# CALCULATION OF SUSPENDED SEDIMENT AT GAGING STATIONS

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**Abstract**: A method for calculating stage-discharge relations (rating curves) and suspended sediment concentrations in gravel bedded streams is presented and applied to a reach downstream from a U.S. Geological Survey (USGS) gaging station on Little Prickly Pear Creek, MT. The approach uses a fluid-mechanically based model to convert measurements of stage into discharge and boundary shear stress fields appropriate for determining sediment transport. The model does not use empirical roughness coefficients, such as the Manning coefficient, but rather determines channel roughness from field measurements of the channel geometry and the dominant physical and biological roughness elements in the modeled reach. The theoretical flow rating curve produced by the model is in excellent agreement with direct measurements of discharge made by the USGS. An empirical relation between the concentration of fine sediment near the bed and the rate of bedload transport is developed using station sediment data. This relation and a point measurement of concentration as a function of grain size are employed by the model to calculate suspended sediment concentration fields and fluxes in the reach. The approach also can be used to generate a sediment rating curve. Our method has the potential of providing accurate estimates of stream flow and suspended sediment loads less expensively than conventional gaging methods.

## INTRODUCTION

The conventional USGS procedure for gaging discharge in rivers is to measure stage and then to calculate discharge from an empirically generated rating curve. Measuring stage is relatively easy using a pressure gage and is not particularly expensive. To determine an empirical rating curve, however, requires making discharge measurements at a wide range of stages and then fitting a curve to the stage-discharge data field. Although this approach has been used for over a century, attesting to its accuracy and robustness, procurement of the data necessary to generate an accurate empirical rating curve can be time consuming and expensive. By developing procedures that account for the fluid mechanical effects of all of the physical and biological roughness elements on the entire potentially wetted perimeter of a geomorphically stable reach of a stream or river, the resistance to flow can be explicitly determined as a function of stage, making possible a completely predictive model for the flow in that reach at all stages. Using such a fully predictive model (namely, one with no empirically adjusted coefficients) a "theoretical rating curve" can be constructed. We have developed such a model and tested the rating curves produced by it against the empirical rating curves at seven gaging stations [two in Kansas (Kean and Smith, 2005), three in Colorado, and two in Montana]. In all cases, the variance of the discharge measurements around our "theoretical rating curves" is comparable to or less than that around the empirical rating curves generated from the same data.

In addition to providing a less labor intensive and potentially more accurate means of calculating discharge at a gaging station, our model provides all of the fluid-mechanical parameters required to calculate bed-material (bedload and suspended-load) transport within the measurement reach. This paper describes how calculations of suspended sediment in a gravel bedded stream can be incorporated into the theoretical rating curve model. The approach is applied to a reach downstream from USGS gage station 06071300, Little Prickly Pear Creek at Wolf Creek, MT (Figure 1). Monitoring streamflow and suspended sediment concentrations on Little Prickly Pear Creek is particularly important for ecological reasons, because it is a major spawning tributary for migratory rainbow and brown trout from the Missouri River. Discharge measurements at the station are used to test the theoretical discharge rating curve calculated by our model. Daily values of suspended sediment concentrations recorded by the USGS from 1962-1967 are used to develop an empirical relation between the concentration of suspended sediment near the bed and the rate of bedload transport. This relation permits the calculation of accurate suspended sediment concentration fields using one or more point measurements of the sediment concentration as a function of grain size. The point sample is used to quantify the wash load and the amount of bed material of each sand size available for transport in suspension. The latter depends on the amount of fine sediment contributed to the channel and on the flow history of the stream. The combined flow and sediment transport model is then used to (1) reconstruct the flow and sediment transport fields for a high discharge in Little Prickly Pear Creek, and (2) demonstrate the effect that density stratification can have on the velocity and sediment concentration fields for flows with moderate to high concentrations of sand.

Figure 1 (a) Downstream view of Little Prickly Pear Creek from bridge. (b) View upstream from middle of the measured reach.

## MODEL COMPONENTS

The model for calculating a theoretical stage-discharge relation is composed of two parts: a set of procedures for quantifying the various contributions to the total flow resistance in the channel and a flow model into which the results of these procedures are embedded. The description that follows is for the components necessary to calculate a rating curve and the suspended sediment transport fields for Little Prickly Pear Creek, which is relatively straight and which has a flow resistance due primarily to bed roughness and drag on the bank vegetation. A more detailed description of the model components required to develop a rating curve for narrow channels with these characteristics is given in Kean and Smith (2005). Their paper also outlines the procedures required to incorporate flow resistance caused by lateral stresses on irregularly shaped banks, which are not needed to address the flow and sediment transport in Little Prickly Pear Creek.

