Relationship of Unmeasured Sediment Discharge to Mean Velocity

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Abstract—Unmeasured sediment discharges were computed by subtracting the measured suspended-sediment discharges at alluvial sections from total sediment discharges that had been either measured at nearby contracted sections or computed from the modified Einstein procedure. Average curves show a general increase of unmeasured sediment discharge per foot of stream width as a function of about the third power of the mean velocity. At constant mean velocity the unmeasured sediment discharge per foot of width generally increases with concentration, especially with suspended sands concentration adjusted for depth of stream. Such adjusted concentrations of suspended sands seems to be reasonably good measures of the availability of sands. This availability is the relative rate of transport of sands for a given condition of flow and is related to particle sizes and cohesiveness of sediments of the stream bed and banks. Relationships of unmeasured sediment discharge to mean velocity and to concentration can be applied successfully in several kinds of sediment computations.

Introduction—The rate of suspended-sediment discharge of a stream is usually based on an average of the concentrations of depth-integrated samples of suspended sediment for each of several verticals in a cross section. This average concentration is multiplied by the rate of water discharge and by a conversion factor to obtain the suspended-sediment discharge in tons per day or in other suitable units. Thus, the measured suspended-sediment discharge is computed from all the flow through the cross section but from less than the true average suspended-sediment concentration, because depth-integrating samplers do not normally collect water-sediment mixture within three to five inches of the stream bed, and suspended-sediment concentrations are highest near the bed. The difference between the total sediment discharge of a stream and the measured sediment discharge may be termed the unmeasured sediment discharge. The unmeasured sediment discharge consists of bed-load discharge (the discharge of sediment that moves along in essentially continuous contact with the bed of the stream) and part of the suspended sediment that is discharged below the lowest point of travel of the sampler nozzle in the vertical. The ratio of the sediment discharge through the sampled zone to the total sediment discharge has been discussed by *Chien* [1952].

This paper points out relationships to mean velocity of different factors that determine the unmeasured sediment discharge and gives empirical relationships for computing unmeasured sediment discharge from mean velocity and concentration of suspended sediment. In general, the theoretical relationships and many of the assumptions that were stated by *Einstein* [1950] are followed in the paper.

Unmeasured sediment discharge—For simplicity, the unmeasured sediment discharge and its theoretical relationship to mean velocity are discussed, as much as possible, in terms of water and sediment discharge per unit of stream width and for one range of particle sizes.

The unmeasured sediment discharge per unit width can be expressed by

$$q_{us} = i_B\, q_B - k c_m\, q_{uw} + k \int_{2D}^{a} c_y\, \bar{u}_y\, dy \qquad (1)$$

in which q_{us} is the unmeasured sediment discharge of particles in the size range for which the geometric mean size is D

- i_B is the fraction of bed load in the size range
- q_B is the rate of bed-load discharge per unit time and unit width
- k is a conversion constant
- c_m is the concentration from depth-integrated samples of sediment of the given size range
- q_{uw} is the water discharge through the unsampled zone
- a is the distance from the stream bed to the lowest position of the sampler nozzle in the vertical during sampling
- c_y is the suspended-sediment concentration of particles of the size range at a point in the vertical
- $\bar{u}_y$ is the time-averaged velocity at the point
- y is the distance of the point above the stream bed

The two positive terms on the right-hand side of (1) are for bed-load discharge and for total discharge of suspended sediment through the unsampled

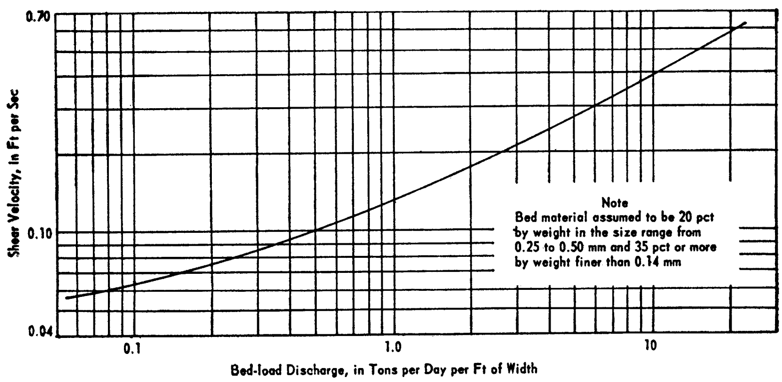

FIG. 1 – Relationship of shear velocity to rate of bed-load discharge of particles from 0.25 to 0.50 mm

zone. The negative term represents that part of the suspended-sediment discharge that occurs through the unsampled zone but is computed in the measured suspended-sediment discharge. Sediment particles finer than sands (< 0.062 mm) are nearly uniformly distributed throughout the vertical, and the unmeasured increment of these fine sediments is usually negligible. Hence, (1) will be discussed for a range of particle sizes within the limits of sand sizes, a size range for which unmeasured sediment discharge is significant.

Theoretical relationships to mean velocity—The different parts of the right-hand side of (1) are shown in the following discussion to be functions of mean velocity, but they vary somewhat with other factors.

