PREDICTION OF THE GRAIN SIZE OF SUSPENDED SEDIMENT; IMPLICATIONS FOR CALCULATING SUSPENDED SEDIMENT CONCENTRATIONS USING SINGLE FREQUENCY ACOUSTIC BACKSCATTER

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Abstract: The collection of samples of suspended sediment transported by streams and rivers is difficult and expensive. Emerging technologies, such as acoustic backscatter, have demonstrated the promise to decrease the cost and allow more thorough sampling of sediment in transport in the water column. One critical piece of information required to use single frequency acoustic backscatter to calculate the concentration of sand-sized sediment in the water column, is the vertical distribution of sediment particle size. In this study, techniques to predict the size of suspended sand particles are examined and their use with acoustic backscatter data to predict sediment concentration is explored. Methods to predict the size of sediment in suspension using bed sediment and flow criteria had mean absolute differences of from 7 to 50 percent as compared to measured values. When the sample nearest to the bed of the stream was used as a reference, the mean absolute differences between calculated and measured sizes were reduced to 5 percent. These errors in size determination translate into errors of 12 to 84 percent in the prediction of sediment concentration using backscatter data from 1 MHz single frequency acoustics.

INTRODUCTION

Knowledge of the amount of sediment being transported by streams and rivers is important for several reasons. The sediment transport rate at a given cross-section represents the net erosion rate from upstream sources. Sediment transported downstream can fill reservoirs, reduce channel capacities, and impair aquatic habitats. Sediment has been identified by the U. S. Environmental Agency as the largest single pollutant of the nation's waterways (1996 National Water Quality Inventory Section 305(b) Report to Congress). Detrimental effects to fish (Newcombe and MacDonald, 1991; Newcombe and Jensen, 1996) and aquatic invertebrates (Kuhnle et al., 2001) have been directly related to increases in the magnitude and duration of suspended sediment concentrations.

Yet, collection of suspended sediment transport data using standard techniques (Edwards and Glysson, 1999) requires a large financial investment for personnel to collect and analyze samples, and may put personnel in danger collecting samples during thunderstorms and floods (Kuhnle et al., 2000). Furthermore, collection of suspended sediment samples in the bottom 20 percent of the flow, where most of the bed derived suspended sediment is transported, is very difficult or impossible on streams and rivers with dunes or other bed forms on the bed. Conventional samplers collect a physical sample of the sediment and water mixture, which requires each sample to be labeled, transported, and analyzed for sediment concentration and other sediment characteristics in a laboratory (Edwards and Glysson, 1999). The transport of sediment by streams and rivers is inherently variable in time and space and it is often difficult to collect a sufficient number of samples to define representative transport rates for the expected range of flows of a stream or river (Wren et al., 2005).

Recently efforts have been intensified to develop surrogate techniques to replace the conventional sampling techniques which collect a physical sample of the sediment and water mixture (Wren et al., 2000; Gray, 2005). Technologies that have been identified as being useful for measuring suspended sediment transport include: acoustic backscatter, digital-image analysis, laser diffraction, optical velocity, and pressure difference (Kuhnle and Wren, 2005). One technology that has been recognized as having promise for the automatic collection of suspended sediment concentration data is single frequency acoustic backscattering (Kuhnle and Wren, 2005). Commercially available instruments designed to measure velocity profiles in rivers have been successfully used to collect acoustic backscatter data that is proportional to the concentration of suspended sediment (Gartner and Cheng, 2001; Topping et al., 2004). Perhaps the most important limitation to calculating suspended sediment concentration using acoustic backscatter is the need for an independent measure of the sediment size with depth above the boundary (Wren et al., 2000; Gartner and Cheng, 2001; Kuhnle and Wren, 2005). This problem has been approached by using several frequencies of acoustic backscatter simultaneously to arrive at solutions of sediment size and concentration (Hay and Sheng, 1992; Crawford and Hay, 1993; Thorne et al., 1994). However, the range of grain sizes and concentrations commonly found in alluvial rivers continues to complicate solving for sediment size and concentration using only acoustic backscatter (Smith, 2004). This study will explore the available techniques to predict the size of sediment in suspension with application to calculating suspended sediment concentration using backscatter data from single frequency acoustics. The accuracy of employing this technique will be compared to physical samples of suspended sediment collected in a laboratory flume channel and from samples collected on two rivers.