**Bed roughness**: In channels with gradually sloping banks, width-to-bankfull-depth ratios greater than about 10, and gravel beds that are devoid of significant form-drag-producing topographic elements, the vertically averaged velocity at any position in the channel ($\bar{u}$) can be related directly to the local boundary shear stress ($\tau_b$) through the expression

$$\bar{u} = \left(\tau_b / \rho\right)^{1/2} \beta = u_* \beta \tag{1}$$

where $\rho$ is the density of water, $u_*$ is the local shear velocity, and $\beta$ is a non-dimensional roughness coefficient that is a function of the size of the bed material, the flow depth ($h$), and the shape of the velocity profile. In this case, the boundary shear stress is that appropriate for calculating bed material transport, and is given by $\rho g h S_f$. Here $g$ is the acceleration of gravity and $S_f$ is the friction slope. Under these conditions, the velocity profile will be quasi-logarithmic in shape (see Wiberg and Smith, 1991), and $\beta$ will have the form

$$\beta = \left[\ln\left(h/z_o\right) - 0.74\right] / \kappa \tag{2}$$

where $\kappa$ is von Karmann's constant equal to 0.408 (Long et al., 1993). The roughness height, $z_o$, can be related to the moments of the particle size distribution for the gravel composing the bed. An adequate approximation is $z_o = 0.2D_{84Z}$, where $D_{84Z}$ is the diameter at the 84$^{th}$ percentile of the size distribution for the vertically oriented axes (Wiberg and Smith, 1991). Alternatively, if the diameters of the vertically oriented axis are half of the nominal diameters ($D_N$), the approximation $z_o = 0.1D_{84N}$ (Whiting and Dietrich, 1989) can be used.

**Vegetation roughness**: In vegetated portions of the channel (edges), the velocity and boundary shear stress are reduced by drag on the plant stems, which can be calculated using the method of Smith (2001). The stems are modeled as a randomly distributed array of circular cylinders that have a mean stem diameter ($D_s$) and mean spacing ($\lambda$) specified from field measurements. In this application the stems are assumed to be rigid and extend throughout the entire flow depth. Drag on the field of stems acts as body force on the fluid, and the average drag force on an individual stem ($F$) is given by

$$F = \tfrac{1}{2}\rho C_D D_s h\left(u_{ref}\right)^2 \tag{3}$$

where $u_{ref}$ is reference velocity and $C_D$ is the drag coefficient of a single stem, which for the flows of interest here is constant and equal to 1.2. The reference velocity is defined as $u_{ref} = [(\int_{z_o}^{h} u^2 dz)/h]^{1/2}$, where $u$ is the local velocity within the field of stems. A suitable approximation for the reference velocity can be made using (1), (2), and a shear velocity that reflects the reduced boundary shear stress caused by the form drag on the stems (Smith, 2001 and 2004). By converting the drag force on a single stem into a drag stress (that is, by dividing (3) by $\lambda^2$) and separating it from the total boundary shear stress, Smith (2001) obtained an expression for the boundary shear stress within the stems, which is given by

$$\tau_b = \frac{\rho g h S_f}{1+\sigma_D} \text{ where } \sigma_D = \tfrac{1}{2} C_D \beta^2 \frac{hD_s}{\lambda^2} \tag{4}$$

**Channel Flow Model**: Owing to the fact that the study reach is relatively straight and does not contain large amplitude bars that would steer the high velocity core of the flow from side to side in the channel, a simple steady, one-dimensional model is sufficient to resolve the dominant flow accelerations in the reach. Application of such a model requires the average velocity for a cross-section, $(u)_{av}$, to be related to the perimeter-averaged shear stress, $(\tau_b)_{av}$. This is done using an expression analogous to (1), given by $(u)_{av} = \beta_r[(\tau_b)_{av}/\rho]^{1/2}$, where $\beta_r$ is the non-dimensional roughness coefficient for the cross-section. The value of $\beta_r$ varies as a function of stage and streamwise position, and this variation can be specified completely a priori using the roughness methods outlined in the previous sections. For a given stage and cross-section, $\beta_r$ is calculated by integrating the unit discharge ($\bar{u}h$), obtained from (1), (2), and (4), across the cross-section and dividing this value by the area of the cross-section and the shear velocity computed from $(\tau_b)_{av}$. Specification of $\beta_r$ in this manner differs from most applications of one-dimensional models, where $\beta_r$, or its equivalent Manning coefficient ($n = R^{1/6}g^{-1/2}\beta_r^{-1}$) or Chezy coefficient ($C = g^{1/2}\beta_r$), is either determined empirically by measuring the water discharge and water-surface elevations (e.g. Wiele and Smith, 1996) or is estimated from experience or the results of previous studies (e.g. Barnes, 1967; Limerinos, 1970).