According to *Einstein* [1950], the rate of bed-load discharge, $i_B q_B$, depends principally on the product of the surface slope of the stream and the hydraulic radius with respect to the sediment particle but varies with other parameters. *Colby* and *Hembree* [1955, pp. 83–89] simplified the computation and made the bed-load discharge per unit width and for a given geometric mean size of particles having a specific gravity of 2.65, expressible as one of two possible functions of the shear velocity. The physical significance of this computed bed-load discharge is somewhat uncertain. The function to be used depends on whether the geometric mean particle size is larger or smaller than 2.5 times the particle size for which 35 pct of the bed material by weight is finer. The curve for bed-load discharge per foot of width as a function of shear velocity is shown on Figure 1 for sediment in the size range from 0.25 to 0.50 mm (geometric mean size is 0.35 mm) and for bed material of which 20 pct by weight is in this size range. The curve is approximately applicable only if D_{35} is equal to or less than 0.14 mm. The other of the two functions is used if D_{35} exceeds 0.14 mm. The bed-load discharge changes rapidly with changes in the shear velocity.

The shear velocity u_* for the curve of Figure 1 was computed from the measured mean velocity $\bar{u}$ in the cross section and from a velocity equation [*Keulegan*, 1938, pp. 707–741] in the form

$$\bar{u}/u_* = 5.75 \log_{10} (12.27\, d/\Delta) \qquad (2)$$

in which d is the depth and Δ is the apparent roughness. The ratio of mean velocity to shear velocity varies directly with the logarithm of the ratio of 12.27 times the depth to the apparent roughness and hence changes slowly with changes in the latter ratio. That is, the mean velocity is roughly proportional to the shear velocity. (The number 12.27 is for the cross section of a natural stream. Integration of (3), below, throughout the depth of a stream gives about 11.1.) Although some assumptions and approximations are involved in the relationship of Figure 1, the large effect of shear velocity and hence of mean velocity on the rate of discharge of sediment as bed load is evident.

Discharge of suspended sands of a given size range through the unsampled zone $kc_m q_{uw}$ (from depth-integrated measurements) varies with mean velocity. Figure 2 shows a rough correlation of measured concentration of suspended sands with mean velocity for the gaging-station section of the Niobrara River near Cody, Nebr. In general, the concentration of measured suspended sands increases at this section with about the 2.1 power of the mean velocity. This type of relationship can be expected to hold reasonably well for a particular cross section of an alluvial stream. The slope of the relationship curve may be much the same from one stream to another. However, the concentration

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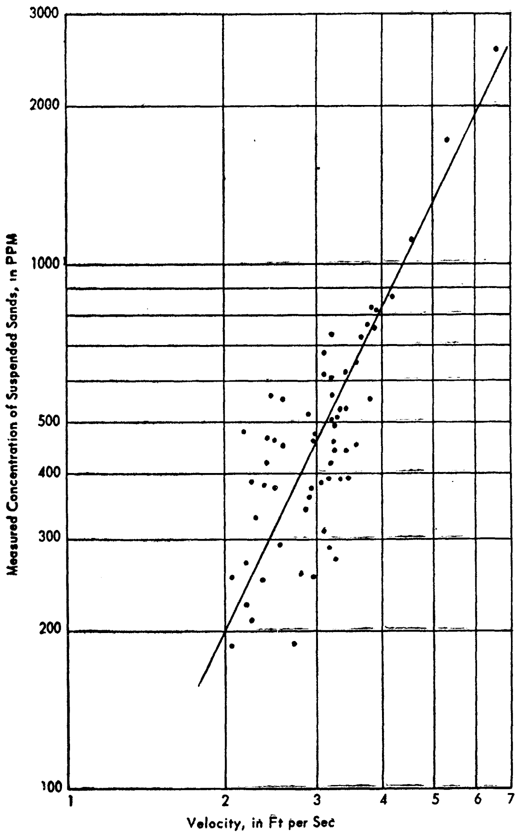

FIG. 2 – Relationship between concentration of suspended sand and mean velocity, Niobrara River near Cody, Nebr.

of suspended sands at a given velocity is likely to differ appreciably from one stream to another because size distributions and quantities of sands that are available for transport differ widely.

The other variable that determines the measured discharge of suspended sediment through the unsampled zone is the flow q_{uw} through that zone. This flow per unit width of channel is the product of the average velocity through the unsampled zone and the height $(a - 2D)$ of the zone. The height of the zone is relatively constant, and the theoretical average velocity in the unsampled zone is obtained by integrating an equation for velocities at a point such as (3), the same equation that would be integrated to compute mean velocity for the entire vertical. Therefore the average velocity through the unsampled zone should be about proportional to the mean velocity for the entire vertical except for the effect of changes in the ratio of depth of the water to depth of the unsampled zone.

The suspended-sediment discharge, $k \int_{2D}^{a} c_y \bar{u}_y dy$, of particles of a given size range through the unsampled zone is also largely a function of mean velocity. The limits of integration are usually much the same for all cross sections but vary somewhat with particle size and with the type of sediment sampler and method of using it. Both velocity and concentration at points in the vertical within the unsampled zone are functions of mean velocity.

