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연속점 채취를 이용한 유사량 계산
Sediment Discharge Based on a Time-Integrated Point Sample

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Abstract

A procedure for computing total suspended sediment load is presented based on a single point-integrated sample, a power velocity distribution, and Laursen's sediment concentration distribution equation. The procedure was tested with field data from the Rio Grande River. Computed concentrations agreed well with depth-integrated measurements corrected for unmeasured load using nominal values of β, κ, and w. Even better agreement was obtained when site-specific data were used to define the x and z exponents of the velocity and concentration distributions. The difference between total suspended load computed using a single measurement and this procedure and conventional computations based on depth-integrated measurements is well within sampling error. There are major advantages in estimating total suspended load using a single time-integrated suspended-sediment point sample. Less field time is required; sampling costs are greatly reduced; and sampling can be more frequent and better timed to measure the changing sediment load. Single-point sampling makes automatic sampling procedures more feasible.

요 지

일점 연속 채취, 멱 속도 분포 및 Laursen의 토사농도 분포식을 이용한 총 부유 유사량 계산 방법을 제안하였다. 이 방법은 미국 리오그란데 강에서 채취한 자료에 의해 검증되었다. 이 방법으로 계산된 농도분포는 β, κ, 그리고 w의 보편적인 값을 사용하여 계산한 보정 전수심 채취방법과 잘 일치하였다. 지역특성에 맞는 농도와 속도 분포식의 계수 x와 z를 사용하였을 때는 더 좋은 결과를 얻을 수 있었다. 일점 채취에 사용한 이 방법과 일반적으로 많이 쓰는 전수심 채취를 사용한 방법과의 총 유사량의 차이는 채취때 생길 수 있는 오류 정도로 작은 것이었다. 일점 연속 채취에 의한 총 부유 유사량 측정은 여러 가지 중요한 이점을 가지고 있다. 채취 시간에 및 비용을 절감할 수 있으며 채취를 자주 할 수 있고 유사량 변화에 신속하게 대응 할 수 있다. 또한 이 방법은 미래에 추구해야 할 자동채취 방법으로 사용될 수 있다.

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1. Introduction

In conventional point-integrating sampling, velocity and concentration are measured at a number of points in the vertical to estimate the average concentration. The more points, the more precise and reliable this method is. However, it quickly becomes too time-consuming to be practicable for frequent routine sediment measurements. Less time-consuming and less costly methodology is required for collecting mear-continuous sediment data, time-integrated point sampling, or automated sampling. A one-point suspended sediment sampling method has many potential advantages, and is probably necessary for any practical automated system.

Recently Ingram et al. (1991) suggested that time-integrated suspended-load point samples would result in better evaluation of the sediment load than depth-integrated. They proposed a procedure (TSL procedure) to measurement and other stream data. The proposed technique used the concentration "in the bed-load zone" based on the Einstein bed load formula (Einstein, 1950) and modifications by Burkham and Dawdy (1980). The measured point-sample concentration and the calculated "bed-load" concentration were used to find z in the Rouse (1937) sediment concentration distribution equation. This is a major deviation from the theory of suspended sediment behavior and is a rather artificial concept. It is near the bed that all concentration distributions are suspect for several reasons. This study is an effort to refine and improve their proposed procedures.

2. Research Objectives

Several questions were investigated in this research:

(1) For a single-size sediment, what is the "best" level for taking a point sample that will be representative of average concentration in the vertical (Jung et al. 1994b).

(2) For a sediment mixture, what is the best level for taking a point sample that will be representative of the sediment size distribution and average concentration in the vertical.

(3) Is there a simple computation procedure that permits finding the average suspended-sediment concentration from a single point-integrated sample and calculation of total sediment load.

The relationships used are power equations for the velocity distribution and the suspended concentration distribution for evaluating the suspended load, and the Laursen total load equation (1958) for evaluating the bed material composition and the bed load.

3. Review of Ingram's TSL Procedure

The Total Sediment Load (TSL) procedure for estimating total sediment discharge using single-point suspended-sediment data has been described by Ingram (1988) and Ingram et al. (1991). The procedure was tested with several sets of field data and results compared with loads computed using the modified Einstein procedure (MEP), which extrapolates depth-integrated suspended-sediment data and adds a bed load to get total sediment discharge. The TSL procedure estimates total sediment loads that are similar in magnitude to both turbulence flume measurements and MEP estimates. The similarity in results demonstrates the potential for using a single-point sample and the TSL procedure as an alternative to depth-integrated suspended-sediment sampling.