The discharge for a given stage is determined iteratively by solving the one-dimensional model for the water-surface profile that matches both the stage and a measured water-surface elevation drop through the reach. In addition to discharge, the solution yields a quasi three-dimensional representation of the velocity field, meaning that values of velocity, shear stress, and eddy viscosity are provided by the solution for all points in the flow field. The theoretical rating curve for the reach is generated by repeating the calculation for different stages over the range of flows that can occur at the site. The calculated boundary shear stress fields with the effects of form drag on the shrubs removed are used in the next section to determine bedload and suspended sediment transport in the measurement reach.

Sediment Transport Model: The method of McLean (1992) can be used to calculate profiles of sediment volume concentration ($C_s$) given vertical distributions of shear stress and eddy viscosity and a reference sediment concentration ($C_a = C_s(z=a)$) and size distribution. For sand bedded channels, the concentration at the top of the saltation height of the particles is defined based on the work of Smith and McLean (1977). This formulation for $C_a$ has been employed by Andrews (2000) to calculate suspended sediment concentrations in a predominately gravel bedded stream that had patches of sand on the bed. For gravel bedded streams that do not have distinct patches of sand, however, the Smith and McLean (1977) formulation for $C_a$ is not applicable, because the fine sediment is located within the interstices of the pebbles, which shield the fine sediment from the flow processes that entrain the particles into the moving fluid. A second complication in calculating suspended sediment in gravel bedded streams is that fluid stresses below the level of the largest clasts are reduced due to the form drag on the clasts. This latter complication can be addressed by applying the method of Wiberg and Smith (1991) to calculate the profiles of stress and eddy viscosity down to the level of zero flow. Their method determines the momentum extracted from the flow by drag on each size class of the bed material. The former complication is addressed here for mobile beds without sand patches by developing an empirical model for $C_a$ in a gravel bedded stream using data on daily sediment concentrations recorded at the USGS gaging station on Little Prickly Pear Creek between 1962 and 1967. We hypothesize that $C_a$ is related to the non-dimensional rate of significant bedload transport ($\phi$) by an empirical constant of proportionality ($\alpha$) that depends on the concentration of fine sediment in the bed. Bedload transport is modeled here using a modified Meyer-Peter Müller equation

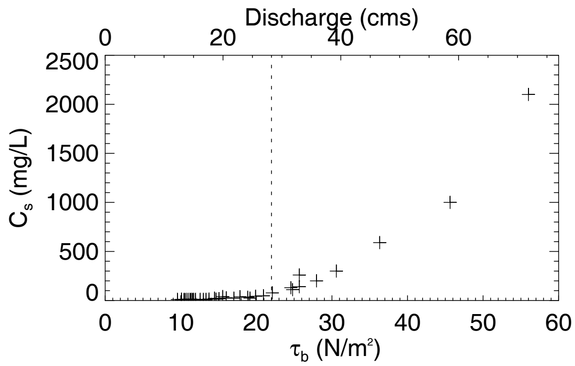



Figure 2 Daily suspended sediment concentration vs. daily discharge and boundary shear stress for the falling limb of the flood on 9 June 1964. The vertical dashed line corresponds to the critical boundary shear stress for significant motion.