Equ. (2) was derived from (3), below, for time-averaged point velocity $\bar{u}_y$

$$\bar{u}_y/u_* = 5.75 \log_{10} (30.2\ y/\Delta) \tag{3}$$

or

$$\bar{u}_y = 5.75\ u_* (\log_{10} 12.27 + \log_{10} d - \log_{10} \Delta$$

$$+ \log_{10} 30.2 + \log_{10} y - \log_{10} 12.27 - \log_{10} d)$$

which combines with (2) to give

$$\bar{u}_y = \bar{u} + 5.75\ u_* \log_{10} (2.46\ y/d) \tag{4}$$

According to this equation, the velocity at a point is equal to the mean velocity in the vertical plus or minus a quantity that varies with shear velocity and with relative distance of the point above the stream bed.

The concentration c_y at a point in the vertical in the unsampled zone depends jointly on the measured concentration c_m and on the vertical distribution of concentration and is, therefore, closely, but complexly, related to mean velocity. The measured concentration of suspended sands has already been shown (Fig. 2) to be related to mean velocity. The vertical distribution of concentration for particles of a given size range has an exponential measure z which can be computed by trial and error from the rate of bed-load discharge and from the product of measured concentration for the size range, depth of the sampled zone, and mean velocity in the sampled zone. An alternative computation bases z on the fall velocity of the sediment particles and on the shear velocity. Whichever method of computation is used, the vertical distribution of sediment concentration is a function of mean velocity but also varies with water temperature, stream depth, and channel roughness.

The different terms in the right-hand side of (1) are thus individually related to the mean velocity, but the relationships are complicated even for one range of particle sizes. Hence, a theoretical method of computing unmeasured sediment discharge from relationships to mean velocity and to other factors becomes difficult and usually requires extensive

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field data. Simpler relationships, which, although only approximate, may be satisfactorily accurate for many uses, can be defined empirically.

Empirical relationships—About 180 experimental determinations of unmeasured sediment discharge at a normal section were readily available. Each determination was the difference between measured sediment discharge at a total-load section and at a normal section. By 'total-load section' is meant a contracted section at which practically the total sediment discharge of the stream is in suspension and can be sampled satisfactorily with a depth-integrating sampler. By 'normal section' is meant a section at which nearly all the stream bed and sometimes the banks, too, are of readily shifting alluvium. Unmeasured sediment discharges divided by the width of the normal section are plotted on Figure 3 against mean velocity at the normal section. Individual points scatter widely from the curve, but the unmeasured sediment discharge increases on the average with about the third power of the mean velocity. The equation for computing the unmeasured sediment discharge Q_{um} of all particle sizes in tons per day from the average curve is

$$Q_{um} = 0.28\ (\bar{u})^{3.1}\ w \qquad (5)$$

in which $\bar{u}$ is the mean velocity in the cross section in feet per second, and w is the width in feet. Within the limits of its experimental definition, this equation is roughly applicable to the computation of unmeasured sediment discharge at a cross section.

As implied in the preceding paragraph, the curve of Figure 3 is intended to show the average unmeasured sediment discharge for given mean velocities. Therefore, it was drawn through arithmetic averages of the unmeasured sediment discharges for each of several ranges of mean velocity. The other curves in this paper were likewise drawn through arithmetic averages of the dependent variable. The curve of Figure 3 is entirely unsuited for the estimating of mean velocity from unmeasured sediment discharges. It differs considerably from a least-squares curve as ordinarily drawn because the slope of such a curve would depend not only on the average unmeasured sediment discharges for given ranges of mean velocity but also on the total range of velocities that are covered by Figure 3.

The plotting of points on Figure 3, especially points for Fivemile Creek, seems to indicate that the unmeasured sediment discharge may be higher

