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VI. Fluvial: Sediment Transport Mechanics

VI. FLUVIAL: SEDIMENT TRANSPORT MECHANICS

A TRANSPORT ALGORITHM FOR VARIABLE SEDIMENT SIZES: APPLICATION TO WIDE SEDIMENT SIZE DISTRIBUTIONS

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__Abstract__: Total sediment transport was estimated as the summation of the transport rate of 12 sediment size fractions which were computed by an algorithm composed of three different transport relations. An effective diameter for critical flow strength is used in the algorithm to account for the effect of the sediment mixture on the initiation of motion of each size fraction. Tests with laboratory and field data sets show that the transport algorithm gives reasonable estimates of both grain size and the rate of sediment in transport.

INTRODUCTION

Any long term program of channel stabilization must consider the transport of sediment through the watershed. For such applications the accurate estimation of the sediment transport rate and its size distribution for streams with widely graded sediment size distributions is important. An imbalance between sediment supply and transport capacity will cause channel adjustments or instabilities to occur. In streams that contain an appreciable percentage of gravel in the bed material, predictions of the transport rates of the different size fractions are important to determine whether bed surface armoring will form. A sediment transport algorithm was developed to allow predictions of the sizes and rates of sediment transport in streams with widely graded bed material. This paper focuses on the parts of the transport algorithm that specifically address the transport of widely graded bed material. The predictions of the sediment transport algorithm is tested with both laboratory and field data.

CALCULATION OF SEDIMENT TRANSPORT

__**Sediment Transport Algorithm:**__ The algorithm used to calculate the transport rates (SEDTRA) uses 12 different size fractions and three different established transport relations (Garbrecht et al., this volume). The transport relations are: Laursen (1958) three size groups from 0.010 from 0.250 mm, Yang (1973) two size groups from 0.250 to 2.000 mm, and Meyer-Peter Mueller (1948) seven size groups from 2.000 to 50.000 mm. Sediment transport is calculated as

$$C_t = \Sigma [C_i * P_i] \qquad (1)$$

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where C_t is the total sediment transport capacity in parts per million by weight (ppmw), C_i is the sediment transport capacity in ppmw for the i^{th} size fraction, and P_i is the fraction of sediment in the i^{th} size group.

Critical Flow Strength for Mixtures: The Shields curve (Miller et al., 1977) has been shown to be a reliable predictor of the flow strength necessary for the initiation of motion of cohesionless particles with a narrow size range under uni-directional flows. For sediments with a widely graded size distribution, however, the differences in the critical flow strength among the different sizes tends to be significantly reduced (Parker et al., 1982; Andrews., 1983; Wilcock and Southard, 1988, Kuhnle, 1992, 1993a). Widely graded sediment beds tend to increase the critical flow strength for initiation of the sizes finer than the mean size and decrease the critical flow strength of the sizes coarser than the mean size. If the effect of the mixture is ignored in the computation of transport rates, the predicted rates for sizes finer than the mean size will generally be over-predicted and rates for the sizes coarser than the mean size will generally be under-predicted. In Figure 1 the effect of