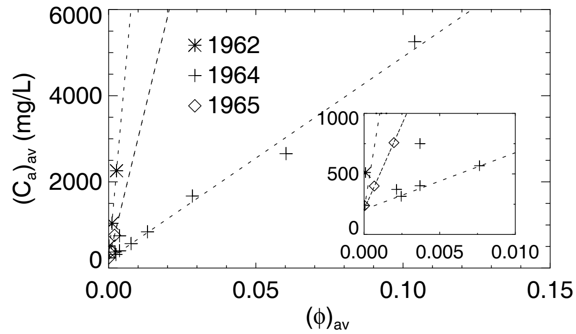



Figure 3 Empirically determined values of $(C_a)_{av}$ versus $(\phi)_{av}$ for selected spring flow events.

$$\phi = 8\left(\tau_* - \left(\tau_*\right)_{crt}\right)^{3/2} \tag{5}$$

where, $\tau_*$ and $(\tau_*)_{crt}$ are the non-dimensional shear stress and critical shear stress respectively. The reference level, $a$, is presumed to be related to the size of the bed material and is taken here to be $D_{50N}/2$, where $D_{50N}$ is the median size of the probability distribution for the measured nominal grain diameters. Basically, when the clasts composing the river bed move, the sand from beneath is released into the flow by the method proposed here. In contrast, when the coarse bed material remains stationary or moves only as marginal transport, sand must build up in patches on the stream bed before significant sediment transport can occur in the manner described by Andrews (2000). These two cases are mutually exclusive and depend on whether the clasts move in significant transport or not.

An example of the dependence of suspended sediment concentrations on shear stress is shown in Figure 2. The figure contains daily values of suspended sediment concentration for the falling limb of the flood on 9 June 1964, which produced the highest measured discharge, as well as, the highest daily sediment concentration recorded in the station's history. The concentrations in the figure are plotted against both discharge and an estimate of the mid-channel boundary shear stress for that discharge. The estimate of boundary shear stress is obtained from application of the theoretical rating curve model to a measurement reach adjacent to the gage station. Although the model for the reach is based on recently measured topography, the reach averaged mid-channel boundary shear stress is assumed to be representative of the stress during the 1964 flood. The figure shows that sediment concentrations increase substantially after a threshold stress or discharge (denoted by the dashed line) is obtained. This threshold is thought to represent the critical shear stress ($\tau_{crt}$) for significant motion of the gravel comprising the bed. The non-dimensional shear stress for this threshold based on the $D_{50N}$ of the present bed is 0.036, which is within the range of observed values for $(\tau_*)_{crt}$ compiled by Buffington and Montgomery (1997). Plots of daily concentration and shear stress for the falling limbs of five other spring flow events exhibit the same trend shown in Figure 2 but have varying critical shear stress thresholds. The values of $(\tau_*)_{crt}$ determined visually for the other flows are 0.037, 0.041, 0.046, 0.037, 0.044. The mean $(\tau_*)_{crt}$ for the six flows is 0.040.

The hypothesis that $C_a$ is linearly related to $\phi$ is tested as follows. For a given flow, where data on daily sediment concentration and discharge are available, the coupled flow and sediment transport model is inverted to find the distribution of $C_a$ across the channel that yields the average concentration field that was recorded for that day. The concentration field is generated by computing concentration profiles at about 50 positions across the channel. The value of $C_a$ for each vertical is specified by the product of the local $\phi$ and a fixed constant for the cross-section that is determined through iteration. Ancillary data on the size distribution for the daily values of concentration is not available, so a log-normal distribution composed of five size classes of sand (0.0625, 0.125, 0.25, 0.5, and 1 mm) is used to represent the fine bed material. The concentration fields are reconstructed for the falling limbs of six spring flows between 1962-1967. Spring flows are used for the analysis, because these flows have the highest discharge and sediment concentrations. Data from the rising limbs of the flows have been excluded, because the total concentration during this time can have greatly varying percentages of wash load generated by initial runoff from the hillslopes and/or bank failures, and the grain size data necessary to separate the wash load from suspended bed-material load is not available.

The results of these calculations for three of the six floods are shown in Figure 3. The average of the back-calculated distribution of $C_a$ across the cross-section, $(C_a)_{av}$, is plotted in relation to the cross-sectional average of the non-dimensional bedload transport rate, $(\phi)_{av}$. The data for each flow is fairly linear demonstrating that our model for $C_a$ is appropriate. The volumetric concentration at $(\phi)_{av} = 0$ for these trends is nearly the same, and the mean for the six flows in units of mg/L is 266. This intercept ($(C_a)_o$) represents the value of $C_a$ at the beginning of significant bedload transport. In the absence of wash load, $(C_a)_o$ represents the effects of marginal transport of the gravel on the availability of the fine bed material for transport. The value of $(C_a)_o$, however, is very small and consideration of the dependence of $C_a$ for marginal transport is beyond the scope of this paper. If wash load were present, the volumetric concentration of silt and/or clay measured in a point sample, which would be representative of the value throughout the water column, would have to be added to the value of $(C_a)_o$ determined from the marginal transport regime. Based on the results shown in Figure 3, the expression for $C_a$ in Little Prickly Pear Creek is given by