METHODS TO PREDICT SUSPENDED SAND SIZES

If the flow is assumed to be steady and the average sediment concentration is constant at any level, the net vertical flow of sediment will be zero. In other words, the upward movement of sediment will be balanced by the settling of sediment through the water column. The rate of settling through a horizontal area may therefore be equated with the upward sediment movement due to diffusion:

$$Cw + \varepsilon_s \frac{dC}{dy} = 0 \tag{1}$$

where C is the concentration of sediment at a level y above the bed, ε_s is the sediment diffusion coefficient, and w is the fall velocity of the sediment. The sediment diffusion coefficient is generally assumed to be related to the coefficient of fluid momentum ε_m by:

$$\varepsilon_s = \beta\psi\varepsilon_m \tag{2}$$

where β is the difference in the diffusion of sediment and fluid, and ψ represents the damping of the turbulence by the sediment particles (Van Rijn, 1984). For the concentrations considered in this study $\psi = 1$ was assumed. The distribution of β was taken to be constant with distance above the bed but to vary with flow strength and grain size (Van Rijn, 1984):

$$\beta = 1 + 2\left[\frac{w}{U_*}\right]^2, \quad \text{for} \quad 0.1 < \frac{w}{U_*} < 1 \tag{3}$$

where $U_* = \sqrt{\frac{\tau_0}{\rho}}$, τ_0, and ρ are the bed shear stress and density of the water, respectively.

For low sediment concentrations for each i^{th} size group (C_i), and assuming a parabolic-constant distribution of ε_s (Coleman, 1970) the integration and separation of variables of (1) yields:

$$\frac{C_i}{C_{ai}} = \left(\frac{(a)}{(y)}\frac{(h-y)}{(h-a)}\right)^Z \quad \text{for} \quad \frac{y}{h} < 0.5 \tag{4a}$$

$$\frac{C_i}{C_{ai}} = \left(\frac{a}{h-a}\right)^Z e^{[-4Z(y/h-0.5)]}, \quad \text{for} \quad \frac{y}{h} \geq 0.5 \tag{4b}$$

(Van Rijn, 1984), where h is the depth of the flow, C_{ai} is the concentration of sediment of the i^{th} size group at the reference level a above the bed, and

$$z = \frac{w_i}{\beta \kappa U_*} \tag{5}$$

where w_i is the fall velocity of the i^{th} size sediment, and κ is the von Karman constant. Equation (4a) has been termed the Rouse equation (Rouse, 1937) and has been shown to fit the form of the variation of suspended sediment concentration with depth for a variety of data sets from field and laboratory situations (Vanoni, 1975, p. 80). The prediction of the relative concentration of suspended sediment requires a reference sample near the bed and the values of w_i, β, and κ. The value of κ for this study was assumed to be 0.4, fall velocities were calculated using the relation of Dietrich (1982), and β was calculated using equation (3).

The mean grain size at each distance above the reference elevation was calculated as:

$$\phi_m = \frac{\sum C_i \phi_i}{\sum C} \tag{6}$$

where ϕ_i and ϕ_m are the grain size expressed as the negative log of base 2 of the i^{th} size group and the mean grain size at a depth of y, respectively, and the mean grain size in mm for a given depth (D_m) is

$$D_m = 2^{-\phi_m} \tag{7}$$

Grain sizes in this study were predicted using the Rouse equation, with β defined by eq. 3 (Van Rijn, 1984), because of the close correspondence between suspended sediment grain size measured in laboratory flume experiments and predicted values. The experiments were conducted in a flume at the National Sedimentation Laboratory, which had an adjustable slope channel 30 m in length, 1.2 m in width and 0.6 m in height. The bed material sediment had a median size of 0.52 mm, $(D_{84}/D_{16})^{1/2}$ = 1.54, and a standard deviation of 0.67 ϕ. Dune bed forms with three dimensional plan forms were present on the bed in both the phase I (depth= 0.13 m) and phase II (depth =0.33 m) experiments (Table 1).