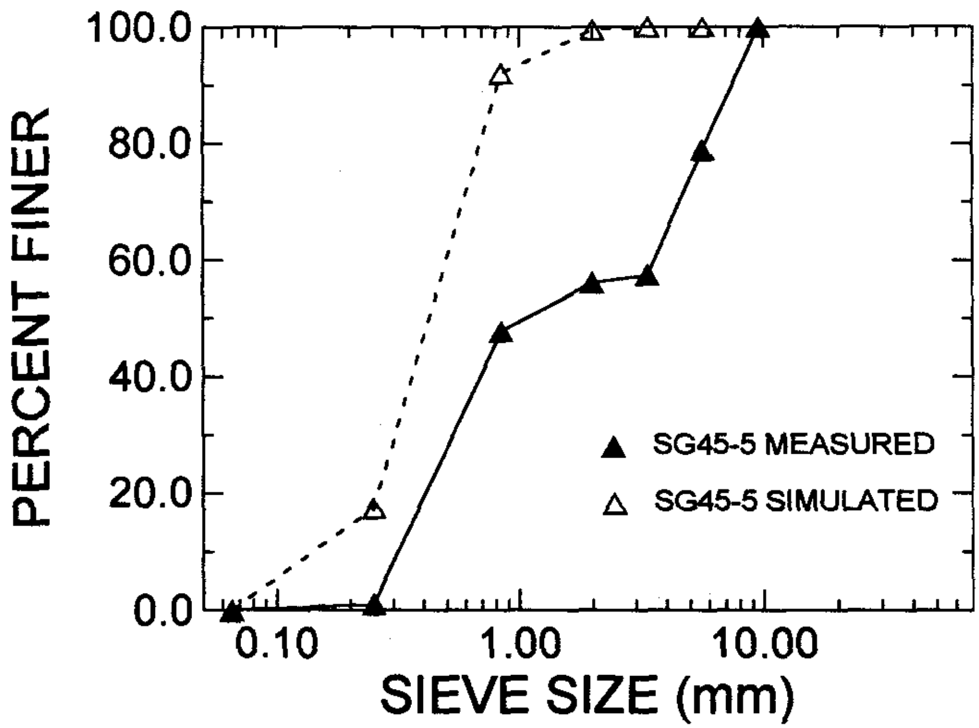

Figure 1. Simulated grain size distribution assuming no effect of the mixture on critical flow strength for initiation of motion; laboratory data from the SG45-5 test run of Kuhnle (1993a).

the mixture on the initiation of motion was ignored, and the resulting over-prediction of the fine sizes and under-prediction of the coarse sizes yielded a predicted size distribution much finer than the measured one.

To account for the effect of the mixture on the critical flow strength of the individual size fractions the critical diameter for initiation of each of the 12 size fractions was defined as

$$D_{ci} = D_i \left(\frac{D_i}{D_m} \right)^{-x} \tag{2}$$

(Garbrecht et al., 1995) where D_i and D_{ci} are mean and critical sediment diameter for size fraction i, respectively; D_m is the mean size of the bed material sediment; and x is a constant. The constant x ranges from 0 to 1. For $x = 1$, the D_m of the sediment is the critical diameter for all size fractions, and all fractions tend to move at the same flow strength. For $x = 0$ each size fraction behaves independently of the others and the D_i for each size fraction is used to calculate the flow strength at which motion begins. Sediment mixtures with a unimodal size distribution tends to have all sizes entrained over a narrow range of flow strengths and are best represented by values of x near one, while sediments with bimodal size distributions retain some size dependency in entrainment and values of x range from less than 1 to 0.

If the critical diameter for initiation of motion is to be predicted for channels for which no sediment transport data is available, a method of estimating x is needed. Wilcock (1993) found that the variation of critical shear stress with size in a given sediment mixture was related to the bimodality of the mixture. The relation between critical shear stress and grain size was found to be nearly a constant for sediment with weakly bimodal or unimodal size distributions, while for sediments with bimodal distributions the critical shear stress was still a function of size, although less so than predicted by the Shields relation (Miller et al., 1977). Wilcock (1993) defined a bimodality parameter B as

$$B = \left(\frac{D_c}{D_f} \right)^{\frac{1}{2}} \Sigma P_m \tag{3}$$

where D_c and D_f are the diameters of the coarse and fine modes, respectively, and P_m is the portion of the sediment mixture contained in the coarse and fine modes. For values of B less than 1.7 Wilcock found that all sizes were entrained over a narrow range of shear stress. For values of B greater than 1.7, the critical shear stress was an increasing function of size. Following after Wilcock (1993) the bimodality parameter B was used to predict the constant x in equation (2). The relation between x and B was defined as

$$x = \frac{1.7}{B} \tag{4}$$

where $x = 1$ when B is less than 1.7, and x approaches zero for high values of B.

