Fluorescent Sand as a Tracer of Fluvial Sediment

GEOLOGICAL SURVEY PROFESSIONAL PAPER 562-E

Fluorescent Sand as a Tracer of Fluvial Sediment

By VANCE C. KENNEDY *and* DOROTHY L. KOUBA

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

GEOLOGICAL SURVEY PROFESSIONAL PAPER 562-E

An investigation of sand movement in a gravel-bed stream

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1970

UNITED STATES DEPARTMENT OF THE INTERIOR

WALTER J. HICKEL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 30 cents (paper cover)

CONTENTS

ILLUSTRATIONS

TABLES

SEDIMENT TRANSPORT IN ALLUVIAL CHANNELS

FLUORESCENT SAND AS A TRACER OF FLUVIAL SEDIMENT

By VANCE C. KENNEDY and DOROTHY L. KOUBA

ABSTRACT

Stream sand coated with fluorescent paint was added at a constant known rate to Clear Creek at Golden, Colo., during a 28-hour period, and the concentration of fluorescent grains was monitored at a point 810 meters downstream from the point of introduction. Stream width in the study reach averaged about 21 meters, mean velocity about 1.4 meters per second, and mean discharge 8.2 cubic meters per second. Flow was very turbulent over a gravel bed.

First-arrival time of fluorescent sand correlated with the square of grain diameter in the range 0.15–0.86 millimeters. Although Clear Creek meanders gently, complete lateral mixing of fluorescent sand was not achieved within the study reach. However, steady-state conditions apparently were achieved for the finer particles, with highest concentrations on the north side and lowest concentrations on the south side of the stream. Lateral mixing of coarser grains was much better than for finer grains.

Suspended-sediment discharges for various size ranges were computed from suspended-sediment samples which do not include sand-sized particles moving near or on the bed and from "dilution" of fluorescent sand which presumably measures total sediment discharges. The sediment discharge computed from the tracer-dilution method was about 30 percent greater than the suspended-sediment discharge computed from suspended samples for the 0.15–0.18 millimeter range and about 200 percent greater for the 0.38–0.52 millimeter range.

INTRODUCTION

A study of the movement of fluorescent sand in Clear Creek about 24 km (kilometers), or 15 miles, west of Denver, Colo., was made during the period May 26–28, 1965. The 0.8 km (half-mile) study reach (fig. 1) began about 300 m (meters), or 1,000 feet, downstream from where Clear Creek leaves the Front Range of the Colorado Rockies and ended within the town of Golden.

The main purpose of the investigation was to evaluate the use of fluorescent sand as a means of measuring sand discharge in a gravel-bed stream. This report summarizes the results of that study and also includes suggestions for other uses of solid fluorescent tracers in stream investigations.

Fluorescent materials have been used extensively in studying the movement of beach sediments (Aybulatov and others, 1961; Russel, 1961; Bruun, 1965; Kidson and Carr, 1962; and Ingle, 1966). Teleki (1966), Yasso (1962), and others have described techniques for coating sand. Glazov and Glazov (1959) and Zenkovitch (1958) indicated that sand coated with fluorescent paint has been used to study fluvial sand movement in the U.S.S.R., but details were not given. There apparently has been very little, if any, use of fluorescent particles as tracers in American streams. Instead, radioactive tracer particles have generally been used here, for example, Krone (in Krone and others, 1960), Hubbell and Sayre (1964), and Cummins (1965).

The radioactive-tracer method has the advantage that the radioactivity of the stream sediments can be measured continuously without removing samples from the stream, and this can be done with great sensitivity. Conversion of the radioactivity data into sediment discharge may, however, require knowledge of both the particle-size distribution on the stream bed and the depth of sediment movement on the bed if surface labeled particles are used. Ordinarily, coring of the bed sediments would be required to obtain this information. The radioactive-tracer method has the disadvantage that it requires clearance from various public agencies before use, and moderately expensive equipment is required to measure the radioactivity and to protect against radiation hazards.

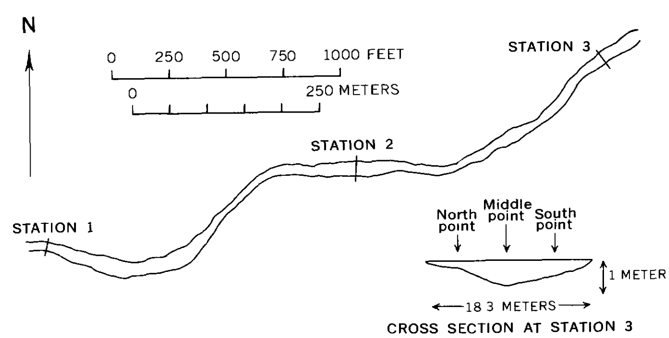

FIGURE 1.—Sketch map of study reach on Clear Creek at Golden, Colo.

Fluorescent-sand tracers are also easily detected, and sensitivity is limited mainly by the size of the sample collected. Aybulatov, Boldyrev, and Griesseier (1961) claim a sensitivity of 1 part per 10 million. Except in clear shallow water, samples of sediment must be taken from the stream before the fluorescent particles can be detected. An ultraviolet light is all that is required for detection, and several different fluorescent colors can be used simultaneously to identify grains differing in size, shape, or specific gravity. When quantitative results are needed, relatively simple counting equipment can be used on fractions separated on the basis of sieve size or fall diameter. Both Teleki (1965) and DeVries (1966) have described instruments for counting fluorescent grains automatically.

ACKNOWLEDGMENTS

This experiment would have been impossible without the help of R. L. Malcolm, E. A. Jenne, R. C. Scott, F. C. Ames, F. C. Canney, and J. O. Johnson. Extensive discussions of the results with C. Nordin, W. W. Sayre, E. V. Richardson, and F. C. Ames have greatly aided in clarifying the significance of the data. A. T. Miesch supervised computer testing of the equations for lateral mixing of sediment. Professor R. B. Krone, of the University of California, kindly read the manuscript and made several constructive suggestions. To these individuals the authors express their great appreciation.

Personnel from the U.S. Bureau of Reclamation provided the washed sized sand from Clear Creek.

METHODS USED IN THIS STUDY

COATING OF GRAINS WITH FLUORESCENT PAINT

Sand from Clear Creek was washed and sieved into three size fractions: 0.15–0.30, 0.30–0.52, and 0.52–1.29 mm (millimeters). Each size fraction of thoroughly dried sand was coated with a different colored paint by placing it in a small motor-driven cement mixer along with an acetone solution of a water-insoluble fluorescent pigment.[1] As soon as a thin layer of the acetone solution had coated the grains, they were spread out to dry on a polyethylene sheet. The resulting poorly cemented aggregates were passed between rubber rollers to reduce them to single grains. The number of fluorescent grains per gram in each size fraction was then determined by counting under ultraviolet light.

Cost of such coating can be less than 4.5 cents per kilogram (10 cents per lb) if lots of several hundred kilograms are prepared.

[1] Care was taken to do the coating outside in a strong breeze in order to reduce buildup of acetone vapors. In the proper proportions air-acetone mixtures are explosive and can be ignited by sparks from a motor turning the cement mixer.

SAMPLING OF STREAM SAND

A pumping sampler of the type shown in figure 2 was used to obtain sediment moving near the stream bed. A rubber suction tube whose inside diameter (I.D.) measured 3.8 cm (centimeters) was placed on a base plate held on the stream bed in such a way that the open end of the tube was located about 15 cm (0.5 ft) back from the front of the base plate facing upstream. Water moving just above the bed entered the tube, passed through a 19 liter glass bottle, and then through a centrifugal water pump before returning to the stream. Coarse sediment settled in the glass bottle while fine sediment continued on through the pump. The glass bottle was replaced at intervals so that accumulated sediment could be removed. Although a considerable amount of sorting by size occurred during such sampling, this does not matter because it is the ratio of fluorescent to nonfluorescent grains in a particular size range that is important.

Three depth-integrated water-sediment samples were collected at station 3 during the period of study. Each sample consisted of a composite of subsamples collected at 15 equally spaced stream verticals in the cross section (U.S. Inter-Agency Comm. on Water Resources, 1952, p. 60–63; 1963). Sieve analyses of the suspended sands were made for two of the three composite samples. Such depth-integrated samples should be representative of silt and clay concentrations throughout the full depth of the stream because of uniform distribution throughout the stream vertical. However, because the sampler intake nozzle is lowered only to a point about 9 cm (0.3 ft) above the stream bed, coarser sand-sized particles moving mainly on or near the stream bed are not adequately sampled.