Table 1 Experimental conditions in laboratory flume experiments.

	Flow discharge (m^3/s)	Flow depth (m)	Water surface slope	Mean flow velocity (m/s)	Froude number	U_* (m/s)
Phase I	0.3403	0.3280	0.00304	0.851	0.47	0.0798
Phase II	0.08157	0.1273	0.00301	0.526	0.47	0.0558

Suspended sediment samples and bed elevation data were collected 23.5 m downstream of the inlet tank using "L" shaped samplers with inside diameters of 4.4 mm (11/64 in) and outside diameters of 6.4 mm (1/4 in). All samples were collected isokinetically (sampler intake velocity = mean channel flow velocity) to avoid bias in the sampling of the suspended sediment. Errors in the concentration of suspended sediment, assuming suspended sediment was 0.15 mm in diameter and the intake velocity of the samplers was within ±20% of the local flow velocity, would be expected to be within ± 5 % based on the testing reported in Report no. 5 (1941). Samples were collected at 2-minute intervals, for either 20 or 40 seconds over 2-hr periods at five different heights above the mean bed elevation. A continuous record of the bed height was collected at the same sites with a 1 MHz acoustic device at 30 Hz.

The suspended sediment samples were composited based on height above the bed for each of the two flow conditions. This yielded sufficient material to determine the size distribution of the sediment at the five heights using sieve analysis. The sample nearest the bed was used as a reference with eqs. 4, 5, and 6 to calculate the size of sediment in suspension. The correspondence between the mean measured (D_{mm}) and mean calculated (D_{mc}) grain sizes for the two experimental conditions was quantified by calculating the mean absolute percent difference:

$$M_{pd} = 100 * \frac{\sum \left(\frac{|D_{mc} - D_{mm}|}{D_{mm}} \right)}{N} \tag{8}$$

where N is the number of measurements of suspended grain size above the bed. Values of M_{pd} for the phase I and phase II experiments were 6.0 and 2.5 %, respectively. On this basis, the Rouse equation (eq. 4), with β from eq. 3 (Van Rijn, 1984), was chosen to calculate the sizes of suspended sediment using reference values.

<u>Entrainment Relations:</u> In many instances it is difficult or impossible to collect a sample of the suspended sediment near the channel bed for use as a reference sample with eq. 4. This is especially true when the bed material has been shaped into large three-dimensional dunes by the flow. To fill the need for reference data, entrainment relations have been developed by a number of researchers to calculate the near bed reference concentration of suspended sediment using information on the flow strength, bed material grain size distribution, and the fall velocity of the grains. Seven entrainment relations were evaluated by Garcia and Parker (1991). Of these relations the best predictors were those proposed by Smith and McLean (1977), and Van Rijn (1984). Based on the determinations of Garcia and Parker (1991), the relations of Garcia and Parker (1991), Smith and McLean (1977), and Van Rijn (1984) were evaluated for their ability to predict the size of suspended sediment. Of the three entrainment relations chosen, the only one explicitly developed to consider individual sizes is the relation of Garcia and Parker (1991). The relations of Smith and McLean (1977) and Van Rijn (1984) were modified to apply to each grain size individually and scaled by the fraction of each grain size class in the bed material.