Ingram used the following procedure and relationships to integrate the single-point suspended-sediment sample data over the entire cross section:

(1) Determine concentration of each fraction of mean size d of the suspended-sediment sample.

(2) Divide the bed-material sample (taken at the same time as the suspended sample or another time) into the same size fractions.

(3) Determine the bed-load using a slight modification of the Burkham-Dawdy (1980) modification of the Einstein (1950) bed-load function.

(4) Obtain the concentration at the "bed" by dividing the bed load by the flow in a layer above the bed of thickness 2d and velocity $11.6U*$. (This product is not shown to be the actual flow in this layer, and $11.6U*$ is the velocity at the edge of the laminar sub-layer.)

(5) Use the Rouse sediment concentration distribution equation with the exponent z as the unknown. The measured concentration of the point sample and the calculated bed-load concentration at level 2d are known, and the z obtained is no longer equal to $w/\beta\, \kappa\sqrt{\tau_0/\rho}$.

(6) Plot the z values for each size fraction, and compute a regression equation to smooth the relationship between z and d.

(7) Recompute the bed-load concentration using the regressed value of z, and convert into bed-load.

(8) Integrate each size fraction over the vertical to obtain the suspended-sediment load using the recomputed bed-load concentration, the regressed z value, a modification of Keulegan's modification of the Prandtl velocity distribution, and Rouse's suspended-sediment concentration distribution.

(9) Sum the total sediment load (suspended and bed) of each size fraction per unit width and multiply by the active width of the sampled cross section to compute total sediment load.

In a general sense, the TSL concept is the only way a point sample can be used to estimate the total sediment load of the total flow. It is in the details of how this integration is carried out that one must look to evaluate the TSL procedure. There are many details; some of minor consequence, others of such major consequence that they raise questions as to how well the TSL procedure would work on other streams. The most questionable part of the TSL procedure is the use of a computed bed-load concentration (or contact load zone concentration) to determine the z exponent in the Rouse suspended-load concentration distribution. The Rouse distribution (and others) goes to infinity at the bed and does not correctly describe concentrations near the bed. Turbulent mixing near the bed is weak, the particles moving up through the "bottom" layer of the suspension is a matter of sediment entrainment rather than sediment suspension. If the bed is replaced with a screen with a quiescent tank below, the flow will gradually clear. The bed load is dependent on the bed material which changes with time and flow and is also extremely difficult to measure -especially in a major flood.

Other details of the TSL procedure are largely a matter of choices between alternative formulations: Einstein's bed-load function or some other equation; the Burkham-Dawdy modification of Keulegan's modification of Prandtl's velocity distribution or some other velocity distribution; the Rouse concentration distribution or some other distribution; etc. Because all these basic assumptions contribute to the final estimate of total sediment load and because sediment data are never "good enough", it is often difficult to demonstrate that one set of assumed relationships is clearly better than other possible sets. For this reason, it is important that each part of the solution procedure be defensible.

4. Problem Definition

The following relationships for vertical velocity distribution and vertical suspended-sediment concentration distribution were used in this investigation to compute sediment load using single-point sampling data. These distributions were integrated over the vertical, and a bed-load equation was used (Jung, 1993). Both concentration and composition values are needed for the suspended sediment sample.

$$\frac{\bar{u}}{\bar{U}}=(x+1)\left(\frac{y}{D}\right)^{x} \tag{1}$$

$$\frac{C}{C_a}=\left(\frac{a}{y}\right)^{\frac{w}{\beta\kappa\sqrt{\tau_0/\rho}}} \tag{2}$$

A hypothetical bed-material composition that is compatible with the measured suspended-load composition can be obtained by turning the Laursen total sediment load relationships (Laursen, 1958) around. This hypothetical composition can then be compared with the measured bed material composition. The difference between the two should help to explain the usual scatter plots of sediment load versus discharge. The computed bed material, rather than the measured bed material, is used to compute the bed load.

One of the primary features that sets this one-point procedure apart from other methods is computation of the "best a," the level where the average concentration, C_m, equals the measured concentration, C_a. The "best a" for a single sediment size is easily obtained–assuming the defining relationships are correct. The "best a" for a sediment mixture, however, is difficult to define and is very dependent on whether the principal interest is in the concentration or in the composition of the sediment load.