APPLICATION OF THE ALGORITHM

The transport algorithm was applied to sediment transport data collected from two laboratory studies and one field study. These data sets have complete information on the size distribution of the parent material and sediment in transport as well as the information on the flow. The six data sets from these studies are summarized in Table 1. In the two laboratory studies, steady and uniform flows were maintained and experiments were continued until an equilibrium condition was established. Reported sediment transport rates were averages of samples collected over periods of hours. The field data was collected at Goodwin Creek using a boom-mounted DH-48 and modified Helley-Smith sampler. The size distribution used for the bed material at Goodwin Creek was obtained from the size distribution of the sediment in transport at the highest flow for which sediment transport was measured. This was because the sediment in transport did not approach the measured size distribution of the bed material at high flow rates.

Table 1. Summary of Data

mixture name	Reference	Dm (mm)	Distribution type	B	x
SG10 (laboratory)	Kuhnle (1993a)	0.616	bimodal	2.49	0.7
SG25 (laboratory)	Kuhnle (1993a)	0.927	bimodal	2.60	0.7
SG45 (laboratory)	Kuhnle (1993a)	1.454	bimodal	2.73	0.6
1/2 ϕ (laboratory)	Wilcock and Southard (1988)	1.82	unimodal	0.67	1.0
1 ϕ (laboratory)	Wilcock and Southard (1988)	1.85	unimodal	0.37	1.0
Goodwin Creek (GC) (field)	Kuhnle (1993b)	1.189	bimodal	3.10	0.5

Note: The mixture names for the laboratory data (Kuhnle, 1993a) refer to the percentage of gravel in the bed material sediment: SG10 - 10% gravel, 90% sand; SG25 - 25% gravel, 75% sand; SG45 - 45% gravel, 55% sand. The mixture names of Wilcock and Southard (1988) refer to the standard deviation of the bed material sediment.

Total Transport Rates: The simulated total sediment transport rates compared well with the measured transport rates (Fig. 2) from the laboratory experiments of Kuhnle (1993a) over the whole range of measured data. The simulated transport rates also matched well the measured transport rates from Wilcock and Southard (1988) with the exception of the lowest transport rates (Fig. 3). Simulated sediment transport rates were significantly over predicted for the four lowest measured rates for the 1/2 ϕ and 1 ϕ sediments. For the data from Goodwin Creek (GC) the simulated total transport rates were somewhat higher than the measured rates for low and intermediate measured transport rates (Fig. 4).

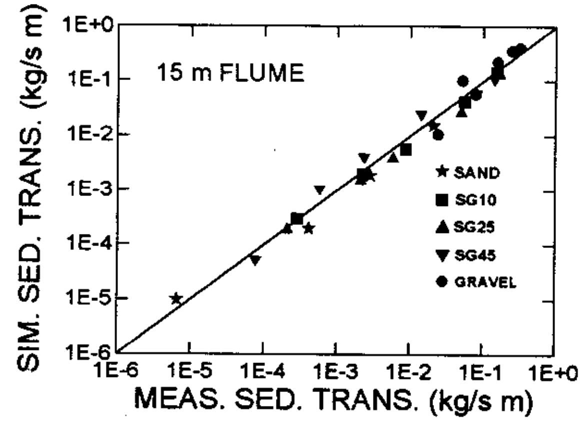

Figure 2. Simulated versus measured total sediment transport rate; laboratory data (Wilcock and Southard, 1988). Solid line represents perfect agreement.

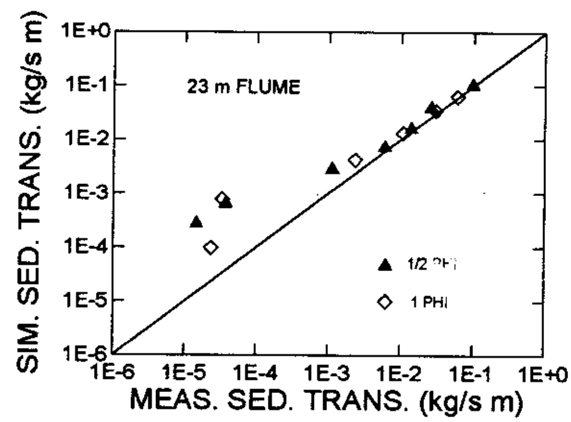

Figure 3. Simulated versus measured total transport rate; laboratory data (Wilcock and Southard, 1988). Solid line represents perfect agreement.