FIELD DATA

Studies in which information on the size of suspended sediment originating from widely-graded bed material at several distances above the bed were sought for this study. The data collected on the Niobrara River (Colby and Hembree, 1955) and the Rio Grande River (Nordin and Dempster, 1963) have information on bed material, flow conditions, sediment concentrations and grain size distributions for multiple elevations for the same flow condition. Data used in this study were restricted to those which consisted of at least four samples of suspended sediment concentration and size distribution at different elevations above the bed for a given flow condition. To remove the effects of hindered settling, data with high concentrations of sediment less than 62 microns in diameter were not used in this study. The data that met the above criteria consisted of 19 verticals with 76 total samples from the Niobrara River (Colby and Hembree, 1955), and 17 verticals with 73 individual samples from the Rio Grande River (Nordin and Dempster, 1963). The sizes of the sediment in suspension ranged from 0.11 – 0.18 mm for the Niobrara, and 0.11 – 0.17 mm and 0.10 – 0.14 mm for the Bernalillo and Socorro reaches of the Rio Grande, respectively. The characteristics of the flows present during the collection of the suspended sediment data used are summarized in Table 2.

Table 2 Summary of conditions for field data.

River	Bed material D_{50} (mm)	Flow depth (m)	Mean flow velocity (m/s)	Water surface slope (x 10^{-3})	U_* (m/s)
Niobrara	0.28	0.46-1.10	0.84-1.34	1.3-1.9	0.077-0.11
Rio Grande					
Bernalillo reach	0.18,	0.43-0.78	0.58-0.95	0.83-0.86	0.061-0.080
Socorro reach	0.31	0.20-0.47	0.72-0.88	0.76-0.98	0.044-0.065

Comparisons Between Calculated and Measured Sizes: The type of comparison desired is between instantaneous measurements and calculated values. This would correspond most closely to the type of information needed to calculate the sediment concentration from a given number of acoustic backscatter readings. The field data from the Niobrara and Rio Grande Rivers were collected sequentially over periods of several minutes for 4 or 5 points in the vertical. The scale of the processes in these channels indicates that changes in the local transport system were likely minor during that period of time.

The mean difference (eq. 8) between the calculated and measured mean grain sizes for each measured point for the Niobrara and Rio Grande Rivers were compared to sizes calculated using the Garcia and Parker (1991), Smith and McLean (1977), and Van Rijn (1984) entrainment relations combined with the modified Rouse equation (eq. 4). Comparisons were also made between calculated and measured sizes using the suspended sediment sample closest to the bed as the reference value for equation 4.

The mean differences for the three entrainment relations and Rouse equation yielded percent differences of 10.3, 17.5, and 37.0 for the Smith and McLean (1977), Garcia and Parker (1991), and Van Rijn (1984) relations respectively (Table 3). The percent differences for the Rio Grande data followed the same relative order (Table 4). In all cases using the sample collected closest to the bed yielded a better result for sediment size prediction than the three entrainment relations (Tables 3 and 4).

Table 3 Niobrara River grain size data (Colby and Hembree, 1955). Comparison between calculated and measured suspended sediment grain sizes.

Method of obtaining reference information for modified Rouse equation.	Mean absolute difference (mm)	Mean absolute percent difference
Garcia and Parker (1991)	0.026	17.52
Smith and McLean (1977)	0.014	10.28
Van Rijn (1984)	0.052	37.03
Reference sample (w/o ref. comparisons)	0.007 (0.010)	5.04 (6.70)

POTENTIAL ERRORS IN CONCENTRATION WITH ACOUSTICS

The potential errors that would result from calculating the concentration of the suspended sediment using acoustic backscatter data with incorrect sediment size information were analyzed. The concentration of suspended sediment from acoustic backscatter data may be calculated using Cheng and Hay's (1993) approach:

$$C = \frac{V_0 \rho}{B^2 f_\infty^2 x} \tag{9}$$

where V_0 is the voltage generated from acoustic backscattering, ρ is the particle density, B is the frequency dependent system constant, $x = kr$, where k is the wave number, r is the radius of the sediment particles, and f_∞ is the form factor which is a function of x.