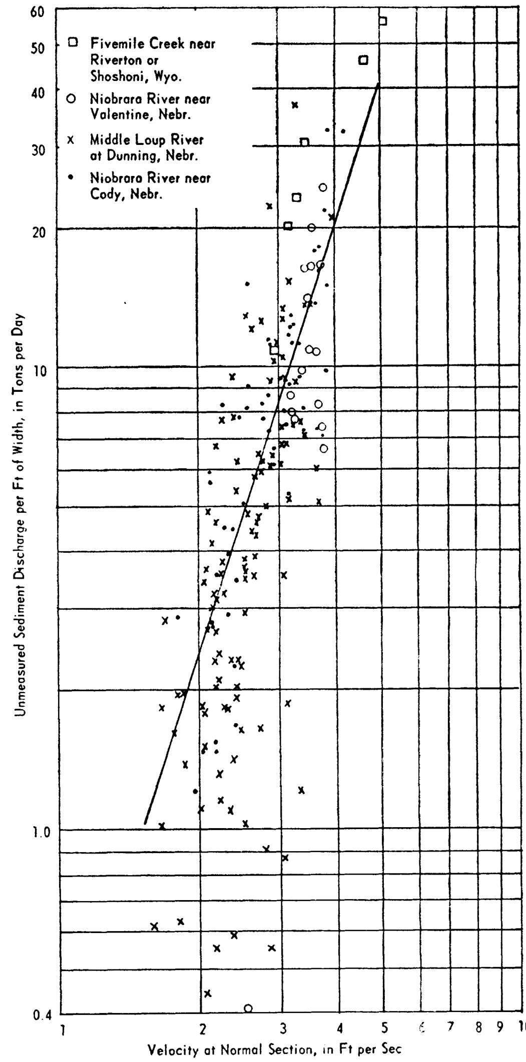

FIG. 3 – Relationship between unmeasured sediment discharge and mean velocity

for a given velocity if the suspended-sediment concentration is high. Hence, ratios, called ratios of departure, were computed for the points on Figure 3. Each ratio was the quotient that was obtained by dividing an experimental determination of unmeasured sediment discharge per foot of width by the unmeasured sediment discharge per foot of width as indicated by the mean velocity and the curve of Figure 3. The ratios were then plotted (Fig. 4) against the mean concentrations of depth-integrated samples at the normal sections to see whether some of the scatter of individual points was associated with differences in concentration of suspended sediment. The slope of the curve of Figure 4 is poorly defined. It indicates that for a

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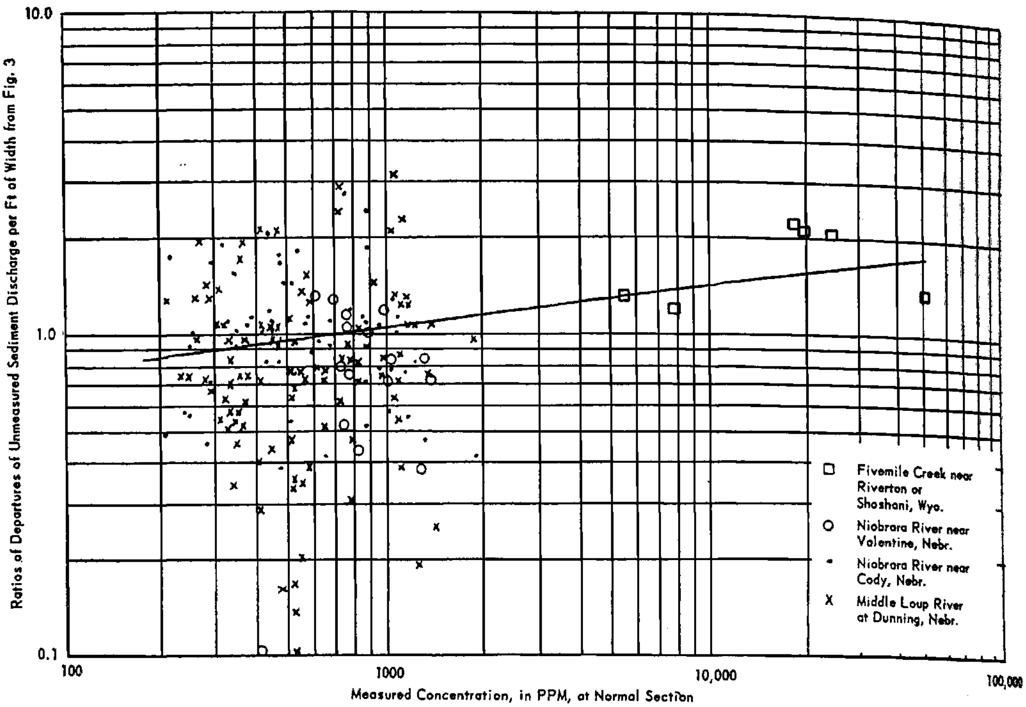

FIG. 4 – Concentrations plotted against the ratios of unmeasured sediment discharge to average unmeasured sediment discharge from Figure 3

given velocity the unmeasured sediment discharge increases generally with perhaps the 0.35 power of the concentration of suspended sediment. (The upper end of the curve was drawn below the average of the six points for Fivemile Creek partly because the points for other stations did not show a definite increase in unmeasured sediment discharge with increased concentration.) Scatter of points from the curve is so great that no further attempt was made to explain the scatter in terms of other factors.

The curve of Figure 3, and hence (5), should be understood to express average variation of unmeasured sediment discharge with mean velocity. The curve probably would be considerably different if other factors were kept constant and only velocity and unmeasured sediment discharge were permitted to vary. Actually, an increase in velocity is usually accompanied by an increase of suspended-sediment concentration. Such an increase will certainly occur if the supply of sediment remains constant in terms of both quantity and particle sizes. The supply of sands may be approximately constant at a cross section of an alluvial stream but is likely to differ widely from stream to stream or from one part of a stream to another. Therefore, the adjustment of Figure 4 may not be needed to compute unmeasured sediment discharges for different velocities and concentrations at a particular cross section because the curve of Figure 3 already contains an adjustment for average change in concentration with change in velocity.

If the scatter from the curves of Figures 3 and 4 was caused entirely by inadequacy of the correlations, these curves would be unsatisfactory for computing unmeasured sediment discharge. However, much of the scatter results from inaccuracy of the determinations of unmeasured sediment discharge. These determinations, although very valuable information, are differences between two measured sediment discharges each of which is likely to be somewhat inaccurate. Furthermore, the normal sections were from a few hundred feet to more than a mile from the total-load sections, and changes, either temporary or semipermanent, in net rate of scour or fill between the sections may cause large inaccuracies in the determinations. Some method for experimentally determining more exact unmeasured sediment discharges is badly needed to make the experimental information more suitable for establishing empirical relationships to parameters other than mean velocity.