Basic data needed for the computation are: cross-section shape, width, area, and hydraulic radius of the sampled section; flow depth D at the sampled vertical; sampling height above the channel bed; concentration and composition of the suspended-sediment sample; channel discharge; water temperature; and channel slope.

Manning's equation can be used to compute the overall roughness (Manning n). Using this n (or a local b if it seems more reasonable), slope, and depth, the local mean velocity can be found. Values of $\tau_0=\gamma DS$, $\kappa=0.4$, and $\beta=1$ are used except when variations of these factors were tested.

In this investigation the computation steps are as follows:

(1) Calculate the z value for each size fraction of the point sample; fall velocity, w, for a natural sediment particle; and shear velocity, $\sqrt{gys}$. Use $\kappa=0.4$, $\beta=1.0$ in computing the Rouse exponent (unless experience indicates otherwise).

(2) Integrate $\int C\bar{u}dy$ from a to D for each size fraction. Divide the integral by flow rate per unit width to obtain average concentration, C_m (Jung, 1993).

$$C_m = \frac{JC_s y_s^{z}}{(J-z)D^J}(D^{J-z} - a^{J-z}) \quad (3)$$

where J is equal to x+1 and ranges from 5/4 to 8/7; ys is the level at which the point sample is collected; and C_s is the concentration of each size fraction of the point sample collected at the level y_s. The mean concentration can be multiplied by the discharge per unit width to find the total suspended load of that size fraction. The C_m of each size fraction can be summed to find the total suspended–sediment concentration in the vertical.

(3) Multiply Cm by an area factor to find the overall mean concentration. The area factor will be site specific and requires specific studies at several flows for definition. Determining the area factor was not a part of this research, but hopefully the value should not very different from unity because of lateral turbulent mixing.

(4) Use the results of step 2 and find the "best a" for each size fraction, the point in the vertical where $C_m/C_a=1$. Now we can write (Jung, 1993):

$$\frac{C}{C_a} = \left(\frac{a}{y}\right)^z \quad (4)$$

$$\frac{C}{C_s} = \left(\frac{y_s}{y}\right)^z \quad (5)$$

and using C_m form Eq. (5) as C

$$\frac{C_m}{C_s} = \left(\frac{y_s}{a}\right)^z \quad (6)$$

"a" is the "best a: for that size fraction (where $C_m/C_a=1$); and C_m is average concentration of the size fraction in the vertical.

Variations on these four steps can be used to investigate several aspects of sediment transport and sediment transport measurement.

5. Field Data Used

The best and most comprehensive published data set found was the U.S. Geological Survey (USGS) special study on the Rio Grande conveyance channel in New Mexico (Culbertson et al. 1972). Field measurements were taken near the San Marcial and Nogal Canyon gaging stations, in New Mexico. Several point samples were taken in a vertical, and a depth–integrated sample was included as well as a bed–material sample. The size distributions of the samples, cross–section characteristics, and stream slopes were given.

6. "Best a" for a Natural Sediment Mixture

The level at which a sediment mixture is sampled so that $C_m=C_a$ is difficult to determine. Each fraction (fine to coarse) should be sampled at a different elevation, and this cannot be done in single–point sampling. The difficulty can be overcome by using correction coefficients to convert sampled concentrations (of the various size fractions) to the concentration at the "best a" for each fraction.

To find the correction coefficients to relate the sampled concentrations of each size fraction to the mean concentration of that fraction in the vertical, the Laursen concentration distribution(Eq. (7)) can be used, and can be expressed as Eq. (8)

$$C_m = KC_s \quad (7)$$

$$K = \left(\frac{y_s}{a}\right)^z \quad (8)$$

K is a correction coefficient for converting the sampled concentration of each size fraction to mean concentration of the fraction in the vertical.

For fine sediment, the sampling height y_s would be less than the best a, but because z is small, the correction coefficient K would be only slightly less than unity. For coarse sediment, the same sampling height y_s would be greater than the best a, and the correction coefficient could be considerably greater than unity. This and other possible errors in the measurement of coarse sediment will be discussed at greater length in the next paper.

Samplers as presently designed cannot physically sample "close" to the bed, and conditions close to the bed are variable in space and time, especially with a duned or anti-duned bed. This can lead to errors that may be large, especially for coarse sediment.