Table 4 Rio Grande grain size data (Nordin and Dempster, 1963). Comparison between calculated and measured suspended grain sizes.

Method of obtaining reference information for modified Rouse equation.	Mean absolute difference (mm)	Mean absolute percent difference
Garcia and Bernalillo reach Parker (1991) Socorro reach	0.018 0.017	14.18 14.68
Smith and Bernalillo reach McLean (1977) Socorro reach	0.010 0.008	7.62 6.61
Van Rijn (1984) Bernalillo reach Socorro reach	0.066 0.028	51.30 24.11
Reference sample Bernalillo reach (w/o ref samples) Socorro reach	0.007 (0.009) 0.004 (0.005)	5.88 (7.56) 3.49 (4.60)

In Figure 1 the expected error in acoustically measured suspended sediment concentration caused by using an incorrect sediment particle size is depicted. These plots were prepared using data collected in a jet tank at the National Center for Physical Acoustics, University of Mississippi. The tank recirculated the water and sediment mixture and discharged a steady concentration of particles and sediment from a downwards oriented vertical jet (Smith, 2004). The data from the measurement volume of the jet consisted of backscatter amplitudes, sediment concentrations, and sediment particle sizes. The system constant (B) in equation 9 was solved for with the other variables being either known or measured. The two variables that depend on the sediment size in eq. 9 are f_∞ and x. In a channel with suspended sediment in transport, the sediment sizes at a level above the bed must be measured or estimated. Error in the concentration is introduced when incorrect particle sizes are used. Each line in Figure 1 results from assuming the particles in the insonified volume were of a given size. The x-axis represents the correct particle size with each line representing the assumed particle size. This results in an error of zero when the correct particle size is used. Achieving an error of zero percent was only possible because the system constant was calculated from the data used in the size estimate. The system constant is a weak function of sediment particle size and a mean value must be used in practice. The sensitivity of the calculation of sediment concentration using the acoustic backscatter technique is observed to be asymmetrical with the direction, negative or positive, of the error in sediment particle size

