$ against relative transparency does not appear to yield better results than shown in figure 16.

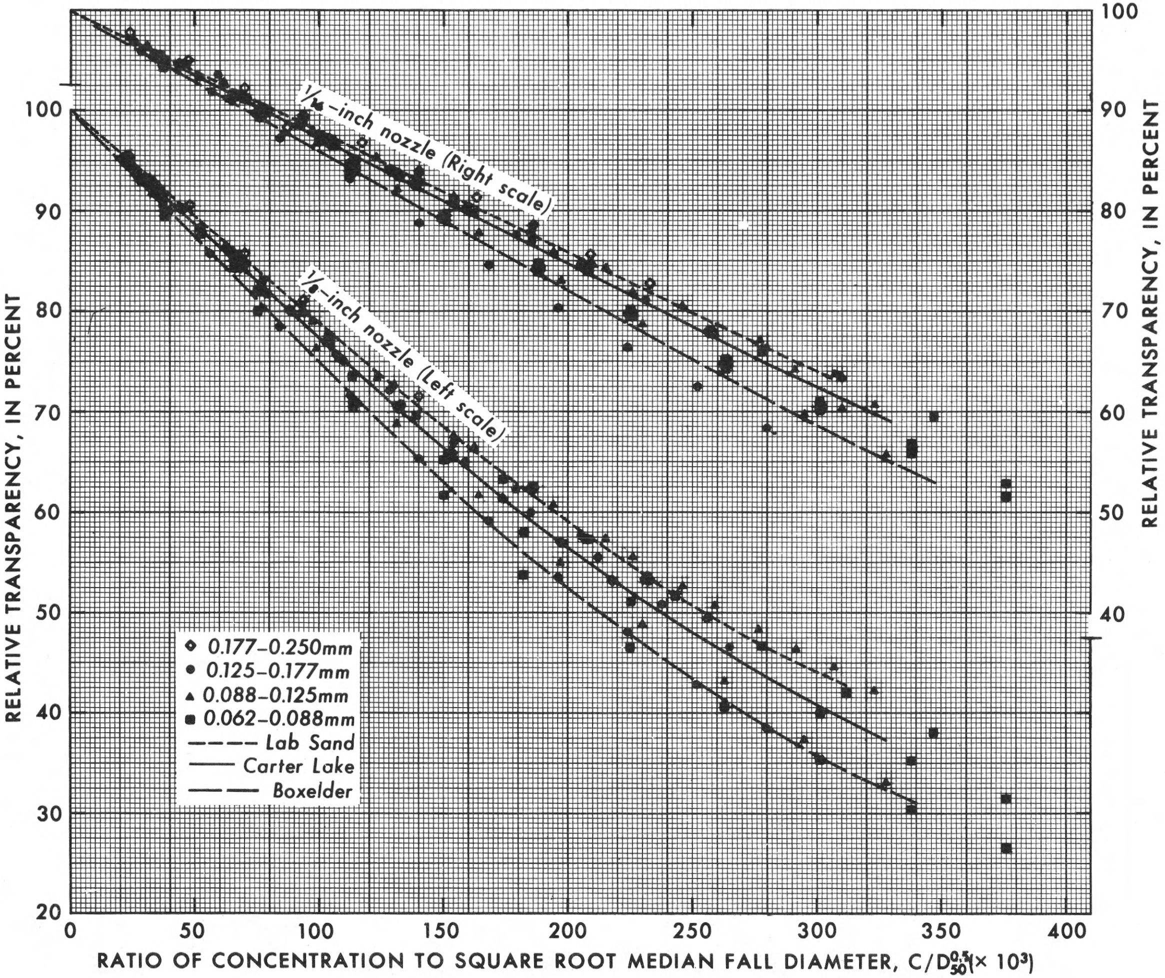


Figure 16.--Relative transparency for all sand classes and sediments as a function of the ratio of concentration to square root of median fall diameter.

The instrumental sensing is mainly the result of light passing between the projected area of the particles, partly by light transmitted through the particles and partly by light reflected from the surface of the particles. Therefore the total projected area and (or) the surface area of the particles in the light path should be closely related to the attenuation by the light beam, as detected by the instrument system. Consequently, instead of using D_{50}, analysis by use of both particle projected area and particle surface area was attempted. Neither analysis yielded better results than for the use of $C/D_{50}^{0.5}$ (fig. 16).

Fine Sediment and Mixtures

As indicated in figure 7, the Carter Lake and Boxelder sediments are a natural mixture of fines and sands. For practical use of the turbidimeter, it is necessary to be able to relate relative transparency data to concentration for such mixtures. The basic relative transparency data for the Boxelder mixture finer than 0.177 mm and mixtures finer than 0.062 for both Boxelder and Carter Lake are given in table 1 and plotted in figure 10.