7. Comparison of Computed Average Suspended Sediment Concentrations by Various Methods

Computed concentrations of four size fractions and total suspended load determined by four methods, based on data at three field stations, are compared on Figs. 1, 2, and 3. The methods used are labeled as follows:

The M1 value in each group is the depth-integrated sample uncorrected.

The M2 value is a corrected depth-integrated concentration that takes into consideration the difference in concentration when integrating to a lower limit ($2d_{50}$) with a nominal z value. The correction, as the figures indicate, is small for the finest fractions, relatively large for the coarsest fraction, and substantial for the next less coarse fraction. The overall correction is also substantial. The M2 value is considered most likely to be correct.

The M3 value is integrated based on the lowest point sample (with a lower integration limit of 2d50) and a nominal z for each size fraction. In almost all cases the point samples give higher concentrations than the corrected depth-integrated sample.

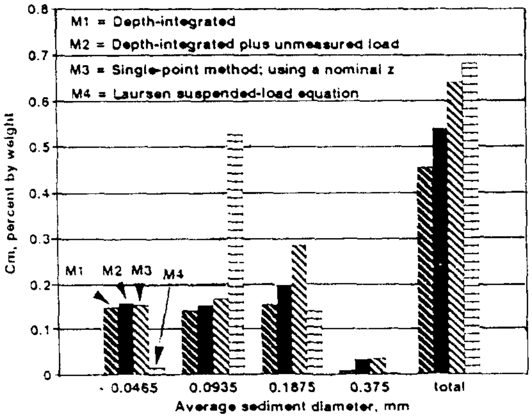

Fig. 1. Comparison of Average Suspended Sediment Concentrations (C_m) Data at Station 2249 (No Correction)

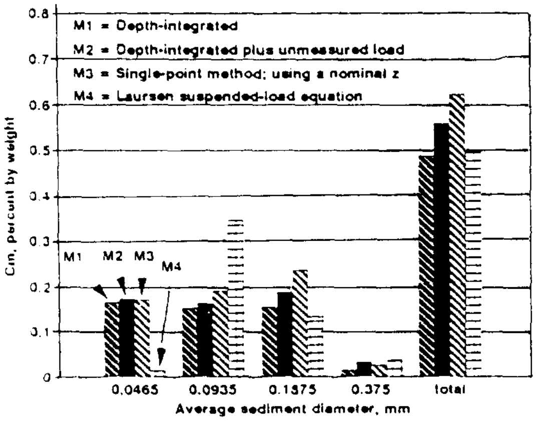

Fig. 2. Comparison of Average Suspended Sediment Concentrations (C_m) at Gaging Station 2243 (No Correction)

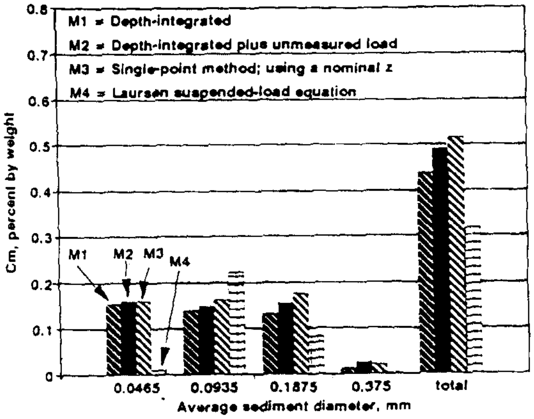

Fig. 3. Comparison of Average Suspended Sediment Concentrations (C_m) at Gaging Station 1318 (No Correction)

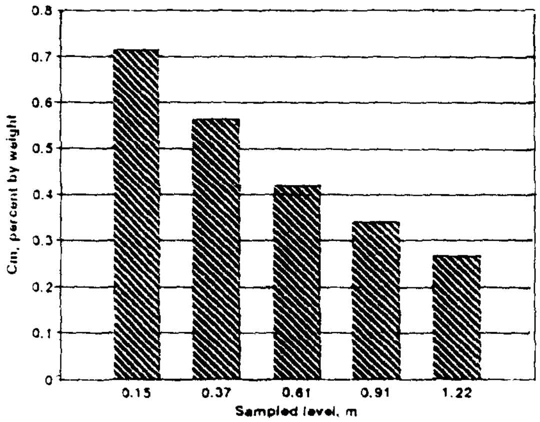

Fig. 4. Comparison of Average Suspended Sediment Concentrations (C_m) Using Point Samples at Different Water Levels with Normal z at Gaging Station 2249