SAMPLE PROCESSING

Each sediment sample was dried and sieved into eight size fractions covering the range 0.15–1.29 mm. Each size fraction was then placed in a vibratory feeder device with a spiral trough and observed under ultra-

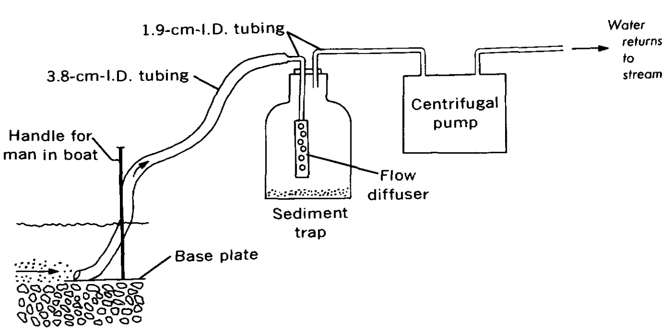

FIGURE 2.—Sketch of equipment used in sampling transported stream sand.

violet light as the grains moved out of the feeder in virtually single file. The number of fluorescent grains of each color was recorded using a hand tabulator.

THE EXPERIMENT

The study reported here was intended to test the usefulness of the "steady-dilution" method (Clayton and Smith, 1963; Lean and Crickmore, 1963, 1966) as applied to the measurement of sediment discharge in Clear Creek at Golden, Colo. The test was made using fluorescent particles instead of radioactive materials as described in the articles mentioned, but the same general principles apply.

If a tracer of concentration C_1 is added to a moving stream of material at a constant rate q, the tracer will mix with the moving material, and at some point downstream a uniform concentration of the tracer in the material will be achieved. If C_0 is the concentration of the tracer in the material before addition of tracer in the experiment, Q is the rate of transport of material, and C_2 is the concentration of tracer after uniform mixing occurs, the following equation applies:

$$qC_1 + QC_0 = (Q + q)C_2.$$

If C_0 is taken as zero and Q is very large compared to q, then the equation is, in effect:

$$qC_1 = QC_2 \text{ or } Q = \frac{qC_1}{C_2}.$$

Where stream sand is transported mainly in suspension, samples collected at a station downstream from the point of tracer addition would be expected to show tracer concentrations increasing rather rapidly at first, then gradually reaching a "plateau" of constant concentration. If the tracer is moving on, or just above, the bed, the speed of movement may be low, and the concentration of tracer may increase slowly at the sampling point. When the constant concentration is reached, it is assumed that as many grains are passing the sampling point as are being added upstream. Normally, in order that such a constant concentration be reached, not only must the tracer be added at a constant rate, but the sand discharge being measured must also remain constant.

In this study a mixture containing 89 grams each of red 0.52–1.29-mm sand, yellow 0.30–0.52-mm sand, and green 0.15–0.30-mm sand was tossed into the middle of Clear Creek every 3 minutes beginning at 2 p.m. May 26 and ending at 6 p.m. May 27, 1965. The fluorescent sand was added at station 1 (fig. 1), and moving sediment was sampled intermittently at station 3 about 800 m (2,650 ft) downstream during the periods from 2:05 p.m. May 26 until 5:42 p.m. May 27 and from 10:12 a.m. until 5:30 p.m. May 28, 1965. One set of three samples was obtained at station 2, about 400 m (1,300 ft) downstream from the point of fluorescent-sand addition, between 1:00 and 3:00 p.m. on May 27, 1965. Blue fluorescent sand of 0.30–0.52-mm diameter was added in two batches, one at 6 p.m. May 26 and the other at 6 a.m. May 27.

During the first 28 hours of the experiment while fluorescent sand was being added, water discharge changed from about 8.8 to 7.8 m^3 per sec (cubic meters per second), or from 310 cfs (cubic feet per second) to 275 cfs. At the end of 62 hours, when the final sampling was completed, discharged was about 6.6 m^3 per sec (235 cfs). Average velocity of the water was approximately 1.4 m per sec (meters per second), or 4.5 fps (feet per second), but maximum velocities were probably in the range 2 m per sec, or 6–7 fps, within the study reach.

Depth integrated samples collected at station 3 indicated 72 mg/l (milligrams per liter) suspended sand 19 hours after the beginning of the experiment and 65 mg/l at 26.5 hours, suggesting that there may have been some decrease in sediment discharge. However, this difference may be within the accuracy of the sediment sampling method and, hence, have little significance. A sample collected 1 hour after beginning the experiment was lost in processing.

Flow was over sediment whose average size was estimated to be a few centimeters but which contained cobbles as much as about 1 decimeter in diameter. Although some scattered showers occurred during and prior to the study period, the stream water remained relatively clear. Presumably, the natural sand being transported was derived from the bed and bank material in the channel system upstream from the study reach.

Sediment samples were also collected at station 3 (fig. 1) by a pumping sampler for 15-minute periods during the first 2 hours. Thereafter, almost all samples were collected by pumping for 30-minute periods. Although most samples were collected at or near the midpoint of the stream, several were obtained near the north and south quarter points in order to determine the distribution of fluorescent material across the stream.

RESULTS

The changes in concentration of fluorescent particles with time at station 3 are shown in figures 3–10. ("Concentration," as used in this paper, refers to the ratio of fluorescent grains to nonfluorescent grains in a particular size range.) Narrow size ranges must be considered separately because the speed of transport and rate of mixing varies with grain size.

The time scale remains the same in each figure, although the concentration scale is changed for the various grain sizes. In figures 3–5, particles ranging from

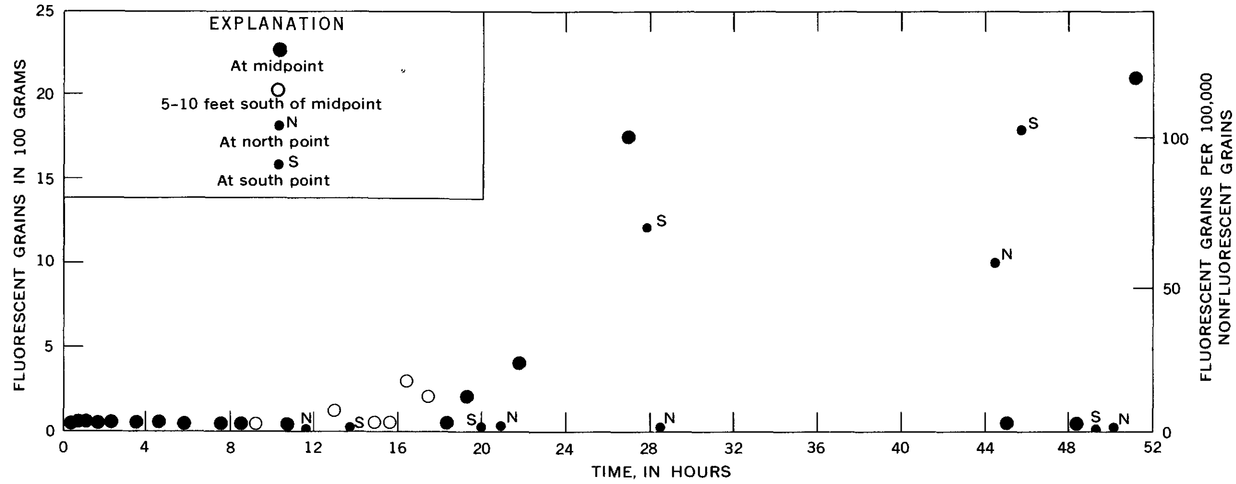

FIGURE 3.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.99–1.29 mm.