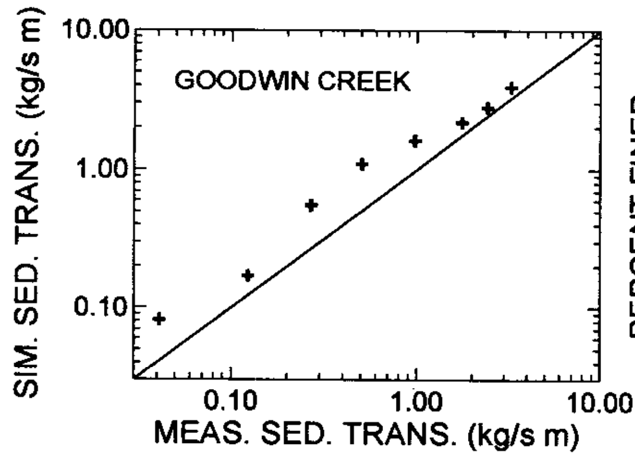

Figure 4. Simulated versus measured bed material transport rate; Goodwin Creek (Kuhnle, 1993b). Solid line represents perfect agreement.

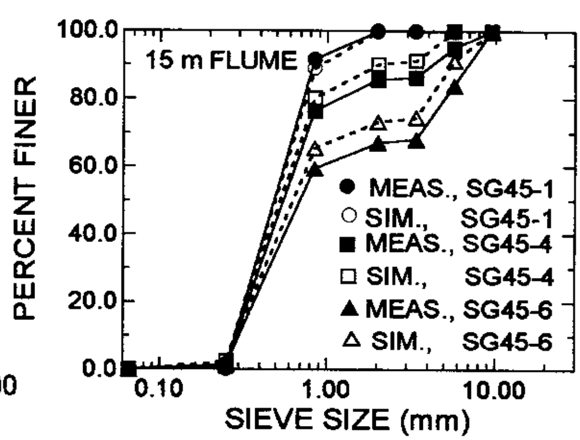

Figure 5. Simulated and measured grain size distribution of sediment in transport; laboratory data (Kuhnle, 1993a).

__Size Distribution of Transported Sediment:__ The simulated and measured size distributions of the sediment in transport compared well for the SG series of data. Three examples from SG45 are shown in Figure 5 and are representative of the fit of the simulated data for the other 2 series of SG experiments. The correspondence of the simulated size distributions with the measured distributions is reasonable for intermediate and high transport rates for the 1/2 and 1ϕ sediments, but show some significant deviations for low transport rates (Fig. 6). Measured size distribution of the sediment in transport from Goodwin Creek is reasonably simulated by the model. Lower transport rates (GC-3), however, also show substantial deviations from the simulated size distribution (Fig. 7).

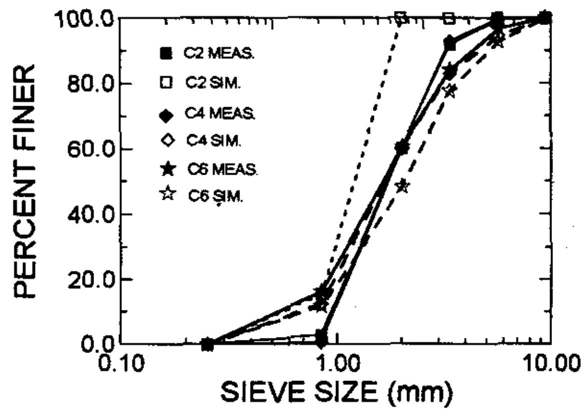

Figure 6. Simulated and measured grain size distribution of sediment in transport; 1 ϕ laboratory data (Wilcock and Southard, 1988).