Computed unmeasured sediment discharges as

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Functions of mean velocity—Unmeasured sediment discharges can be computed from information at a single cross section. Although the computation procedure is complicated and uncertain in some details, the unmeasured sediment discharges thus computed have a more consistent relationship to mean velocity than experimental determinations have. One procedure for computing total sediment discharge by extrapolating and interpreting data for a single section has been explained by *Colby* and *Hembree* [1955, pp. 66–98]. It is known as the modified Einstein procedure and requires mean velocity, width, and average depth of the cross section, average depth at sampling verticals, water temperature, bed-material samples for particle-size analysis, and depth-integrated samples of suspended sediment to be analyzed for particle size and concentration. Some results of applications of the procedure have been discussed by *Schroeder* and *Hembree* [1956].

Many unmeasured sediment discharges were computed by subtracting measured sediment discharges at a normal section from total sediment discharges as computed for the same times by the modified Einstein procedure. These unmeasured sediment discharges per foot of width were plotted against mean velocity. One average curve was drawn for sediment stations in the Rio Grande basin and another for other stations. The two curves are shown on Figure 5 together with the average curve from Figure 3. The three curves are reasonably consistent and would agree better if adjusted for differences in average concentration.

Adjustments for concentration—Readily available unmeasured sediment discharges per foot of width from modified Einstein computations were listed without screening to eliminate those that were computed from unsuitable field data. Then each one was divided by the unmeasured sediment discharge per foot of width as indicated by the mean velocity and by the appropriate curve of Figure 5. The quotients were plotted against concentration of suspended sediment to define curves *B* and *C* of Figure 6. Curve *A* of Figure 6 is redrawn from Figure 4 for comparison. For a given mean velocity, these curves indicate an increase in unmeasured sediment discharge with increasing concentration of suspended sediment. Such an increase is logical for sediment coarse enough to be appreciably more concentrated near the stream bed than higher in the vertical. However, the concentration of finer sediment probably has little relationship to the quantity of unmeasured sediment discharge.

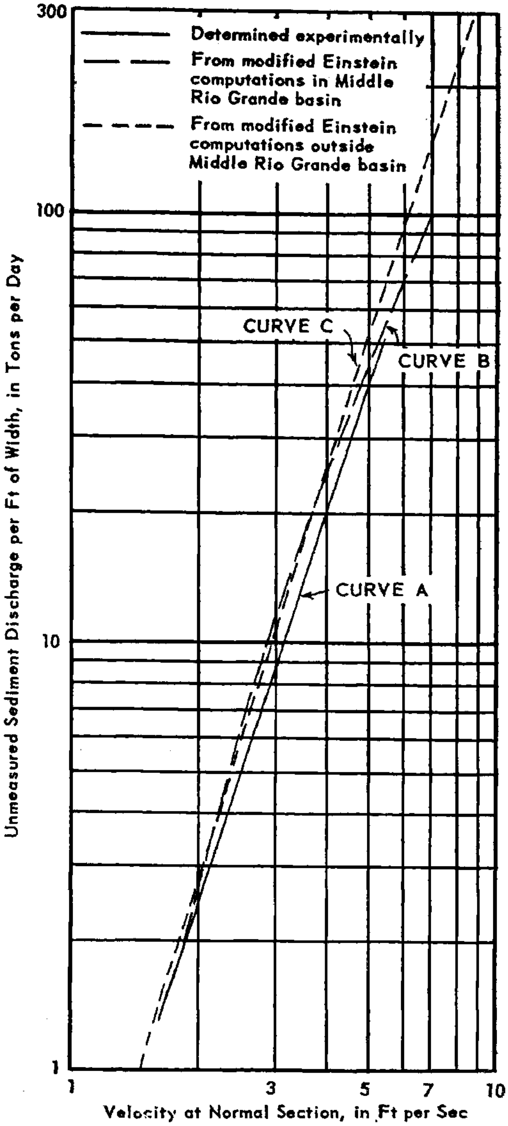

FIG. 5 – Comparison of average curves of unmeasured sediment discharge plotted against mean velocity

An average adjustment for concentration (Fig. 6) is insufficient to explain the low unmeasured sediment discharges that were computed by the modified Einstein procedure for some sediment stations. Perhaps the effective supply of sands that can be picked up readily, which depends on configuration of the stream bed as well as on sizes and quantities of sediment, is much lower relative to the flow at these stations. If so, a measure of the availability of sands might correlate well with departures of unmeasured sediment discharge from