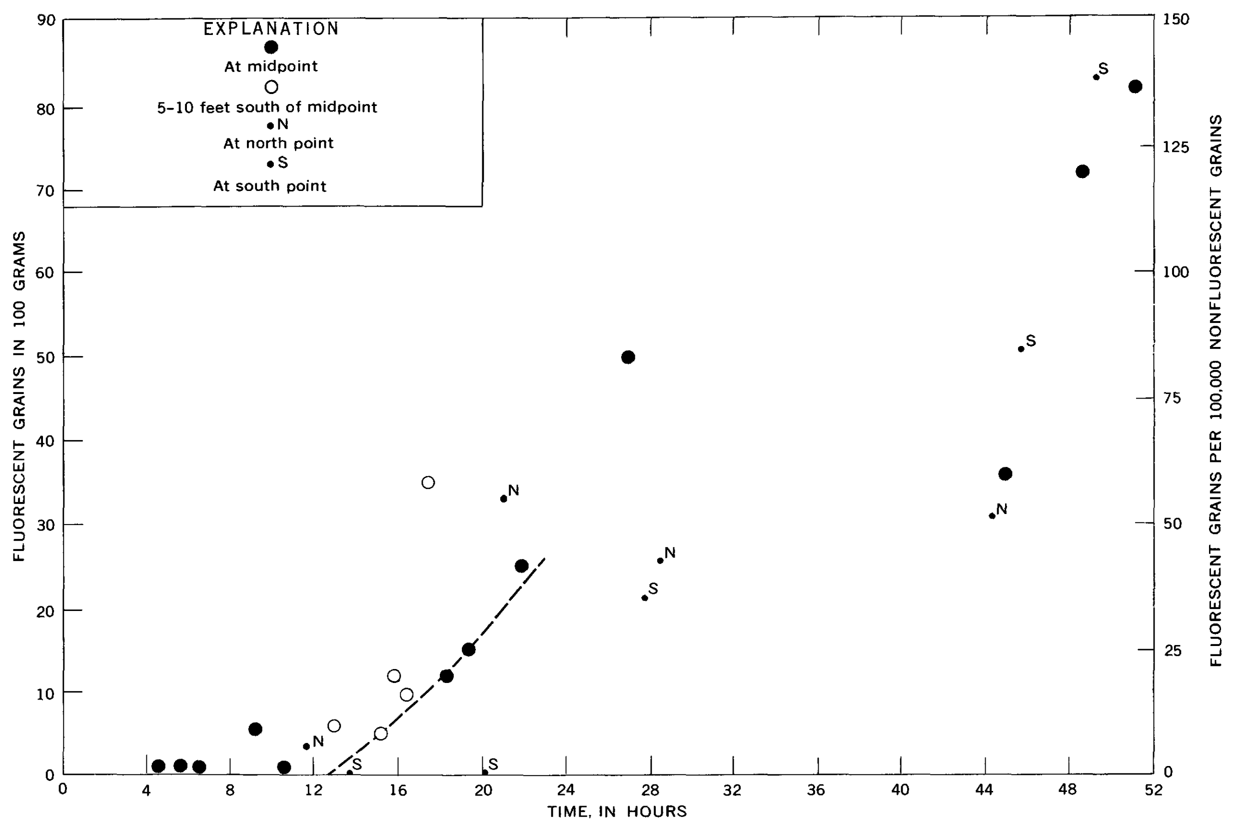

FIGURE 4.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.86–0.99 mm.

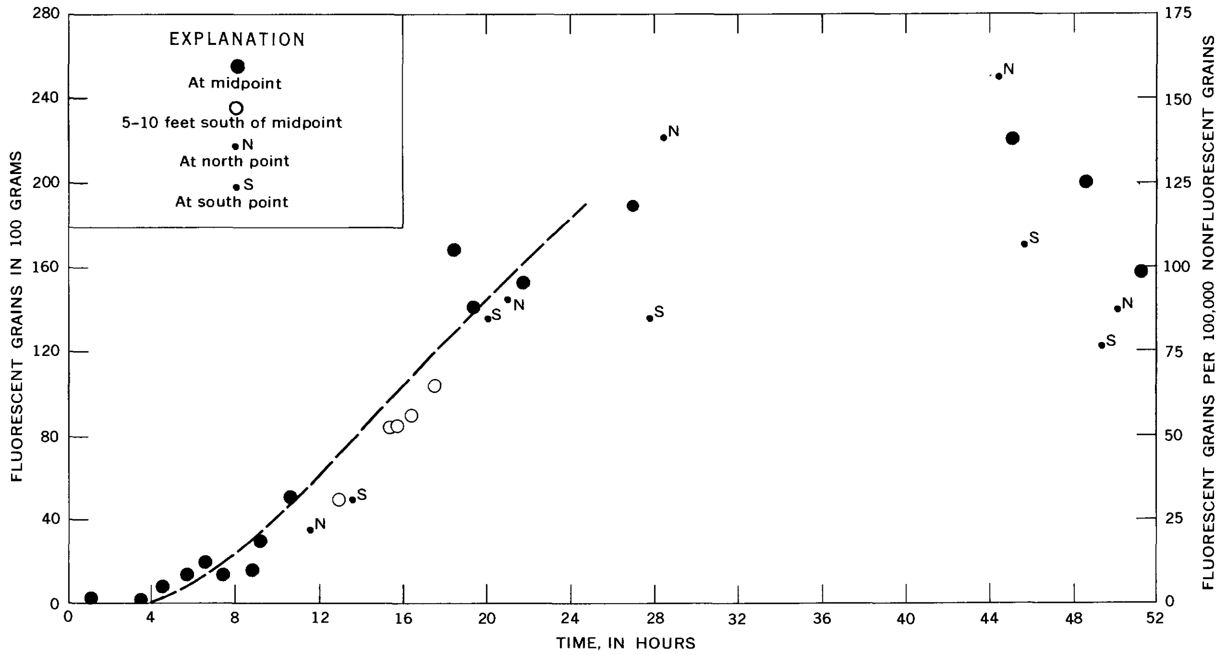

FIGURE 5.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.52–0.86 mm.

1.29 to 0.99 mm, 0.99 to 0.86 mm, and 0.86 to 0.52 mm in sieve diameter are considered. The scattering of points decreases with decreasing grain size; this is, in part at least, due to the larger number of fluorescent grains added in the finer fractions (table 1). In both the 0.86–0.99-mm and 0.99–1.29-mm size ranges, most of the samples collected contained less than 50 grams of material and less than 10 fluorescent grains. A constant plateau concentration was not achieved within the size range 0.52–1.29 mm. It should be noted (figs. 3–5) that relatively high concentrations of tracer particles in the 0.52–0.99-mm range were still present at station 3, 20 hours after tracer addition ceased.

When one examines the curves for the finer grain sizes (figs. 6–10), a tendency to reach a constant concentration is apparent, and there is generally less deviation from a smooth curve than in the curves for the coarse sand. As grain size decreases, the time required for the first arrival of tracer particles at station 3 decreases (fig. 11), and there is an increase in the rate of removal of tracer particles from the study reach after tracer addition stopped (figs. 3–10).

TABLE 1—*Average number of fluorescent grains per minute added to Clear Creek in various size fractions*

Size range (millimeters)	*Number of grains added per minute*	*Size range (millimeters)*	*Number of grains added per minute*
0. 15–0. 18	272, 000	0. 38–0. 52	76, 000
. 18– . 25	763, 000	. 52– . 86	32, 000
. 25– . 30	225, 000	. 86– . 99	4, 600
. 30– . 38	147, 000	. 99–1. 29	67

RELATION OF GRAIN VELOCITY TO GRAIN SIZE

The relation of maximum speed of movement to particle size was evaluated by plotting the time of the first arrival at station 3 against the square of the diameter of the smallest grains in a particular size fraction. The result for the 0.15–0.86-mm size range is virtually a straight line (fig. 11). The 0.86-mm material traveled at about 1.5 cm per sec (centimeters per second) or 3 feet per minute, which is $1/100$ the average velocity of the water between stations 1 and 3 and hence must have spent an appreciable part of the time on or near the stream bed. The fact that its time of first arrival lies on the same line as the finer sizes suggests that, throughout the 0.15–0.86-mm size range, the same general laws of transport may apply even though the coarser grains have spent a much greater percentage of time near or on the bed. Selection of the time of first arrival for the 0.99-mm sand is difficult because of the very few grains being transported in this size range. The point for 0.99 mm does not line up exactly with the other points in figure 11. This may be due simply to sampling error or to an actual change in the relation between grain velocity and grain size.