$$C_a = \alpha\phi + \left(C_a\right)_o \tag{6}$$

The value of $\alpha$ depends on the amount of sand in the bed, which, in turn, depends on the source of the fine sediment and the flow history. As is typical in most suspended sediment transport problems, it is easier and more accurate to specify $\alpha$ by one or more point measurements of concentration and a size distribution than to measure the concentration and size distribution of fine sediment in the riverbed during a flood. Although $\alpha$ can vary with time in a given stream, it represents the state of the bed after the last sand transporting event and there is no reason that it should vary with cross-stream position during a particular flood.

Table 1 Summary of channel characteristics for Little Prickly Pear Creek at Wolf Creek, MT

| Reach Characteristics: | Roughness Characteristics: |
|---|---|
| Location: Lat. 47°00'19" Long. 112°04'10" | $D_{50Z}$: 21 mm $D_{84Z}$: 47 mm (vertical axis) |
| Drainage Area: 987 km$^2$ | $D_{50N}$: 47 mm $D_{84N}$: 81 mm (nominal diameter) |
| Reach Length: 132 m | $z_o$: 0.009 m |
| Meas. water-surface slope at 1.1 cms: 0.0033 | Mean willow stem diameter: 0.018 m |
| Meas. water-surface slope at 29 cms: 0.0035 | Mean willow spacing: 0.258 m |

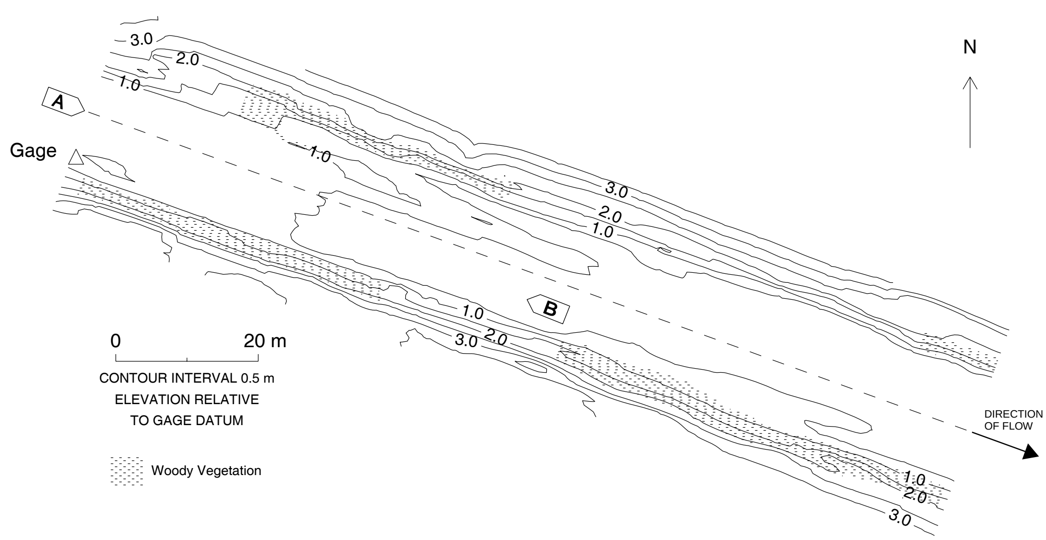



Figure 4 Map of surveyed reach. Arrows A and B indicate the approximate positions where the photos in Figure 2 were taken.