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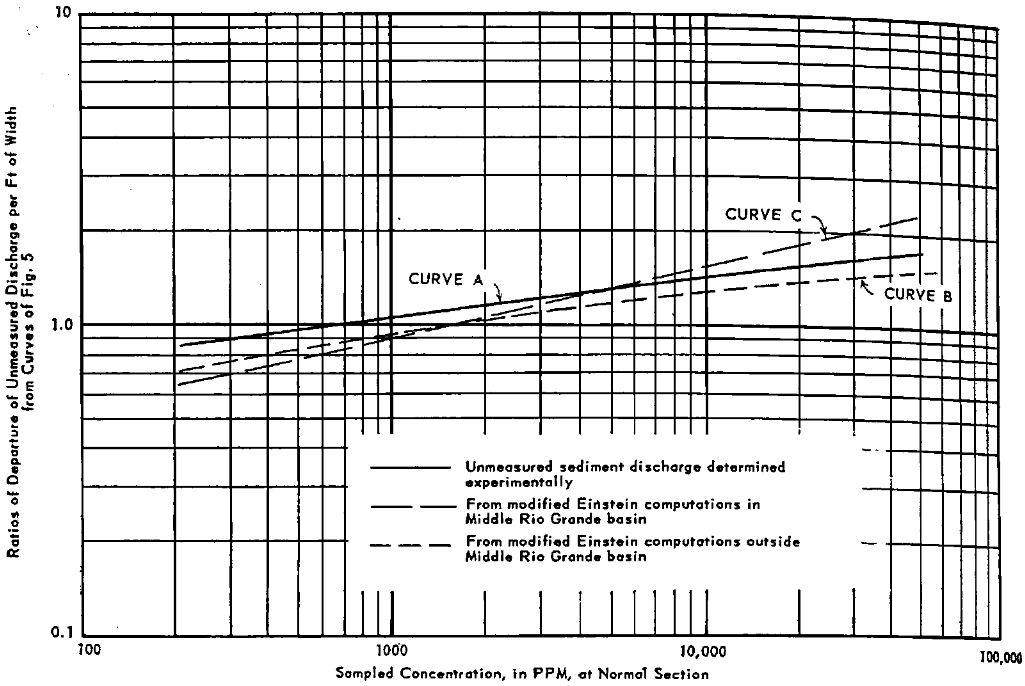

FIG. 6 – Average relationships between ratios of departure from the curves of Figure 5 and concentration of suspended sediment

the average curves of Figure 5. The measured concentration of suspended sands at a given mean velocity might be a practical measure of this availability. In other words, if the measured concentration of suspended sands is unusually high for a given mean velocity, the effective availability of sands is high, and this high availability is likely to make the unmeasured sediment discharge higher than usual for the given velocity. However, in two streams that flow over beds of the same sediment composition and same configuration but widely different depths of flow, the measured concentration of suspended sands for equal velocities will be considerably lower for the deeper stream. Thus, measured concentrations of suspended sands require adjustment for depth of flow to make them reasonably consistent measures of the effective availability of sands, and the relative adjustment for depth will vary with mean velocity.

Figure 7 shows relative concentrations of suspended sands for different depths and velocities. It is based on 100 ppm of suspended sands (any convenient concentration might be used) at a mean velocity of one foot per second and a depth of two feet. The concentration for a constant depth of two feet was assumed to increase with the square of the velocity. Adjustments for depth at different velocities were computed from theoretical relationships and for an assumed effective size of bed material. A better adjustment diagram than that of Figure 7 could be prepared from more numerous and precise computations and from experiments. Fortunately, an exact diagram is not necessary.

A ratio of the known concentration of measured suspended sands to the relative concentration from Figure 7 is a measure of the effective availability of sands. Availability ratios are plotted on Figure 8 against ratios of unmeasured sediment discharge to the average unmeasured sediment discharge from curve *C* of Figure 5. The curve through the plotted ratios can be used to adjust unmeasured sediment discharge for changes in availability of sands.

The points on Figure 8 represent a wide range of cross sections and concentrations. Average depths ranged from 0.4 to 55 ft, mean velocities from 1.1 to 8.0 ft per sec, widths from 15 to 2760 ft, measured suspended-sediment concentrations from 57 to 140,000 ppm, concentrations of suspended sands from 5 to 26,600 ppm, and computed unmeasured sediment discharge per foot of width from 0.4 to 346 tons per day. In view of these wide ranges and the inaccuracies in computed unmeasured sediment discharges, scatter of points from

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the average curve of Figure 8 is not excessive. Of 162 plotted points, 142 are within 50 pct, and 113 are within 25 pct of the average curve. Some points farthest from the curve, for example the low points at availability ratios of 1.05 and 2.0, are based on field data that are unsuitable for computing total sediment discharge. Points for the Mississippi River at St. Louis, Mo., scatter more than for most sediment stations because the unmeasured sediment discharge is only one to ten per cent of the total sediment discharge. Expressed in percentage of total sediment discharge, the computed unmeasured sediment discharges by the modified Einstein procedure are more accurate than for most stations, but they are less accurate than for most stations when expressed in tons per day. Also, at St. Louis the sediment load of the Missouri River is not completely mixed with the sediment load of the Mississippi River. Thus, some scatter from the average curve is caused by inaccuracies in basic data and in the computations of unmeasured sediment discharge per foot of width. Some scatter results from the inadequacy of the average relationships to give the same unmeasured sediment discharges as the much more complex modified Einstein procedure, which is theoretically more correct.