The fact that there is a good inverse correlation between velocity and the square of grain diameter for sand movement in Clear Creek raises the question as to whether a similar relation may exist under other conditions also. A plot of grain size versus grain velocity of beach sand was prepared by Ingle (1966, p. 158). Although the plot showed much scatter, there was a

369-125 O—70——2

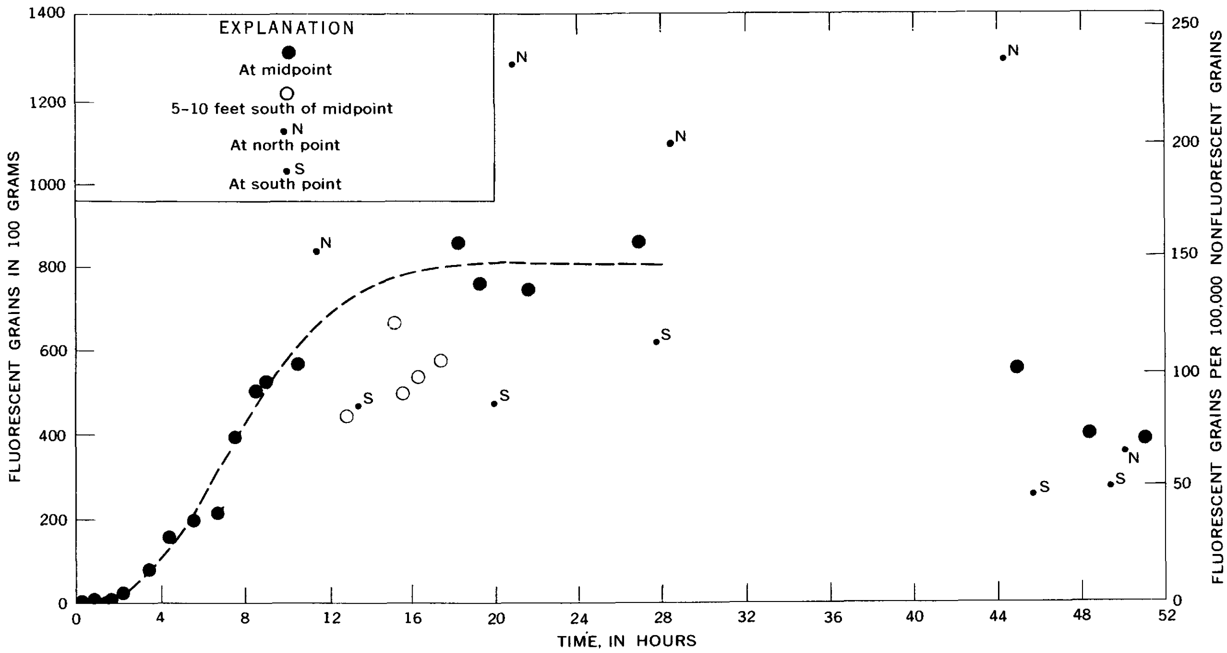

Figure 6.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.38–0.52 mm.

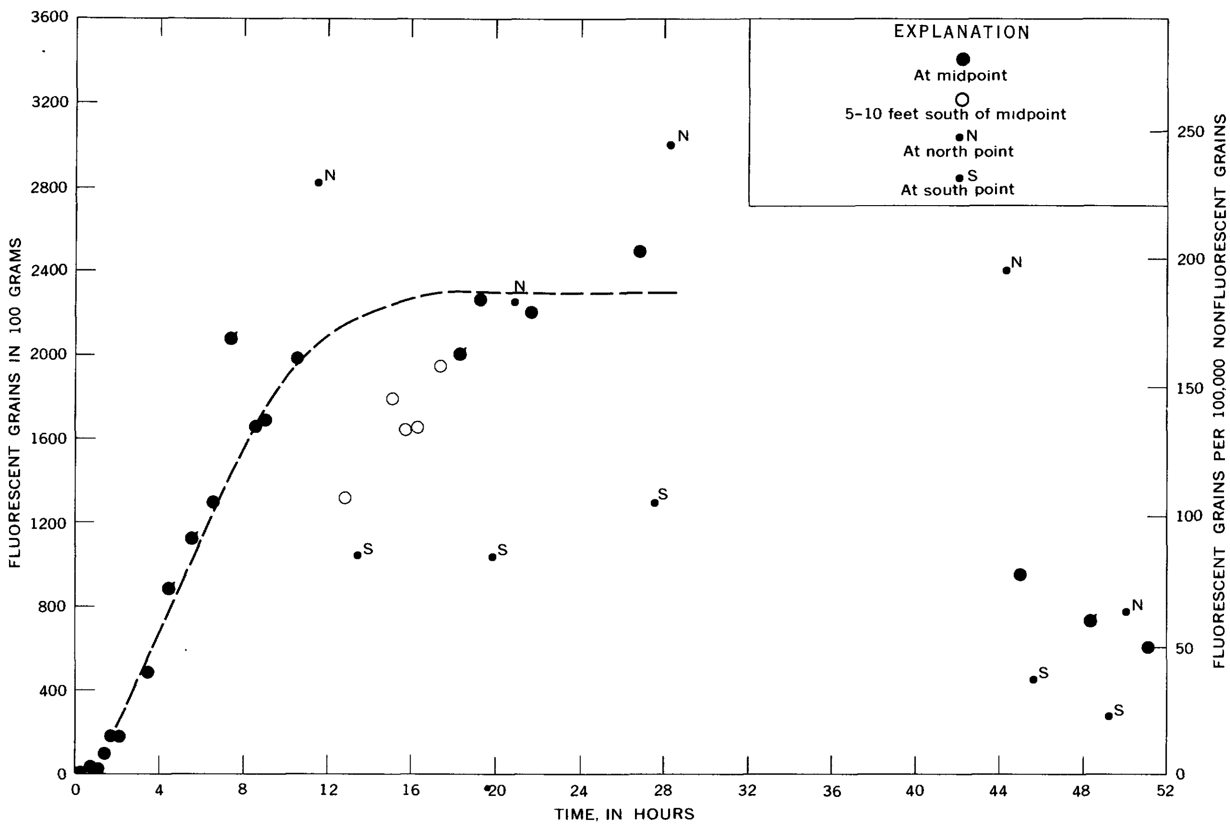

Figure 7.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.30–0.38 mm.

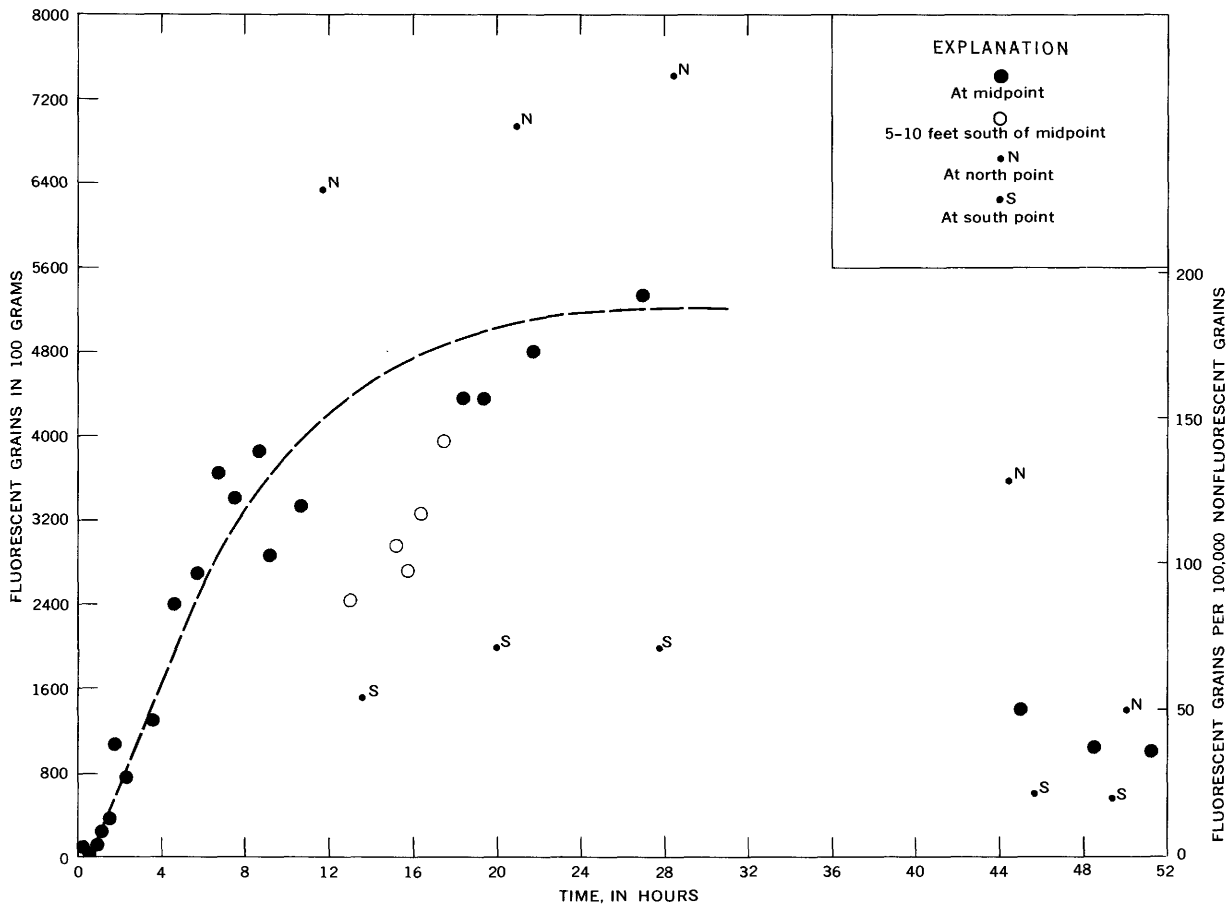

FIGURE 8.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.25–0.30 mm.