For the Boxelder sediment finer than 0.177 mm, figure 7 shows the median size, D_{50}, to be 0.063 mm and $D_{50}^{0.5}$ is, therefore, 0.251 mm. The value of the ratio 10,000 to 0.251 (39.8×10^3), together with a relative transparency of 54.6 for 1/8-inch nozzle, plots much too low on figure 16. For Boxelder sediment finer than 0.062 mm, which in reality should be regarded as a mixture, D_{50} is 0.041 and $D_{50}^{0.5}$ is, therefore, 0.202. The value of the ratio at 10,000 (49.5×10^3), together with a relative transparency of 31.6 (1/8-inch), also plots much too low on figure 16. Therefore, it is not possible to use $D_{50}^{0.5}$ for the mixtures containing fines to account for the effect of particle size on relative transparency. Further investigation is required to determine whether some size smaller than the median or a transform other than $D_{50}^{0.5}$, or both, is required.

Low Concentrations

The high sensitivity of the instrument to small changes in concentration for both the silty Boxelder and the clayey Carter Lake sediments insures that the instrument will operate satisfactorily on streams to much less than 100 mg/ℓ of sediment, where such low concentrations involve mostly fines. Figure 17 illustrates the relationship of relative transparency to low concentrations of Boxelder and Carter Lake fine sediments using the 1/16-inch nozzle. The sensitivity of the instrument could be increased by using either the 1/8-inch or 1/4-inch nozzle. As indicated in figure 14, the relative opacity, for low concentrations tends to be proportional to the relative nozzle size at low concentration values, where the relative transparency approaches 100.

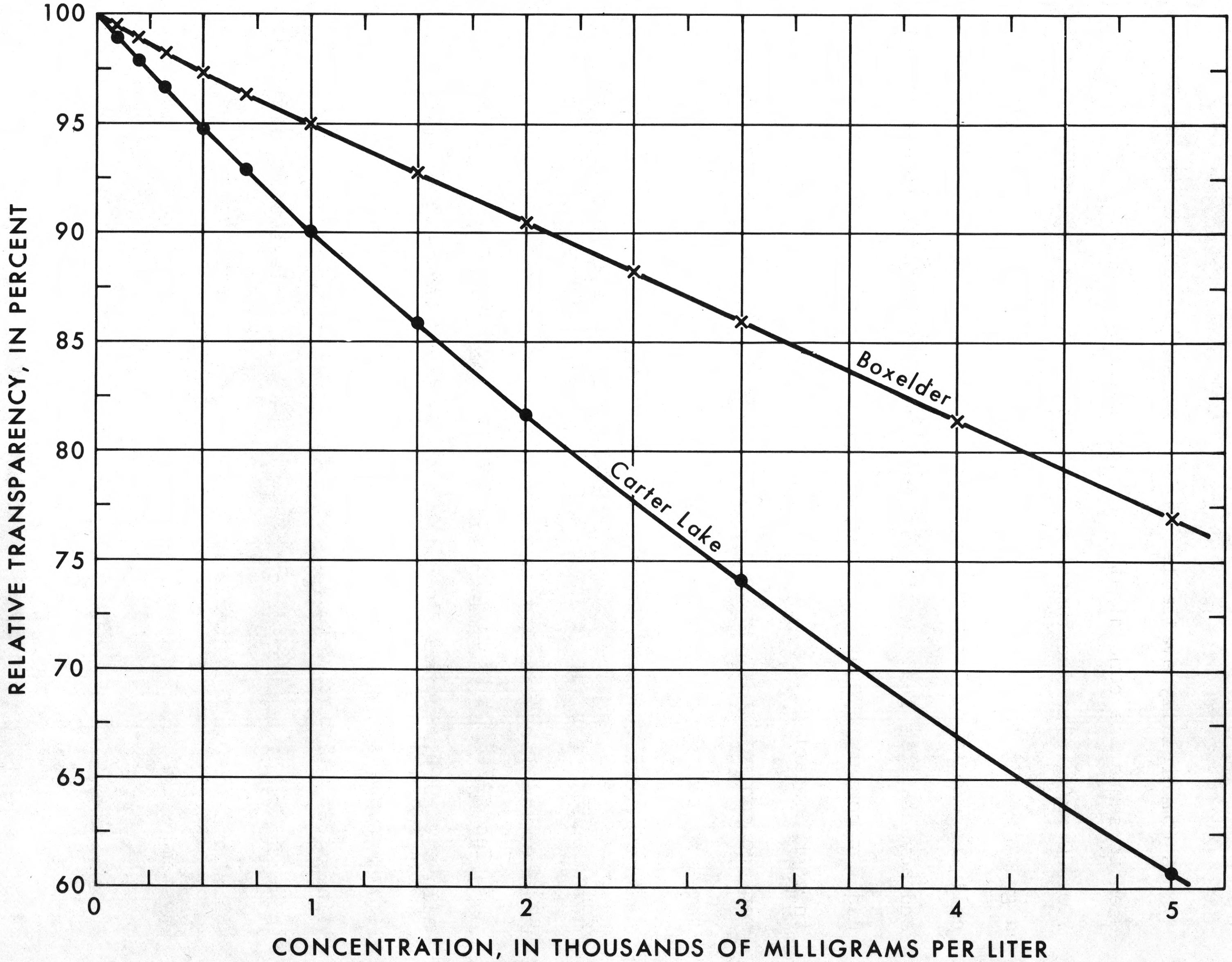


Figure 17.--Relationship of relative transparency to low sediment concentrations of Boxelder and Carter Lake fine sediments (<0.062 mm) using 1/16-inch nozzle.