Curve *C* of figure 5, the curves of Figure 7, and the average curve of Figure 8 provide a short graphical method for computing about the same unmeasured sediment discharge that might be computed by the modified Einstein procedure. Mean velocity, width, average depth, and concentration of suspended sands are all required. The size distribution of the bed material is not needed because the availability ratio depends partly on this size distribution. An unmeasured sediment discharge, which includes all particle sizes, can be computed from these curves by dividing the measured concentration of suspended sands by the relative concentration from Figure 7 for the given depth and mean velocity. This availability ratio determines on Figure 8 a ratio of departure from Curve *C* of Figure 5. Curve *C* and the mean velocity together give an unmeasured sediment discharge per foot of width, which can then be multiplied by the ratio of departure and by the width of the stream in feet to obtain the unmeasured sediment discharge in tons per day for the cross section. Because this procedure contains an adjustment for the effective availability of sands, it may be more applicable than the modified Einstein procedure for streams whose beds have large areas of relatively unshifting material.

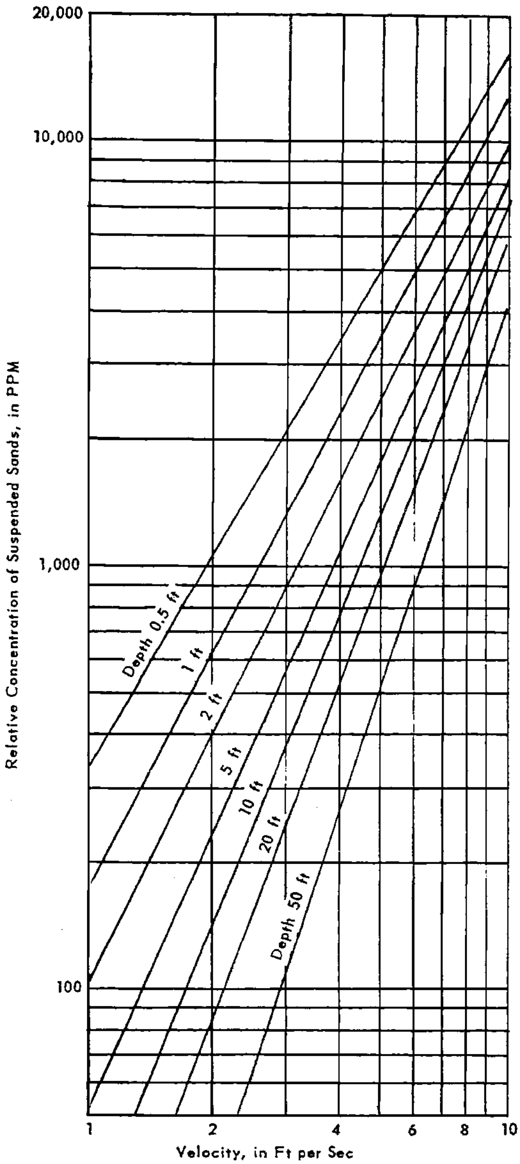

FIG. 7 – Relative concentrations of suspended sands for different depths and mean velocities

The procedure has two disadvantages. One is that it gives no breakdown of the unmeasured sediment discharge into size ranges. The other is that it requires good determinations of mean velocity because the relative concentration (Fig. 7) varies roughly as the square of the mean velocity and unmeasured sediment discharge varies as about the cube of the mean velocity. The mean velocity should be for a cross section that is normal to the direction of flow, so any horizontal angle corrections should be applied to the increments of

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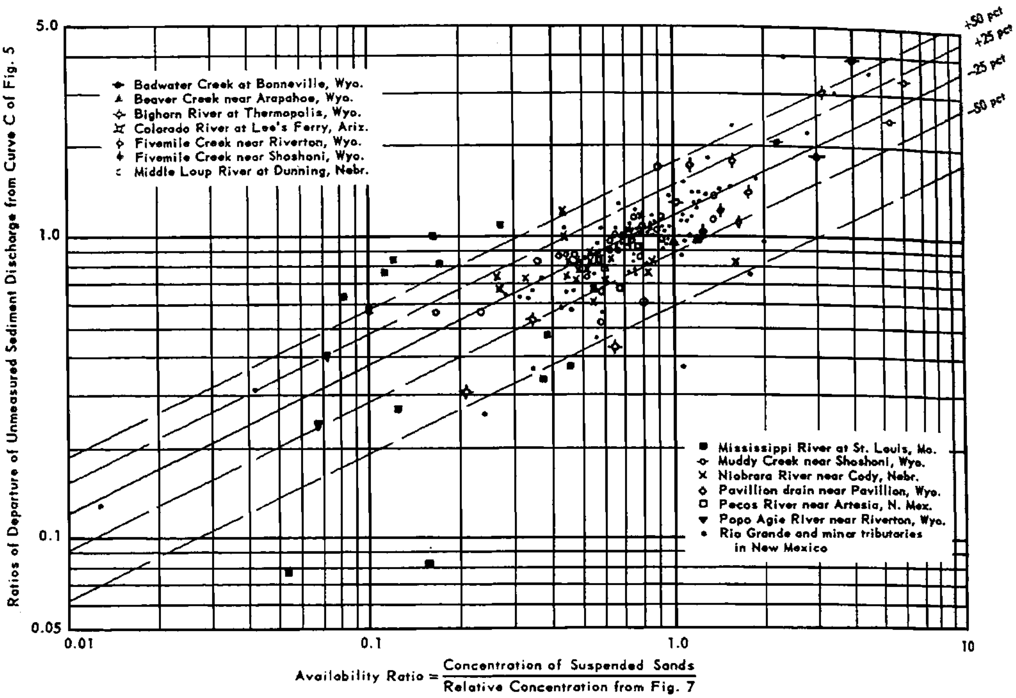