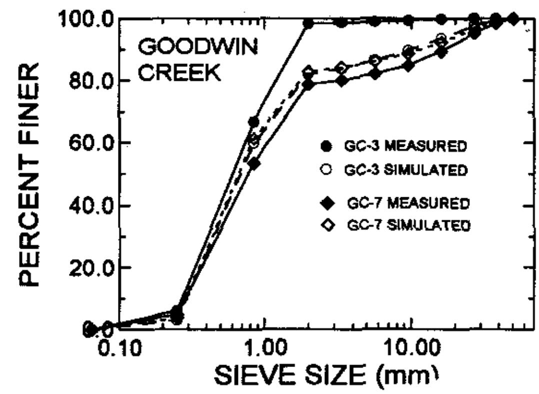

Figure 7. Simulated and measured grain size distribution of sediment in transport; Goodwin Creek (Kuhnle, 1993b). A low (GC-3) and a high transport rate (GC-7) example are shown.

DISCUSSION

With the exception of the data from the low transport experiments of Wilcock and Southard (1988), the simulated total transport rates and size distributions provide reasonable predictions of the measured data from the two experimental studies. The fact that the low flow points of the 1/2 and 1 ϕ beds are not predicted well by the transport algorithm may be due to the fact that these experiments were conducted at flows very close to the critical flow strength of the bed material. In this range of flows, accurate measurement of flow and sediment transport rate is very difficult. Small errors in measured flow values can lead to large errors in predicted transport because of the steepness of the transport relations. Also, for flows close to the critical flow strength, migration rates of bed forms that may be present are very slow, and it is very difficult to sample for sufficiently long times to assure that a representative sample is collected.

With the exception of the size distribution data of the lowest flows, the transport algorithm does an adequate job of predicting the transport in Goodwin Creek (GC). However, the input size distribution used was that of the sediment in transport at the highest sampled flows rather than that of the measured bed material. This choice was made because the size distribution of the sediment in transport on Goodwin Creek does not approach the bed material size distribution even at the highest sampled flows. These flows have boundary shear stresses of about ten times the critical shear stress of the mean grain size of the bed material as calculated using the Shields curve (Miller et al., 1977). The size distribution of the transported sediment approaches that of the bed material in the data from the two experimental studies used in this study. For this reason the assumption was made that the effective size of the bed material was the same as that from the highest sampled flows. An alternate explanation may be that some of the sand sizes may be actually supply controlled, or wash load, rather than being part of the bed material load.

CONCLUSIONS

Using the proposed sediment transport algorithm, the size distribution and rate of transport of the bed material load has been simulated adequately for two data sets collected in laboratory channels and one field study with widely graded bed material. Accurate predictions of the sediment transport required that the size distribution of the bed material be categorized as unimodal or bimodal using the bimodal parameter (*B*) suggested by Wilcock (1993). The bimodal parameter was successfully used to predict the nature of the relation between the critical flow strength and the critical size of bed material for the beginning of motion which led to an increased accuracy of the predictions.

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A TRANSPORT ALGORITHM FOR VARIABLE SEDIMENT SIZES: FUNDAMENTAL CONCEPTS AND EQUATIONS

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Abstract: A sediment transport capacity algorithm for channels with widely graded sediment distributions is presented. The computed transport rates compared reasonably well to measured laboratory and field data representing a wide range of channel, flow and sediment characteristics. The transition in transport rates between successive sediment size fractions that are computed by different transport equations was good for transport rates above 500 ppmw. For lower transport rates the Laursen and MPM equations predicted lower values than the Yang equation. The sediment transport algorithm performed well in light of the very broad range of intended applications. Issues regarding the distribution of transported sediment are presented in a companion paper.

INTRODUCTION

Sediment transport capacity for a channel with uni-modal sediment size distribution can generally be estimated using an established transport equation. However, it is more difficult to accurately estimate the transport capacity for channels with bi-modal or widely graded sediment size distributions by a single equation. The simultaneous presence of silts, sands and gravels in varying proportions makes the choice of a representative sediment size and corresponding transport equation very difficult. This is further complicated by the potential development in time of bed surface armoring as a result of preferential transport of fine materials.