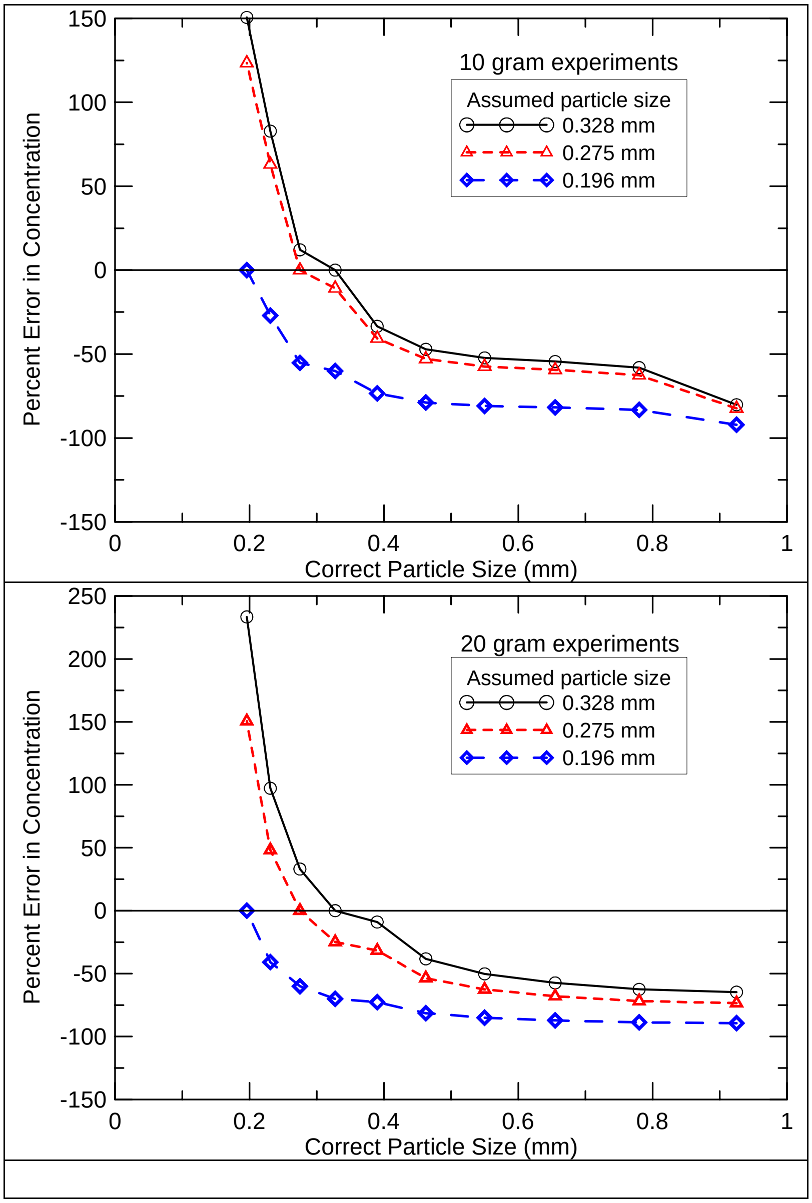

Figure 1 Errors in concentration due to incorrect grain size calculated using acoustic backscattering data from jet tank.

(Fig. 1). Therefore, mean errors between calculated and measured suspended sediment grain sizes were calculated separately for the negative and positive differences:

$$M_{di} = \frac{\sum (D_{mc} - D_{mm})}{N} \tag{10}$$

where the subscript i is either n for negative differences or p for the positive differences.Expected errors were calculated for the data from the Niobrara and Rio Grande Rivers using the error determinations from the laboratory jet experiments. If we assume that the actual size of the sediment in suspension is 0.196 mm, and that the errors by using the next smaller grain size (0.165 mm) are 100%, the errors in concentration calculated using acoustic backscattering along with the calculated suspended sediment sizes from the four different methods of estimating sediment size may be calculated. The weighted mean errors for suspended sediment concentration calculated using acoustics for the Niobrara data ranged from 20 to 84% using grain sizes calculated with the three entrainment functions and reference sample coupled with the Rouse equation. Preliminary error determinations for the Rio Grande data ranged from 12 to 55%. The lowest errors were obtained using the reference sample with the Niobrara and Rio Grande data. More precise error determinations will be made following the completion of further jet tank experiments with finer sediment sizes.

It is notable that the greatest errors in predicted suspension concentration do not necessarily correspond to the greatest differences between calculated and measured values. This result occurs because of the asymmetrical nature of the error curves around zero (Fig. 1), which illustrate the greater magnitude of errors for particle sizes which are less than rather than greater than the actual sediment size. The suspended sediment size determinations have been shown as a potential source of significant errors in the determination of suspended sediment concentration and the method chosen to estimate the grain size needs to be checked with physical samples to establish its accuracy.

CONCLUSIONS

Methods to predict the size of widely graded bed material sediment in suspension transported by streams and rivers have been explored using laboratory and field data. The percent difference between grain sizes calculated using entrainment functions and a modified form of the Rouse equation yielded mean differences of 37, 18, 10 and 5% for the Niobrara River data for the Van Rijn (1984), Garcia and Parker (1991), Smith and McLean (1977), and reference sample methods respectively. For the Rio Grande River data mean differences were 51, 14, 8, and 6% for the Bernalillo reach and 24, 15, 7, and 3% for the Socorro reach, for the Van Rijn (1984), Garcia and Parker (1991), Smith and McLean (1977), and reference sample methods respectively. The size predictions of the four methods were coupled with acoustic backscatter data collected in a test tank with a vertical jet to arrive at sediment concentration. These concentrations had preliminary errors ranging from 12 to 84% with the most accurate predictions of concentration from the reference sample and the Smith and McLean (1977) methods.

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