SUMMARY AND RECOMMENDATIONS

A commercially available "falling-stream" turbidimeter has been used to sense the concentration of suspended sediment to over 100,000 mg/ℓ. The instrument measured the relative transparency of a gravity-induced smooth flat sample stream by sensing with a photocell the amount of light transmitted through the stream. The unique and advantageous feature of this instrument is that the sample stream did not contaminate and thereby change the calibration of the system through contact with the optics. The range of measurement of sediment concentration could be extended through the possible use of three nozzles of different nominal thicknesses to provide a range of light transmissivity for a given concentration and kind of sediment. The sensivity of the measurements could also be extended by adjustments to the recording equipment.

Tests were made on a bright quartz laboratory sand, a silty alluvial soil from the flood plain of Boxelder Creek, Colo., and a clayey residual soil near Carter Lake, Colo. Only the fractions finer than 0.250 mm were used because of difficulty in pumping suspensions of coarser fractions. In a field installation, fractions coarser than 0.250 mm could be hydraulically separated from the system.

The data and analysis from the experiments suggest the following specific conclusions:

1. Concentrations of fine sand exceeding 100,000 mg/ℓ, and of clayey sediment exceeding 40,000 mg/ℓ, could be satisfactorily sensed with the 1/8-inch nozzle. Therefore, it is expected that good results can be obtained under field conditions for natural fluvial sediments at concentrations exceeding 100,000 mg/ℓ with the 1/16-inch, if not with the 1/8-inch nozzle.

2. The indicated relative transparency was found to be approximately inversely proportional to the nozzle size for high rates of transparency (low concentration). That is, a 1/16-inch nozzle would transmit two times as much light as the 1/8-inch nozzle would, for the same type and concentration of sediment. The ratio diminished with higher concentrations and would theoretically approach unity with an opaque mixture.

3. As expected, the relative transparency decreased with particle size for a given type and concentration of sediment.

4. The relationship between relative transparency and concentration was found to be unique for each type of sediment for a given size class.

5. For studies with sand sizes, it was found that the ratio of concentration to the square root of the median size in the class collapsed the curves, so that the impact of the type of sediment was apparent. Extrapolation of the use of this ratio to finer sediment was unsuccessful.

6. In regard to the lower limit of useful concentration sensitivity, good results could be obtained to less than 1,000 mg/ℓ for the 0.177 - 0.250 size class using the 1/8-inch nozzle; or theoretically, to 500 mg/ℓ for the 1/4-inch nozzle if it were used. For the clayey sediment, the relative transparency was 98.9 at 100 mg/ℓ for the 1/16-inch nozzle. Therefore, it is expected that reliable results could have been obtained to 20 or 25 mg/ℓ with this nozzle and, therefore, to 5 or 6 mg/ℓ with the 1/4-inch nozzle. The lower concentration limit for natural sediments, because of the impact of the fines, would be expected to be in the range of 10 to 20 mg/ℓ without "electronic" adjustment.

The experiments were discontinued before data could be collected to make a sensitivity analysis to determine the upper and lower concentration detection limits for different types and sizes of sediment. Additional data were also needed to extend the study of the effect of particle size into at least the silt sizes in order that a more precise analysis of composite sized sediments could be made.

The results show that the instrument has potential use for sensing relative sediment concentration in streams. Therefore, a project should be undertaken to modify the instrument with the main objectives being to simplify and reduce the cost, to improve the means of obtaining increased sensitivity at low concentrations, and to integrate a low-cost recorder into the system, and (or) insure compatibility with recorders at gaging stations. If these objectives could be attained, then the instrument would be acceptable for widespread field use. An alternative to the pumping or above-water system normally used would be to develop a submersible "flow-through" sensor to avoid the many problems of pumping. The recording system could be on the bank or at some other remote point.

The instrument should prove most useful for field use on small streams, where frequent observations are more important than the absolute accuracy of each observation. In urban areas it is nearly impossible and (or) very expensive to define the nature of the rapidly changing concentration by conventional suspended-sediment sampling or pumping sampler techniques. Small drainage areas usually insure a reasonably constant particle-size distribution and color of the suspended sediment. Therefore, the "rating" for the instrument would be better defined for a small basin than for a large basin.

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