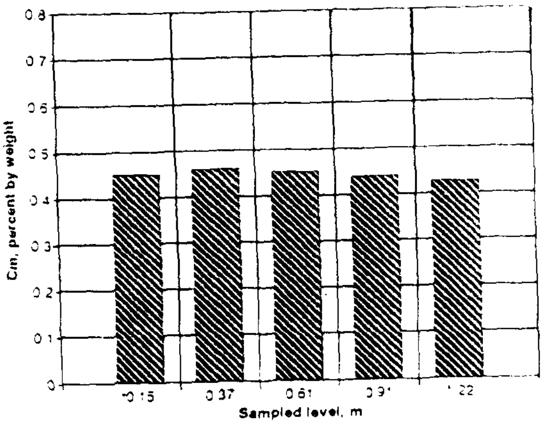

Fig. 5. Comparison of Average Suspended Sediment Concentrations (C_m) Using Point Samples at Different Water Levels with Corrected z at Gaging Station 2249

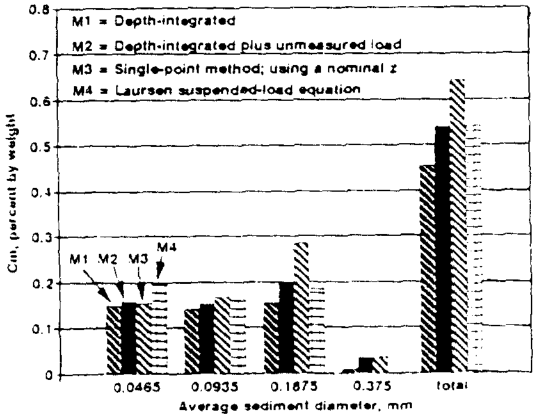

Fig. 6. Comparison of Average Suspended Sediment Concentrations (C_m) with Corrected Bed Material Composition at Gaging Station 2249

The M4 value is that estimated using the Laursen suspended load relationship. The prediction for total suspended load is high for one station and low for two stations, and it is better for total suspended concentration than for each size fraction. The measured bed material composition was used in this prediction.

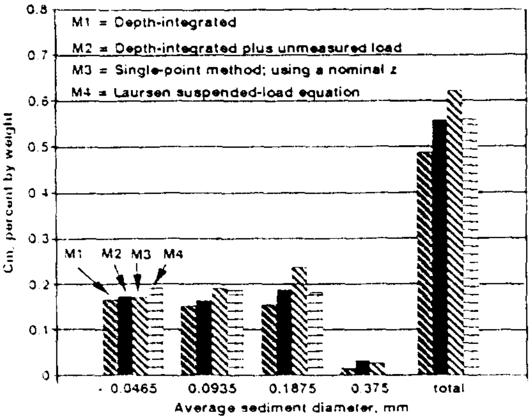

Fig. 7. Comparison of Average Suspended Sediment Concentrations (C_m) with Corrected Bed Material Composition at Gaging Station 2243.

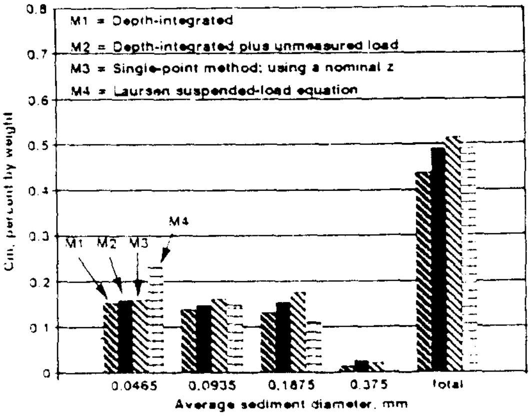

Fig. 8. Comparison of Average Suspended Sediment Concentrations (C_m) with Corrected Bed Material Composition at Gaging Station 1318.