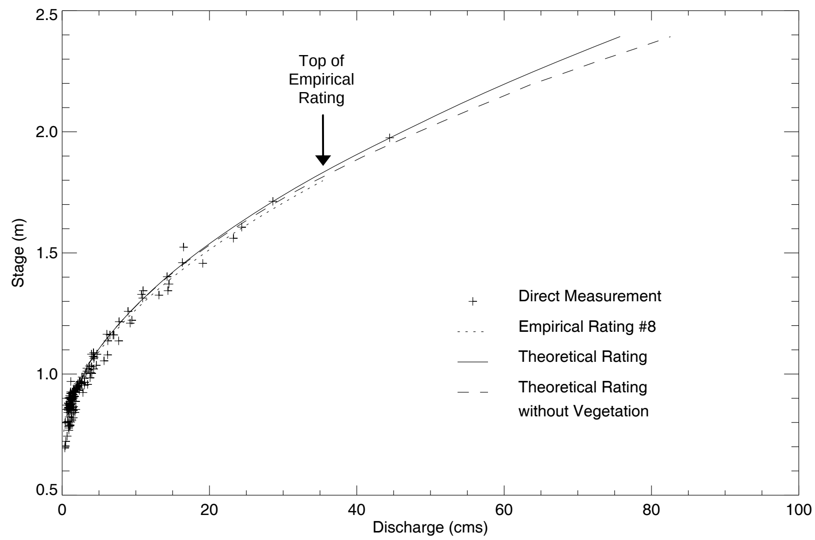


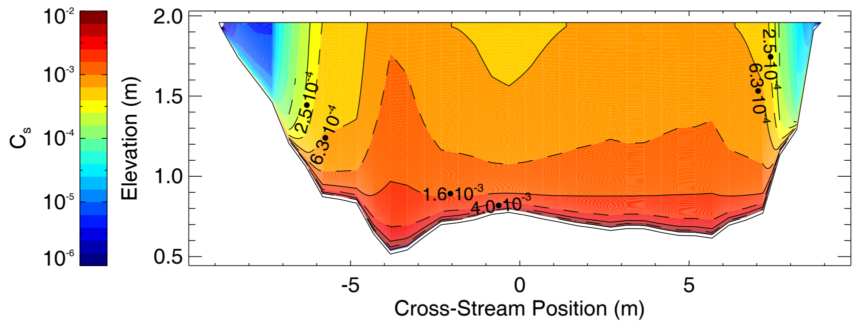

Figure 5 Comparison of rating curves and measurements for Little Prickly Pear Creek. Stage is relative to the USGS gage datum. Direct measurements of discharge are shown for the station's present location (established 1991).

## APPLICATION TO LITTLE PRICKLY PEAR CREEK

The field measurements required to make the model for the site were made by a two person crew on 26 October 2004. A summary of these measurements is given in Table 1.The shape of a reach downstream from the USGS gage was measured by surveying 22 cross-sections spaced about every 6 m using high-precision GPS surveying equipment (Figure 4). The size of the bed material was determined from Wolman pebble counts made at three locations in the reach (Wolman, 1954). The short, intermediate, long, and protrusion axis of each pebble was recorded. All four measurements are required to apply the model of Wiberg and Smith (1991), which is used in the computation of velocity and turbulence profiles. The stem density of the willows along the bank was determined by counting and recording the diameter of stems within two 3m x 3m plots adjacent to the channel. The location of the willows was mapped during the survey. The bed $z_o$ for the reach is specified from the measured size distribution of the bed material through $z_o = 0.2D_{84Z}$. Water-surface profiles were surveyed at low flow at the time of the main field work and at high flow on 11 May 2005. These profiles show that the water-surface elevation drop across the reach, which is a boundary condition in the model, remains nearly constant as a function of stage.

A comparison of the theoretical rating curve with the USGS discharge measurements and empirical rating curve is shown in Figure 5. In general, there is good agreement between the theoretical rating curve and both the direct measurements and empirical rating curve. The theoretical rating curve calculated without the effects of drag on vegetation shows that this source of flow resistance is only important at very high stages. A quantitative comparison of the agreement of the empirical and theoretical rating curves with the measurements can be made by comparing the total weighted variance of the two curves about the measurements within the stage range shared by the two curves (see Hill, 1998; Kean and Smith, 2005). In general, the total weighted variances for the theoretical rating curve are comparable to the empirical rating curve.