Also, sediment transport analyses in channel networks require a transport formulation that addresses a broad range of sediment characteristics because longitudinal material sorting and potential changes in morphology and geology in downstream direction can significantly alter the sediment distribution. Traditionally such situations would have been addressed by applying different transport equations to different parts of the network to account for the spatial variability of channel and sediment characteristics. Even though this may produce best estimates for local sediment transport, the spatial redistribution of transported sediment may not reflect sediment processes, but the choice and spatial application of different equations.

This paper presents an algorithm that estimates sediment transport capacity for alluvial channels with widely graded sediment size distributions or for channel networks with spatially varying sediment characteristics. A single algorithm that addresses a wide range of sediment size fractions and distributions allows the computation of a consistent channel sediment transport and redistribution in the large network and a better estimation of sediment transport in channels with bi-modal sediment distributions. In a companion paper the computation of the critical sediment diameter for initiation of motion for bi-modal and widely graded sediment size distributions is presented, and the size distribution of the computed sediment transport is compared to measured distributions.

FUNDAMENTAL CONCEPTS AND ASSUMPTIONS

Transport capacity of bi-modal or widely graded sediment size distributions is estimated by sediment size fraction and with a suitable transport equation for each size fraction. This assumes that each size fraction can be evaluated independently from the others. However, recent studies have shown that individual sediment sizes of a mixture do not behave independently. Bed surface characteristics and flow conditions at the water-sediment interface are different for uniform sediment sizes and mixtures. Small particles are sheltered behind coarse particles in what is called the "hiding effect", and the drag and lift forces on coarse particles is somewhat reduced because the latter are partially imbedded in fine material. This, in turn, impacts the critical flow strength for initiation of motion for each sediment size fractions to the point where, in some cases, all sediment sizes can begin to move at nearly the same flow strength (equal mobility concept) (Kuhnle, 1993; Parker et al., 1982; Wilcock, 1993). The interdependence between sediment size fractions for initiation of motion is incorporated into the algorithm by a critical sediment diameter for each size fraction that is determined as a function of the sediment mixture. As a result the initiation of motion for each size fraction is linked to the mixture.

The above approach is also applicable to sediment size distributions with different gradation and mean diameter. Thus, it is applicable to channel networks with changing sediment characteristics in downstream direction. The previously described discrepancies resulting from applying different transport equations to different parts of the network no longer exists because the same algorithm is applied throughout the network.

The following assumptions are made to estimate the sediment transport capacity in channels: (1) a one dimensional idealization of the flow and sediment transport along the longitudinal channel axis is adequate, and total sediment transport capacity can be estimated from unit width considerations; a width-to-depth ratio greater than 3 is recommended to avoid side wall effects. (2) a set of 12 pre-determined sediment size fractions ranging from silt to gravel (Table 1) cover all expected sediment size distributions; sediment size fractions below the silt range (0.01 mm) are assumed to be transported as wash load; and, (3) existing methodologies can reliably estimate the sediment transport for each of the 12 pre-determined sediment size fractions. Originally, the sediment transport in the gravel range was computed for 4 size fractions using two transport equations. After extended testing, the number of sediment size fractions for the gravel range was increased to 7 and a single transport equation was applied. This produced overall better results.

Table 1. Sediment size fractions and corresponding transport equations.

Class	Lower bound [mm]		Upper bound [mm]	Representative diameter [mm]		Transport equation
1	0.010	-	0.025	0.016	Silt	Laursen (1958)
2	0.025	-	0.065	0.040	Silt	Laursen (1958)
3	0.065	-	0.250	0.127	Silt	Laursen (1958)
4	0.250	-	0.841	0.458	Sand	Yang (1973)
5	0.841	-	2.000	1.297	Sand	Yang (1973)
6	2.000	-	3.364	2.594	Gravel	MPM (1948)
7	3.364	-	5.656	4.362	Gravel	MPM (1948)
8	5.656	-	9.514	7.336	Gravel	MPM (1948)
9	9.514	-	16.000	12.338	Gravel	MPM (1948)
10	16.000	-	26.909	20.749	Gravel	MPM (1948)
11	26.909	-	38.055	32.000	Gravel	MPM (1948)
12	38.055	-	50.000	43.713	Gravel	MPM (1948)