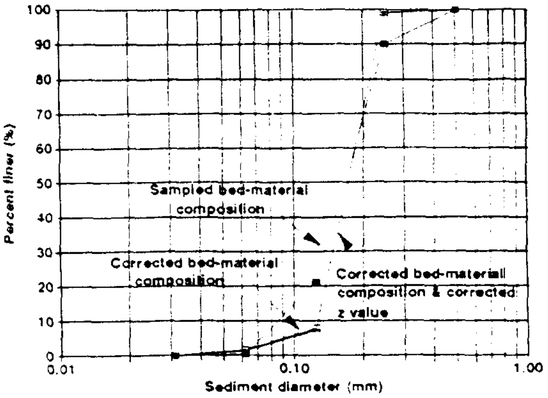

Fig. 9. Comparison of Bed Material Composition for Sampled Bed Material; Corrected Bed Material; and Corrected Bed Material and Corrected z at Gaging Station 2249

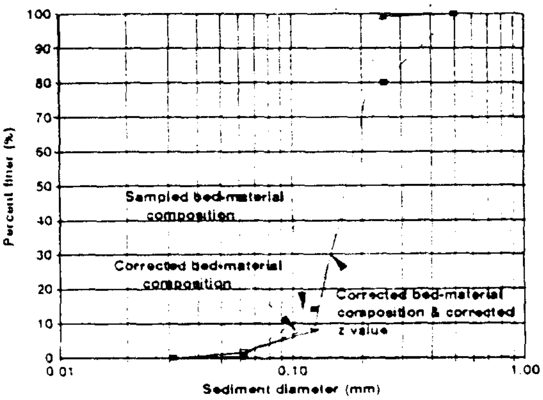

Fig. 10. Comparison of Bed Material Composition for Sampled Bed Material; Corrected Bed Material; and Corrected Bed Material and Corrected z at Gaging Station 2243

8. Sensitivity of Single-Point Sampling Level

Using single-point samples taken at different levels will give different concentrations, as shown in Fig. 4. The reason will be discussed in the next paper. where it is clear that the theoretical concentration distribution curves do not match satisfactorily with measurements when the nominal z value is used. However, if the nominal z is doubled (Jung et al., 1994a), theory and measurements agree quite well. Fig. 5 shows comparison of concentration at the several sampling levels

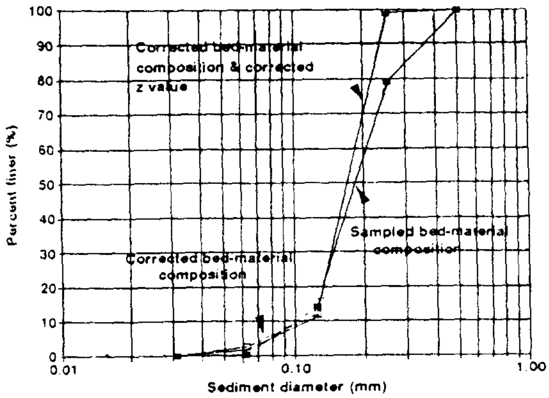

Fig. 11. Comparison of Bed Material Composition for Sampled Bed Material; Corrected Bed Material; and Corrected Bed Material and Corrected z at Gaging Station 1318

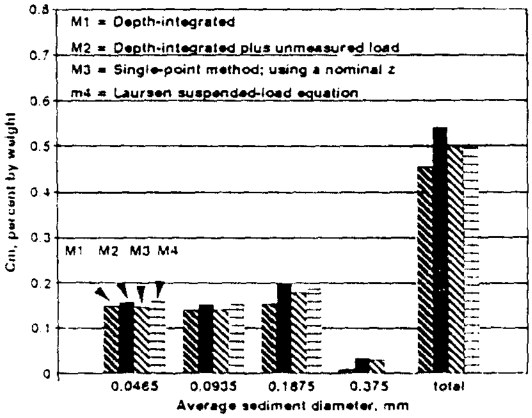

Fig. 12. Comparison of Average Suspended Sediment Concentrations (C_m) with Corrected Bed Material and Corrected z Value at Gaging Station 2249

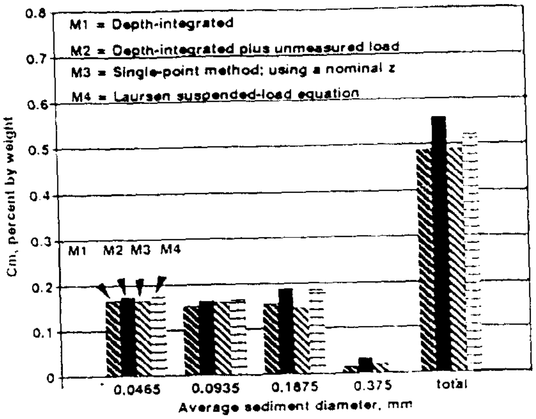

Fig. 13. Comparison of Average Suspended Sediment Concentrations (C_m) with Corrected Bed Material and Corrected z Value at Gaging Station 2243