FIG. 8 – Variation of unmeasured sediment discharge adjusted for mean velocity with a measure of the availability of sands

width and not to the velocities. Also, mean velocities are more representative for sections that have reasonably uniform lateral distribution of velocity than for those that have appreciable cross sectional areas in which the velocity is much lower or higher than the mean velocity.

Applications—Unmeasured sediment discharges for particular times and periods are often needed to supplement records of measured suspended-sediment discharge of streams. The unmeasured fraction is a highly variable proportion of total sediment discharge for most streams and at many stations does not correlate well with water discharge. The relationship to mean velocity does, however, provide a satisfactory basis for estimating unmeasured sediment discharges for many cross sections.

Curves of unmeasured sediment discharge per foot of width versus mean velocity can be drawn for individual sediment stations as well as for groups of stations. Because the general form of the relationship is known, perhaps six to ten determinations of unmeasured sediment discharge may define a reasonably satisfactory curve for a single station. The curve can then be used to estimate the unmeasured sediment discharge at other mean velocities for which the basic field information has not been obtained or is difficult or even impractical to obtain. Thus, the use of the curve may greatly reduce the cost of determinations of unmeasured sediment discharge. However, satisfactory extrapolation of the curve may be impossible, or at least questionable, above bankful stage or for flows when the stream is scoured to relatively unshifting bed material. The curve for an individual station can be used to estimate unmeasured sediment discharges for periods of days, months, or years if stream flow measurements are available from which to estimate mean velocities throughout the periods.

Even though no determinations of unmeasured sediment discharge have been made or no bed-material samples are available for an alluvial cross section, reasonably good estimates of the unmeasured sediment discharges can usually be made from such curves as those of Figure 5. If the concentrations of suspended sediment are either especially high or low, adjustments as indicated by the curves of Figure 6 may be applied. If sufficient information is available, Curve C of Figure 5 and the curves of Figures 7 and 8 can be used to give more dependable unmeasured sediment discharges, especially for concentrations and depths that differ widely from most of those that were used to define

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the curves of Figures 5 and 6. This last type of computation is particularly preferable for cross sections whose stream beds are partly or mainly composed of relatively unshifting material.

Estimates of unmeasured sediment discharge from any of the curves may be used to show that for some sections the unmeasured sediment discharge is a negligible percentage of the total sediment discharge and can safely be disregarded unless the amount of the coarser sediment that is discharged is particularly significant. At the other extreme, the estimates may indicate that the unmeasured sediment discharge is, either in general or at certain seasons or rates of flow, so large a fraction of the total sediment discharge that more exact computations are justified even though such computations may require much expensive field and office work.

Unmeasured sediment discharges based principally on the relationship to mean velocity are only approximations, but the fact should be remembered that the term 'unmeasured sediment discharges' is used because no practical way is known for measuring such discharges directly and with reasonable accuracy on most streams. All that is claimed for the generalized relationships of this paper is that they usually seem to give reasonably good approximations of the unmeasured sediment discharges that might be obtained by spending hundreds or thousands of dollars on additional field measurements and office computations. These relationships are suggested to supplement but not to supersede such measurements and computations and should be revised when more exact information becomes available.

Acknowledgments—Modified Einstein computations for stations in the Missouri River basin and all the experimental determinations of unmeasured sediment discharge by differences between measured sediment discharges were made by personnel under the general supervision of P. C. Benedict, regional engineer, Quality of Water Branch, U. S. Geological Survey. D. Q. Matejka, hydraulic engineer, under the general supervision of J. M. Stow, district chemist, Quality of Water Branch, U. S. Geological Survey, prepared Curves B and did most of the work for Curves C of Figures 5 and 6 and made the computations by the modified Einstein procedure for stations in the Rio Grande basin.

References

Chien, Ning, The efficiency of depth-integrating suspended-sediment sampling, *Trans. Amer. Geophys. Union*, **33**, 693–698, 1952.

Colby, B. R., and C. H. Hembree, Computations of total sediment discharge, Niobrara River near Cody, Nebr., U. S. Geol. Surv. *Water-Supply Paper 1357*, 187 pp., 1955.

Einstein, H. A., The bed-load function for sediment transportation in open channel flows, *U. S. Dept. Agr., Tech. Bul. 1026*, 71 pp., 1950.

Keulegan, G. H., Laws of turbulent flow in open channels, *J. Res.*, **21**, 707–741, 1938.

Schroeder, K. B., and C. H. Hembree, Applications of the modified Einstein procedure for the computation of total sediment load, *Trans. Amer. Geophys. Union*, **37**, 197–212, 1956.

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