The following example is given to illustrate how the theoretical rating curve method can be used together with one or more measurements of sediment concentration and size distribution to calculate suspended sediment concentration fields and fluxes. The example uses USGS sediment measurements made on 13 June 1967 in Little Prickly Pear Creek to reconstruct the concentration field. The measurements, which are given in Table 2, are used to specify both the size distribution of fine sediment in the bed and the value of $\alpha$ that sets $C_a$ across the cross-section through (6). Initial guesses of these parameters are used to calculate the suspended sediment concentrations at the position(s) where measurements were made. Guesses of $\alpha$ and the size distribution of the fine sediment in the bed are improved iteratively until the calculation converges on the measured values. The measured sediment data used in this example is averaged over the cross-section. In practice, a small set of point measurements of concentration and size distribution in the same vertical is preferable, because it provides a better constraint on the calculation. Figure 6 a)




b)

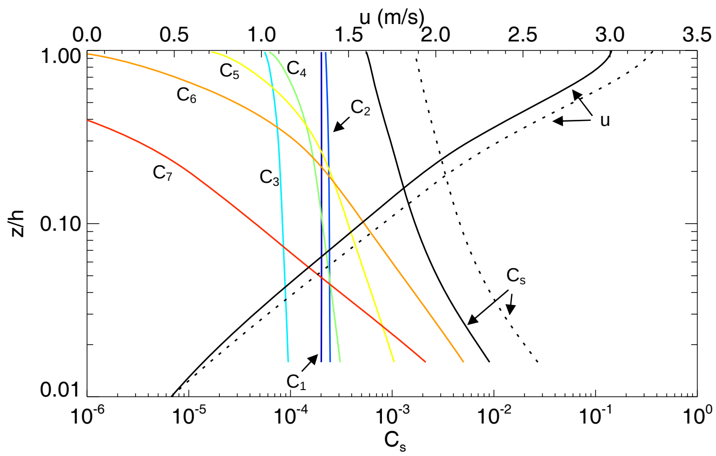



Figure 6 Calculated (a) concentration field and (b) and concentration and velocity profiles in the center of the channel for the 13 June 1967 high flow. The grain sizes of the concentration profiles C1 through C7 are: 0.010, 0.039, 0.094, 0.188, 0.375, 0.75, and 1.5 mm. The dotted lines are the velocity and total concentration profiles for a hypothetical event having 3 times the amount of fine sediment in the bed as in the 13 June 1967 flow.

shows the calculated concentration field at the gage cross-section and the calculated profiles of concentration and velocity in the center of the channel. The value of $\alpha$ determined for this flow is 0.11 and corresponds to a $C_a$ in the center of the channel of 1%. The back-calculated size distribution of the fine material in the bed (listed in Table 2) is dominated by medium sand and differs greatly from the average distribution for the cross-section.

Vertical variations in sediment concentration produced by suspended grain sizes larger than silt create a density gradient that can, if sufficiently large, alter the velocity and turbulence fields. Although this effect is negligibly small in the present example, it can be appreciable for cases having larger amounts of sand. For example, given the same stage, boundary shear stress, and fine sediment size distribution in the bed, raising $\alpha$ by a factor of three creates a density gradient that increases the discharge by 8%. The velocity and concentration profiles in the center of the channel for this case are shown in Figure 6b. It is important to note that a single point measurement of total concentration is not sufficient to evaluate accurately the effects of density stratification, but a single point measurement that is separated into size classes is sufficient for this purpose.

Table 2 Meas. and calc. cumulative size distributions for the 1967 flow ($Q$ = 45.6 cms, $(C_s)_{av}$ = 2780 mg/L).

| Size (mm) | 0.004 | 0.016 | 0.063 | 0.0125 | 0.25 | 0.5 | 1 | 2 |
|---|---|---|---|---|---|---|---|---|
| Measured % finer for cross-section | 8 | 20 | 43 | 50 | 63 | 78 | 97 | 100 |
| Calculated % finer at $z = a$ | - | 2 | 5 | 6 | 9 | 21 | 76 | 100 |

## SUMMARY AND CONCLUSIONS

This paper presents a method for calculating theoretical stage-discharge relations and suspended sediment concentrations and fluxes in gravel bedded streams. The approach utilizes a fluid-mechanically based model that does not rely on empirical roughness coefficients, such as Manning or Chezy coefficients, to convert measurements of stage into discharge, and it determines the distributions of boundary shear stress appropriate for sediment transport calculations. One or more point measurements of suspended sediment size and concentration are used to specify the amount of sand of each relevant size class in the bed and the percentage of silt and clay in the flow. For flows with significant gravel transport, the distribution of sediment concentration throughout the reach and its effect on the velocity field and water discharge are better left for the model to determine than to try to characterize them empirically. A combined calculation/measurement scheme, such as the one presented here, has the potential for substantially increasing the accuracy and reducing the cost of gaging streamflow and sediment. It also provides a foundation for calculating the transport of contaminants sorbed to sediment grains.

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