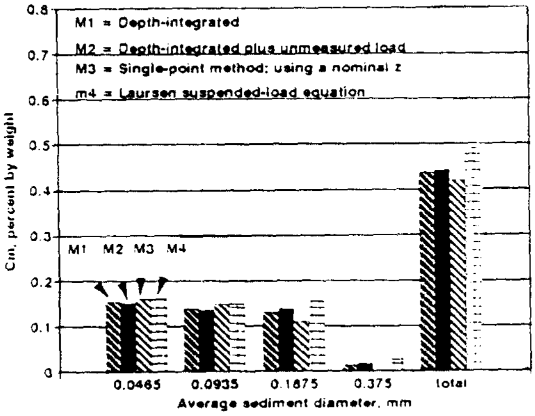

Fig. 14. Comparison of Average Suspended Sediment Concentrations (C_m) with Corrected Bed Material and Corrected z Value at Gaging Station 1318

with the "corrected" (doubled) z, and it is evident that the difference in computed mean concentration is reduced greatly. Presumably this must be due to errors in the variables in z, the Rouse number. These are reasons why values other than the nominal ones could be More importantly, a serviceable z can be obtained from field measurements as was done here.

9. Sensitivity to Bed Material Composition

Figs. 6, 7, and 8 show average concentration predictions at the three measuring stations using the Laursen relationship with bed material composition modified as shown in Figs. 9, 10, and 11. Such a modification in bed material composition can reflect the loss of fine material that can occur in the process of sampling the bed and is within the range reported by Zernial (1961) and Zernial and Laursen (1963), as found in special studies by the USGS of total load for some streams in the Missouri River basin.

10. Sensitivity to z Value in the Rouse Concentration Distribution Equation

Figs. 12, 13, and 14 show the average concentration predictions at the three sampling stations using the Laursen the nominal z value. Variables in this parameter are not yet completely understood. The fall velocity value needed in the computation procedure is the fall velocity of a natural sediment particle in turbulent flow and in the presence of many other particles. The used is for flow in a natural channel with complex planform and complex (and variable) roughness elements. The κ with the power velocity distribution might well be different from the κ of the logarithmic velocity distribution. The β factor needed is a measure of the difference between the mixing of momentum and sediment in suspension over and above the correlation coefficient used in the derivations presented in this study. The scant evidence cited here suggests that the restricted β might have a value of about one and that its variation would be small. In Figs. 12, 13, and 14 the measured depth-integrated sample concentrations, M1, are unchanged; the corrected depth-integrated concentrations, M2, are changed slightly; the single-point integrated concentrations, M3, are changed to some degree; and the Laursen predictions, M4, are changed a little.

The concentration values computed by all four procedures are now quite close. They could be forced to become closer by continuing the forcing procedure, but the point to be made is that reasonable values of variables and parameters result in estimates of sediment load which are close to being the same. To have confidence in estimates of sediment load requires being sure of the variables and parameters used and of the measurements taken. More research is necessary to have more confidence, but from the evidence and results presented here, it would seem that our knowledge at the present time is sufficient for most real problems.

11. Discussion of Results

This study was undertaken to develop a relatively simple computational procedure to estimate the total suspended sediment load of a stream using a single-point suspended-sediment concentration sample. A power law velocity distribution and power sediment concentration distribution were chosen primarily for their mathematical simplicity. The two distributions were derived from modifications of

Prandtl's mixing length theory, including a correlation coefficient for turbulent shear.

The velocity distribution and the concentration distribution can be written with parameters containing variables generally accepted. Better agreement with measurements can be obtained by using parameters derived from measurements at the specific site of interest. The difference between nominal "theoretical" values of the requisite parameters and variables and the empirical values based on measurements can sometimes, and to some extent, be explained by known variations in such things as κ and fall velocity. Mixing length theory is obviously a simplified concept which does not fully describe flow behavior and mixing by large-scale secondary and tertiary flows – phenomena which are between mean flow behavior and random turbulent eddies.