decrease in velocity with increasing grain size. Yasso (1965) found in a study of beach sand movement that sand of 0.701–0.840-mm diameter moved at an average maximum transport velocity of 2.0 cm per sec, whereas sand of 0.589–0.701-mm diameter moved at 2.8 cm per sec. Inasmuch as first arrival times were used by Yasso (1965) in calculating velocity and the finest grains in any size fraction would be expected to arrive first, a comparison of velocity with finest grain size in a size fraction is appropriate. The ratio of speed of transport of Yasso's fine sand to coarse sand was 1.40, whereas the ratio $\left(\frac{\text{diameter of coarse sand}}{\text{diameter of fine sand}}\right)^2$ is 1.42. The fact that these two ratios are virtually the same suggests that in Yasso's study also the speed of sand movement may have varied inversely with the square of grain diameter of the sand.

Because usable data are available for only two grain sizes from Yasso's study, the agreement of sand movement on the beach with sand movement in Clear Creek may be only fortuitous. Nevertheless, it seems worth while to determine whether the inverse correlation of maximum speed of movement with the square of grain diameter is characteristic of sand transport under conditions other than those present in Clear Creek.

MIXING OF FLUORESCENT GRAINS

The concentration of fluorescent particles at both stations 2 and 3 decreases from the north bank to the south bank, and this tendency becomes greater with decreasing grain size. Figure 12 shows a plot of the ratio of concentration of fluorescent grains at the north sampling point to that at the south point for sample sets taken at both stations 2 and 3 (see explanation of fig. 12 for times of sampling). It is apparent that the coarser grains are much better mixed across the stream than are the finer and that mixing improves—as one might expect—as the sediment moves downstream.

Although the points in figure 12 show a considerable amount of scatter, smooth empirical curves have been

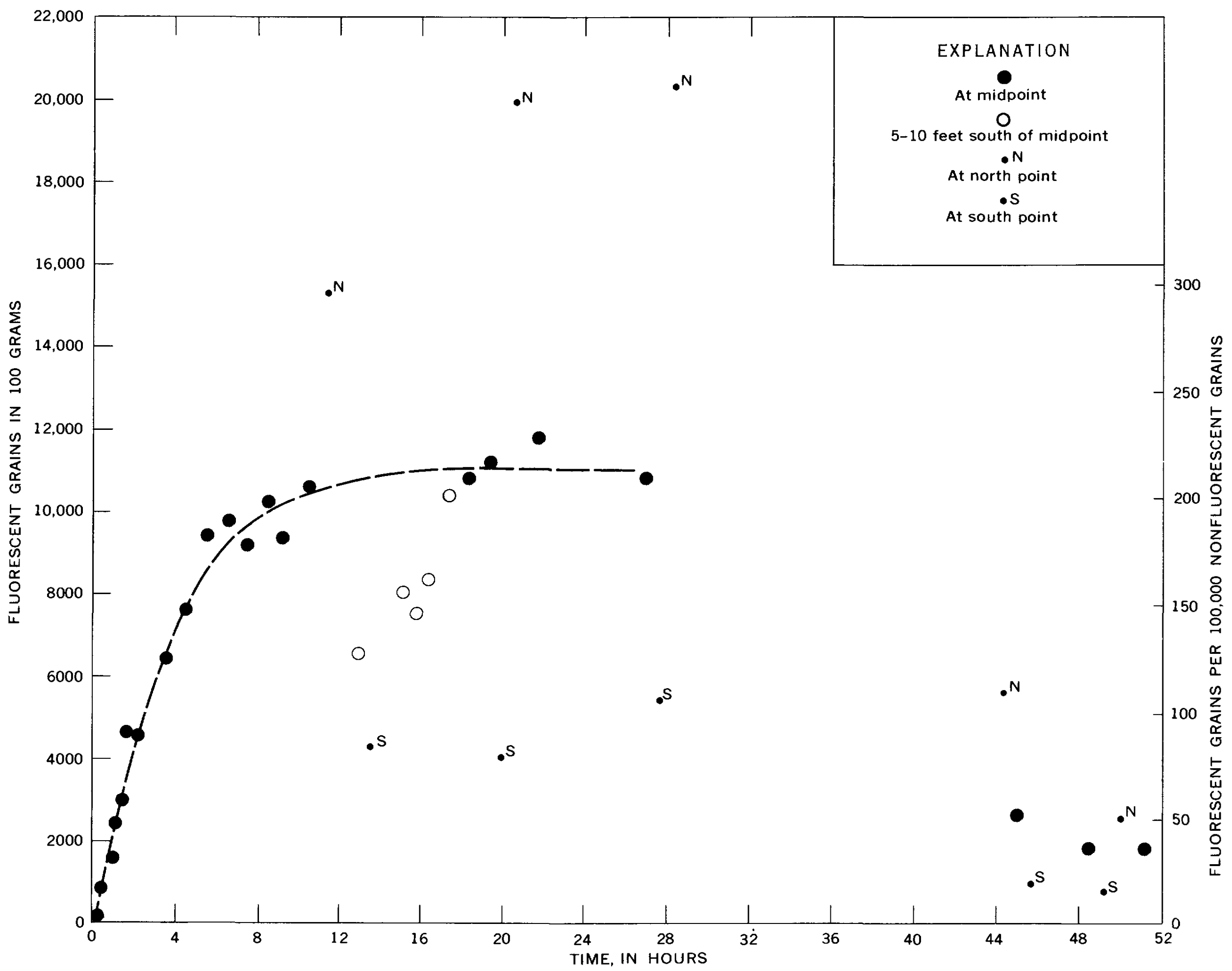

Figure 9.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.18–0.25 mm.

drawn through them that fit the equation $R=1+ae^{bD}$, where R is the ratio

$$\frac{\text{concentration of fluorescent grains on the north side}}{\text{concentration of fluorescent grains on the south side}},$$

D is grain diameter, e is the base of natural logarithms, and a and b are constants. The data at station 3 appear to follow the same equation as the data at station 2 with different values for the constants.

The available information does not suggest the nature of the curves for sizes less than 0.15 mm. However, in the empirical equation as the diameter approaches zero, the quantity e^{bD} approaches 1 and R approaches $1+a$. Thus, clay-sized particles might show an R value of about $1+a$.

It should be noted that the empirical equation appears to apply at the two cross sections sampled, but insufficient data are available to include the effect of downstream distance from the point of tracer introduction.

The fact that the coarser grains are more uniformly dispersed across the stream than the finer at station 3 is attributed to the different methods of movement. The coarse grains move near the stream bed, whereas the finer particles are more uniformly dispersed in the vertical. Although water velocities near the bed are relatively low, frequent changes of direction are necessitated by cobbles on the bed. Thus, lateral mixing is encouraged. At points higher in the vertical, there is less tortuosity in the water movement and finer grained particles there move more directly and rapidly downstream. The net result is to cause better mixing of coarse grains than fine at any specified distance below the point of tracer introduction.