The results of this research and the comparisons with measurements made at stations on the Rio Grande are ample evidence that detailed measurements of flow and sediment are needed initially when setting up a sampling station to properly evaluate and use the later routine measurements. Such an initial site survey would focus on velocity distribution, concentration distribution, bed material variability, and lateral variation of flow conditions for as large a range of flows as possible. Initial surveys of this type are common practice for discharge gaging stations, but they need to be expanded to meet the requirements of predicting sediment transport based on single-point sampling of suspended sediment.

The above discussion applies to determining the sediment load in a single vertical. The load per unit width will vary across the total stream cross-section unless the cross-section is uniform. In natural streams the total cross-section needs to be divided into parts that are almost rectangular, and correction factors must be obtained to account for difference between the concentration of the total load of the stream from that calculated based on the vertical through the sampled point. Those correction values will probably vary with flow and very well may change with time as the stream itself changes.

A judicious, reasoned blending of measurement and theory will permit making a useable estimate of the suspended-sediment load from a single point-integrated sediment sample. The better the physical sampling is performed in all aspects and the better flow and sediment suspension are understood and described, the more accurate the estimate will be, and the more confidence one can have that the estimate is correct.

This study has demonstrated that simple forms of velocity and concentration distribution equations are sufficiently accurate. The most uncertain step in the computational procedure presented is related to the value of the Rouse number $z=w/(\kappa\ \beta\ \sqrt{\tau_0/\rho})$.

Errors in the final estimate of the suspended-sediment load can be the result of errors in different parts of the total procedure (Jung et al., 1994b). In summary, these can be:

(1) Errors in sampler placement and in measurement of stream geometry. The effect of such errors will be presented in a the next paper. For fine material, the effect on the estimate of mean concentration and composition is small; for coarse material the effect can be significant in percent error in absolute values of that part of the suspended sediment load. However, because coarse material is generally a small fraction of total suspended load, the resulting error in total load is

usually small. Therefore, such an error is significant for some types of problems and not for others. The purpose of specific measurements will determine whether or not errors of this type are important and in need of further investigation.

(2) Errors in the descriptive distribution equations and in their usage. Such errors should seldom be so large as to be a problem, although again the effects are greater for coarse than for fine sediment particles. Such errors should be minimized if detailed surveys of flow and suspension are made to adjust "theoretical" relationships to reality. The most uncertain element of the equation describing the concentration distribution is the fall velocity of particles in the field environment. Research on this topic could reduce the complexity of trying to unravel the individual, independent variables of the Rouse number. Such research would be difficult, but could be fruitful. For now, the overall adjustments, based on site-specific measurements, must be relied upon and should yield sufficient reliability and accuracy.

(3) Errors in the sampling procedure or in measuring the concentration and composition of the sample. The impact of such problems was not examined in this study.

To estimate suspended sediment load, the single-point sample provides a total which, in effect, is integrated over the full cross section. To estimate bed load, bed-load sampling or a bed-load equation must be used. In this study the Laursen total load relationship was used with field data with results which were not unacceptable but also were not completely satisfying. When the measured bed material composition was corrected using the suspended load derived from the suspended measured single-point sample, a better estimate of bed load was obtained. This technique could also be used to estimate possible changes in bed material over time or during a flood hydrograph.

12. Conclusions

It has been shown that a single-point sample of suspended-sediment concentration of a stream can be integrated over the vertical to find the average concentration. An initial site survey of the entire cross section is needed to establish a coefficient to be applied to values for the vertical to determine the total suspended sediment load of the stream.

The power law velocity distribution and simplified concentration distribution used in this study are easy and fast to use in computations. Generally accepted coefficients and exponents in those equations describe the distributions adequately, but measurements in the field can improve the accuracy of those descriptions. The measurements needed for this purpose are the velocity and concentration distributions at different rates of flow. More needs to be known about details of turbulent flow behavior; at this time the effect of secondary flow and large-scale vortices can only be speculated on.

A single-point sample provides the reality associated with changes in bed material. A scatter of load as a function of discharge will still exist, but the individual measurements should be acceptably correct even when integrated over the entire flow section. The scatter will be real and dependent on changes in the bed material and flow conditions.

The ultimate in data acquisition for sediment load estimation is an automatic sampling system. The research presented herein establishes ways to evaluate such automatic measurements and provides guidance to designing equipment and procedures. The sampling level should, if possible, change during a flood hydrograph; the sampling should be coordinated with the changing water surface and bed elevations. The technical and practical considerations of sampling were not studied in this research, but this research should be helpful in guiding and evaluating those aspects of the sediment load measurement problem.

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