Because the coarser particles move rather slowly but disperse laterally in a relatively short distance whereas the finer particles move rapidly but disperse laterally over a long distance, there is a tendency for the length of time for complete lateral dispersion to be constant regardless of grain size in a stream like Clear Creek. This suggests that two or three sampling cross sections should be located at various distances downstream from

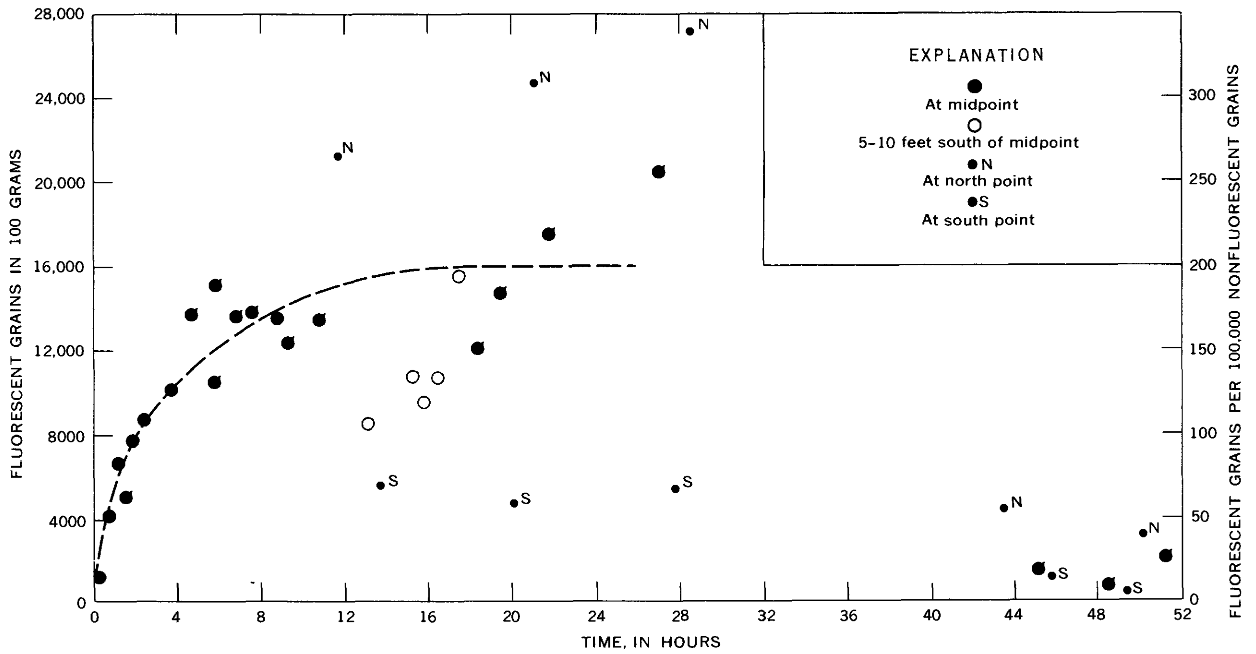

Figure 10.—Concentration of fluorescent grains at station 3 resulting from addition at station 1. Size range is 0.15–0.18 mm.

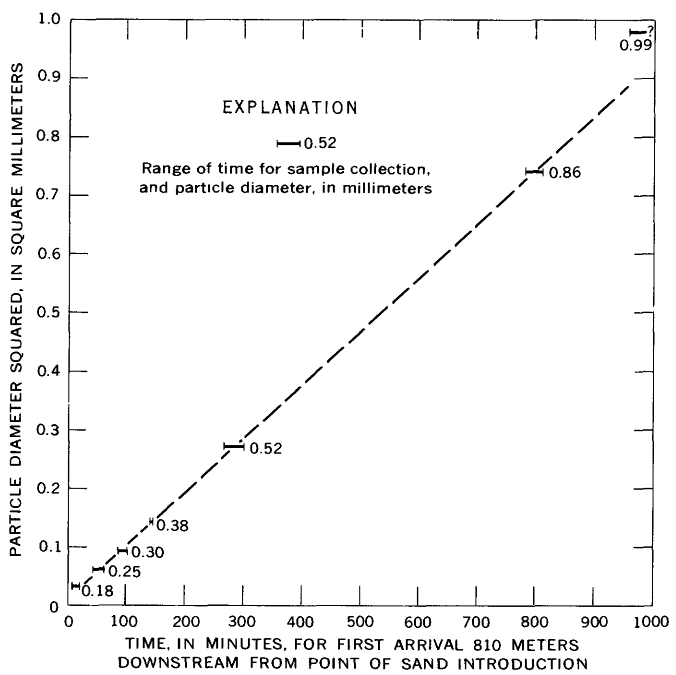

Figure 11.—Relation of traveltime to grain size for fluorescent sand in Clear Creek.

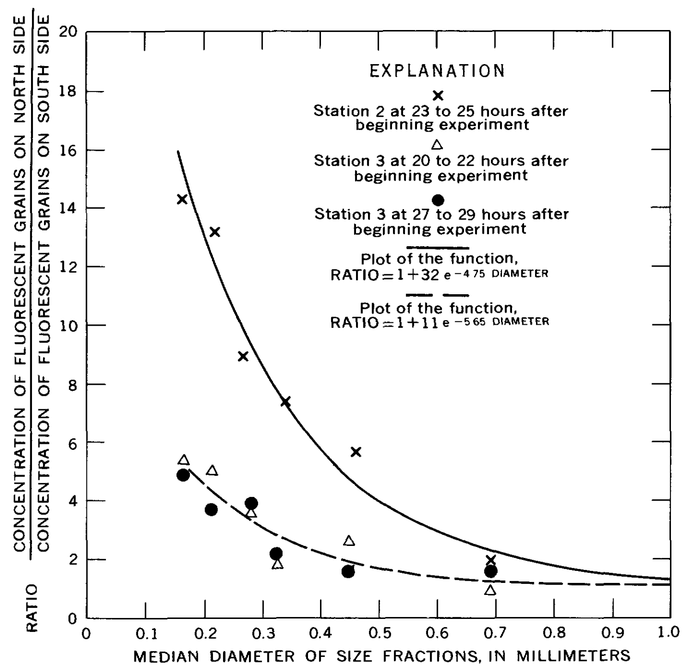

Figure 12.—Lateral mixing of fluorescent sand as related to grain size.

the point of tracer introduction. The closest cross section would be intended for study of the coarser sizes and the farthest cross section for the finest sizes. The period of sampling would be approximately the same at all cross sections.

ESTIMATION OF SEDIMENT DISCHARGE

Uniform mixing of tracer particles and constant sediment discharge are required if an accurate calculation of sediment discharge is to be made using tracer techniques. Also, the concentration of fluorescent particles at the sampling point must reach a constant value. None of these requirements were met perfectly in this study, and the lateral mixing of tracers was poor in the finer grain sizes. Nevertheless, calculations based on available data are enlightening.

Although tracer concentrations tended to be high on the north side of the stream and low on the south side, an average of the two gave concentrations close to those found for samples collected at the midpoint (figs. 6–10). Therefore, the midpoint concentrations may closely approximate those which would be found with uniform mixing.

Because water discharge decreased 11 percent during the first 28 hours of the experiment, it is probable that sand discharge decreased also. The suspended-sediment concentrations mentioned previously suggest this, but the concentration curve of fluorescent particles (fig. 9) for the 0.18–0.25-mm size range indicates in that size range the sand discharge was for the most part constant. If the sand discharge had decreased gradually during the experiment, the degree of tracer dilution would have been reduced and tracer concentration slowly increased.

For purposes of calculation it has been assumed (1) that the tracer concentrations found at the midpoint at station 3 are the same as those that would be found with uniform mixing and (2) that the error due to changing sediment discharge is small compared to other possible errors in the experiment. The remaining requirement, that is, that the concentration of tracer particles at the sampling point reach a constant value, was apparently achieved for some size fraction and not for others.

The apparent "plateau" or constant concentrations are shown by dashed lines in figures 6–10 and are used in calculating the sediment discharge in the various size ranges. The results of such calculations are given in table 2 and also in figure 13 as a cumulative curve.

The sediment discharge in each size fraction is measured independently in the fluorescent-tracer method, so the fact that a smooth curve results from combining the discharge data for several individual fractions suggests that there is at least internal consistency between the discharge estimates.

The sediment discharge calculated from depth-integrated samples is compared with that estimated by fluorescent-tracer measurements in table 2 and figure 13. Although the depth-integrating method measures only suspended load whereas the fluorescent method measures total load in the tracer size range, a comparison was made between them because no accepted reference method was available for this type of stream.

In the finer grain sizes one would expect the depth-integrating and fluorescent methods to agree, but in the coarser sizes which move near the bed, poorer agreement would be expected, and such is the case.

TABLE 2.—*Comparison of sediment discharge in Clear Creek calculated from depth-integrated samples and fluorescent-sand measurements*

Sediment Discharge (metric tons per day)			
Size range (millimeter)	From depth-integrated samples (A)	From "dilution" of fluorescent sand (B)	Ratio B/A
0. 15–0. 18	1. 9	2. 5	1. 3
. 18– . 25	7. 9	10. 0	1. 3
. 25– . 30	3. 5	6. 3	1. 8
. 30– . 38	4. 2	8. 8	2. 1
. 38– . 52	5. 9	13. 7	2. 3

The use of a flow-through trap to collect stream sand in transport inevitably resulted in a tendency to concentrate more heavy minerals than light ones. This tendency is most evident in the finest size particles caught in the trap. In one set of samples, minerals heav-

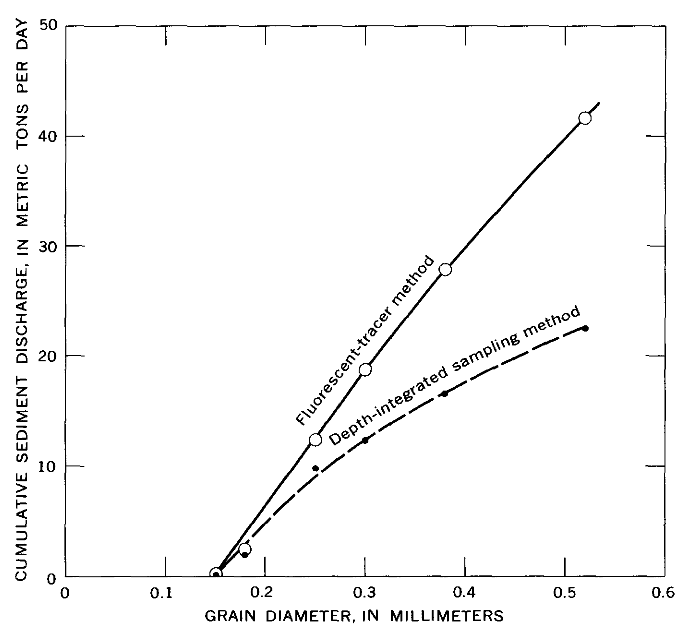

FIGURE 13.—Sediment discharge in relation to grain size as determined by depth-integrated sampling and the fluorescent-tracer method.

ier than bromoform (sp gr=2.9) were found to comprise 10.2 and 7.7 percent of the 0.15–0.18-mm and 0.18–0.25-mm size ranges, respectively. If it is assumed that no more than about 1 percent heavy minerals would be present in an unsorted sample of any size fraction of stream sand in Clear Creek, based on an estimate by Pettijohn (1957, p. 129) of heavy minerals in rocks, the revised estimate of sediment discharge from fluorescent-sand measurements would be 2.2 metric tons (2.4 tons) per day for the 0.15–0.18-mm size range and 9.4 metric tons (10.3 tons) per day for the 0.18–0.25-mm size range. This brings the estimates of sediment discharge for the 0.15–0.18-mm size fraction by the two methods to within about 15 percent of each other. The possible errors in the two methods of measuring sediment discharge as used here may be greater than 15 percent; therefore, one method can be said to provide an approximate check on the other for this particular size range.

EXPERIMENT WITH BATCH ADDITION

The method of continuous addition used in this experiment requires that sediment discharge remain constant long enough for the fluorescent material to mix thoroughly in the stream cross section and also attain a constant concentration at some downstream sampling point. If the stream is narrow and turbulent enough for rapid lateral mixing (vertical mixing is assumed to be very rapid), these requirements may be met in a reasonable time and distance. However, in many streams these requirements probably will not be met, and constant concentrations at the sampling site will not be achieved before the sediment discharge changes significantly.

One possible way to reduce the effects of varying sediment discharge is to add one color of fluorescent sand (color A) at a constant known rate and also a series of different colors (colors B, C, D, E, etc.) of the same size in batches at perhaps 6–12-hour intervals. When batch material of color B is dumped into the stream, it will label the sand passing the introduction point at time *T* and, when half of that batch (or perhaps the peak concentration, as a rough approximation) has passed the sampling point downstream, the dilution factor of color A would then yield an estimate of the sediment discharge at time *T* at the point of tracer introduction (assuming thorough lateral mixing). A series of such time points should permit the calculation of sediment discharge at intermediate times by interpolation using concentrations of color A. If the amount of material in the batches were known and the concentration of color A remained constant for a suitable length of time, the sediment discharge could also be calculated from the area under the time-versus-concentration curve for colors B, C. D, etc. This multiple-color technique would be most applicable under circumstances where longitudinal dispersion was minimal.

To determine the character of the time-concentration curve resulting from batch addition to Clear Creek, an unmeasured amount of blue fluorescent sand of nominal diameter 0.30–0.52 mm was introduced 4 hours and 16 hours after continuous introduction of the red, green, and yellow sand was started. Figure 14 shows the resulting concentration-versus-time curves.

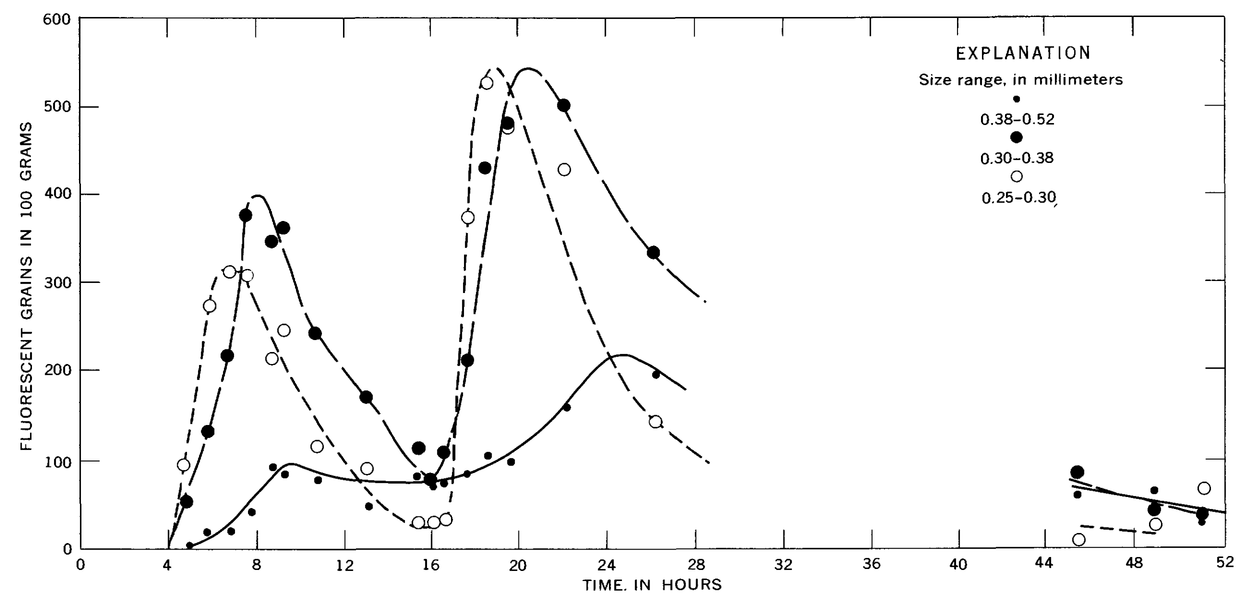

FIGURE 14.—Variation in concentration of 0.25 to 0.52-mm blue fluorescent sand at station 3 after batch addition at station 1.

Although the size fraction used was supposed to have had grains less than 0.30 mm removed, some still remained owing to incomplete sieving. Thus, the 0.25–0.30-mm material undoubtedly had a size distribution skewed far toward 0.30 mm with a median diameter of perhaps 0.29 mm.

Table 3 summarizes the relation of grain size to peaking time after introduction. The data suggest that there may be an inverse correlation between the square of grain diameter and the time for the peak concentration to move downstream to the sampling point.

TABLE 3.—*Time to reach peak concentration of blue grains at station 3 as related to grain diameter*

Size fraction (mm)	Median diameter (mm)	Median diameter squared (mm^2)	Time for concentration curve to peak (min)		Ratio B/C
			Range	Average	
	(A)	(B)		(C)	
0.25–0.30	0.29	0.084	150–160	155	0.54
.30– .38	.34	.116	240–270	255	.46
.38– .52	.45	.202	330–480	405	.50

ESTIMATION OF SEDIMENT IN ACTIVE STORAGE WITHIN A REACH

The shape of the concentration-versus-time curve (fig. 9, for example) can be helpful in estimating the amount of sediment in active storage within the study reach. (Active storage refers to the sediment within the study reach which is moving on the bed or in suspension.) When a constant concentration has been achieved at the sampling station for a particular size fraction, one can assume that, for the size fraction, the concentration of fluorescent sand in sediment moving on the bed is the same as that in suspension. If this is so, and one extends a horizontal line from the constant concentration back to zero time, an area the shape of an inverted trapezoid or distorted triangle will be enclosed to the left of the rising concentration curve. This area is a measure of the amount of fluorescent sand that went into active storage in the study reach before a plateau concentration was achieved. Knowing the amount of fluorescent sand in active storage and its concentration there, one can compute the amount of nonfluorescent sand in active storage.

For a gravel-bed stream it is apparent that a lot of sand cannot be in active storage unless the stream is very turbulent and suspended-sand concentrations are very high. Clear Creek is moderately turbulent but has a low concentration of suspended sand; therefore, one would expect relatively small amounts of sand in active storage there. The calculated sand in active storage in a ½-mile reach of Clear Creek is given in table 4. The amounts are rather small.

In a sand-bed stream, on the other hand, the quantity of sand moving in dunes on the bed may be very large, and this technique should be helpful in estimating the amount of sand in active storage in such streams.

If one can calculate the quantity of sand in active storage in a reach and knows the area of the reach, then the average depth of moving sand can be estimated (assuming that all the sand is moving on the bed). The average thickness for various grain sizes was found to be less than 1 grain diameter in Clear Creek (table 4). In other words, if all the moving sand grains were rolling along the bed, only a fraction of the bed would be covered with sand. In fact, there was relatively little sand on the bed of Clear Creek; material on the bed was composed mainly of particles larger than sand.

One assumption implicit in the above discussion is that no significant amount of tracer material is lost by "permanent" deposition on the bed. If this is not so, the estimate of sediment in active storage will be too high. In any case, this estimate of sediment in active storage will be only a gross approximation unless (1) the length of reach required for complete lateral dispersion is small compared with the length of reach above the sampling point in which lateral dispersion is complete, or (2) the sediment discharge per unit width is virtually uniform across the stream and an average tracer concentration across the sampling section is used.

The fact that complete lateral mixing did not occur within the study reach on Clear Creek means that the calculated figures are somewhat in error.

TABLE 4.—*Sediment in active storage in Clear Creek*

Size range (millimeters)	Sand in active storage (metric tons)	Maximum depth of sand moving on the bed (millimeters)
0.15–0.18	0.3	0.01
.18– .25	1.4	.07
.25– .30	1.5	.07
.30– .38	2.5	.11
.38– .52	4.6	.21

OTHER POSSIBLE USES FOR FLUORESCENT SOLIDS IN STREAM STUDIES

The effects of specific gravity on sediment transport can be evaluated by coating particles of different specific gravities with various colored paints and determining their relative speed of transport. Of course, the sieve size and shape would have to be held as nearly constant as possible for the particles of various specific gravities.

An attempt to do this was made in the present study, but the heavy particles used were magnetic grains removed by electromagnet from Clear Creek sand, and they ranged from a few percent to 100 percent magnetite or high-iron ilmenite. The remainder of these multigranular magnetic particles were commonly composed of quartz or feldspar, thus giving a wide range of actual specific gravities. The results, therefore, were quite unsatisfactory.

Shape effects can also be evaluated using an approach similar to that proposed for determining the effects of specific gravity.

Yet another potential use of fluorescent sand is that of determining the depth of scour in a stream bed during a rise. If fluorescent sand equal in size to the median diameter of the bed material were added continously at a point upstream from the area of interest, the sediment in transit would be labeled with fluorescent particles. As discharge decreased the labeled sediment would be deposited on the bed. After the flow had subsided, one could take cores of the bed sediment and determine the maximum depth of scour by examining the cores under ultraviolet light. In addition, if one added a series of colors in sequence during the time of decreasing discharge, different colored layers of sand would result showing the approximate time during which "permanent" deposition on the bed occurred.

CONCLUSIONS

An experiment conducted in Clear Creek at Golden, Colo., showed that the maximum speed of transport of fluorescent sand-sized particles added steadily to the stream correlated inversely with the square of the grain diameter under conditions where sand was being transported by turbulent water above a gravel bed.. There is a suggestion that the modal speed of transport of sand added to the stream in batches may show a similar relation to grain size. Lateral mixing improved with increasing grain size. Although complete lateral mixing of fluorescent particles did not occur, an estimate of sediment discharge by the fluorescent-tracer method for medium to fine sand showed reasonable agreement with sediment discharge calculated from depth-integrated samples after the differences inherent in the two methods were taken into consideration.

The results of this study suggest that much more effort could be profitably devoted to the use of fluorescent tracers in studies of sediment movement in the fluvial environment.

REFERENCES CITED

Aybulatov, N., Boldyrev, V., and Griesseier, H., 1961, Das studium der sedimentbewegung in flussen und meeren mit hilfe von lumineszierenden farbstoffen und radioactiven isotopen: Petermann's Geog. Mitt. 1. 105, no. 3, p. 177–186; no. 4, p. 254–263.

Bruun, P., 1965, Quantitative tracing of littoral drift, *in* Fed. Inter-Agency Sedimentation Conf., 1963, U.S. Dept. Agr. Misc. Pub. 970, p. 756–765.

Clayton, C. G., and Smith, D. B., 1963, A comparison of radioisotope methods for river flow measurements, *in* Radioisotopes in Hydrology: Vienna, Internat. Atomic Energy Agency, p. 1–24.

Cummins, R. S., Jr., and Ingram, L. F., 1965, Use of radioisotopes in sediment transport studies, *in* Fed. Inter-Agency Sedimentation Conf., 1963: U.S. Dept. Agriculture Misc. Pub. 970, p. 578–592.

DeVries, M., 1966, Applications of luminophores in sand transport studies: Delft Hydraulic Lab., Delft, The Netherlands. Pub. 39.

Glazov, N. V., and Glazov, A. N., 1959, New Instruments and methods of engineering geology: New York, Consultants Bureau, 91 p.

Hubbell, D. W., and Sayre, W. W., 1964, Sand transport studies with radioactive tracers: Jour. Hydraulics Div. Am. Soc. Civil Engineers, v. 90, no. HY3, p. 39–68.

Ingle, J. C., Jr., 1966, The movement of beach sand: New York, Elsevier Pub. Co., 221 p.

Kidson, C., and Carr, A. P., 1962, Marking beach materials for tracing experiments: Jour. Hydraulics Div. Am. Soc. Civil Engineers, v. 88, No. HY4, pt. 1, p. 43–60.

Krone, R. B., Einstein H. A., Kaufman, W. J., and Orlob, G. T., 1960, Methods for tracing estuarial sediment transport processes: California Hydraul. Eng. Lab. and Sanitation Eng. Research Lab., 57 p.

Lean, G. H., and Crickmore, M. J., 1963, Methods for measuring sand transport using radioactive tracers, *in* Radioisotopes in Hydrology: Vienna, Internat. Atomic Energy Agency, p. 111–131.

——— 1966, Dilution methods of measuring transport of sand from a point source: Jour. Geophys. Research, v. 71, No. 24, p. 5843–5855.

Pettijohn, F. J., 1957, Sedimentary Rocks: New York, Harper Bros., 718 p.

Russell, R. C. H., 1961, The use of fluorescent tracers for the measurement of littoral drift: Coastal Eng. Conf., 7th, The Hague, Netherlands, August 1960, Proc., p. 418–444.

Teleki, P. G., 1965, A summary of the production and scanning of fluorescent tracers, *in* Fed. Inter-Agency Sedimentation Conf. 1963: U.S. Dept. Agriculture Misc. Pub. 970, p. 765–768.

——— 1966, Flourescent sand tracers: Jour. Sed. Petrology, v. 36, no. 2, p. 468–485.

U.S. Inter-Agency Committee on Water Resources, 1952, The design of improved types of suspended sediment samplers: Washington Govt. Printing Office, Rept. 6.

——— 1963, Determination of fluvial sediment discharge: Washington Govt. Printing Office, Rept. 14.

Yasso, W. E., 1962, Fluorescent coatings on coarse sediments: An integrated system: U.S. Navy, Office of Naval Research, Geography Br., Project NR 388–057, Tech. Rept. 1, 29 p. (Columbia Univ. Dept. Geology).

——— 1965, Fluorescent tracer particle determination of the size velocity relation for foreshore sediment transport, Sandy Hook, New Jersey: Jour. Sed. Petrology, v. 35, no. 4, p. 989–993.

Zenkovitch, V. P., 1958, Emploi des luminophores pour l'étude du mouvement des alluvions sablonneuses: Inf. Comité Cent. Océanographie Étude des Cotes, Bull. 10, p. 243–253.