SEDIMENT TRANSPORT ALGORITHM

Based on the presented concepts and assumptions, the sediment transport is computed by size fraction as:

$$C_t = \sum [C_i * P_i] \tag{1}$$

where C_t is total channel sediment transport capacity in parts per million by weight (ppmw), C_i is the sediment transport capacity in ppmw for size fraction i, and, P is the fraction of sediment in size interval i. Equation 1 has the same form as the standard representation of sediment transport by size fraction (Stevens and Yang, 1989; Task Committee, 1972), with the exception that the C_i for the different size fraction is computed by different equations.

The sediment transport capacity, C_i, for each size fraction is computed by one of the following three equations (Table 1): (1) Laursen's equation for silts (Alonso et al., 1981; Laursen, 1958); this is a bed material discharge equation based on bed and critical shear stress. (2) Yang's 1973 equation for sand (Yang, 1973); this is a regression-type bed material discharge equation based on stream power, shear velocity and critical velocity at incipient of motion. And, (4) Meyer-

Peter and Mueller's (MPM) equation for gravel (Meyer-Peter and Mueller, 1948); this is a bed load discharge equation based on critical shear stress.

The interdependence between sediment size fractions is accounted for by varying the critical sediment diameter used to calculate the critical flow strength for initiation of motion. The concepts, assumptions and equations for the determination of the critical sediment diameter are presented in the companion paper following this paper.

APPLICATION

The sediment transport algorithm (Equ. 1) is tested against Brownlie's data (Brownlie, 1981). This data consists of 5263 laboratory and 1764 field measurements made under equilibrium or near-equilibrium conditions and for a wide range of channel, flow and bed material characteristics. Field data ranges from mountain creeks to rivers such as the Mississippi. Data having one or more of the following values are not used for testing: water temperature above 35 Celsius (95 Fahrenheit); sediment specific gravity other than between 2.4 and 2.8; energy slopes less than 0.00001; sediment sizes outside the range between 0.01 [mm] to 50 [mm] (predetermined sediment size fractions); gradation greater than 1.5 and 2.0 for laboratory and field data, respectively; channel width-to-depth ratio less than 2 (to avoid side wall effects); and, computed and measured sediment concentration below 3 ppmw are disregarded because they are considered too small to be accurately measured or computed. A width-to-depth ratio as low as 2 was allowed in this study because the laboratory data are mostly from flumes that have smooth side walls which exhibit a reduced side wall effect. Most field data have a width-to-depth ratio in excess of 3.

Total sediment transport: Total measured versus computed sediment transport is displayed in Fig. 1 for a total of 3597 data points. Of these 799 data points represent field data and 2798 laboratory data. In general, the agreement between computed and measured data is good over the entire range of 5 orders of magnitude. About 80% of the computed laboratory data is within a factor of 2 of the measured values, and about 90% within a factor of 3. The data shows a better prediction for finer sediment sizes and higher sediment transport rates than for coarse sizes and low transport rates. This is attributed to the high variability in transport of coarse sizes and the increased measurement variability of low sediment transport rates. The dashed line in Fig. 1 is the regression line for laboratory data. It plots closely to the line of perfect agreement (solid line). The field data in Fig. 1 displays a significantly higher variability compared to the laboratory data with about 55% of the computed field data within a factor of 3 of the measured values, and about 70% within a factor of 5. The scatter of the data is not unexpected for the large span of conditions tested which range from mountain creeks to streams such as the Mississippi. In the context of this study the inherent variability of measured sediment loads is accepted as a characteristic of sediment data and is not discussed any further. For details on this topic the reader is referred to Gomez et al. (1989), Hubbell and Stevens (1986) and Kuhnle and Southard (1988). However, as can be seen from the dotted regression line in Fig. 1, the computed sediment transport values are consistently lower than the measured values. This is in part attributed to the fact that some of the field data has been corrected for unmeasured load, whereas other data were measured only for a center portion of the channel where sediment transport rates are usually the highest.

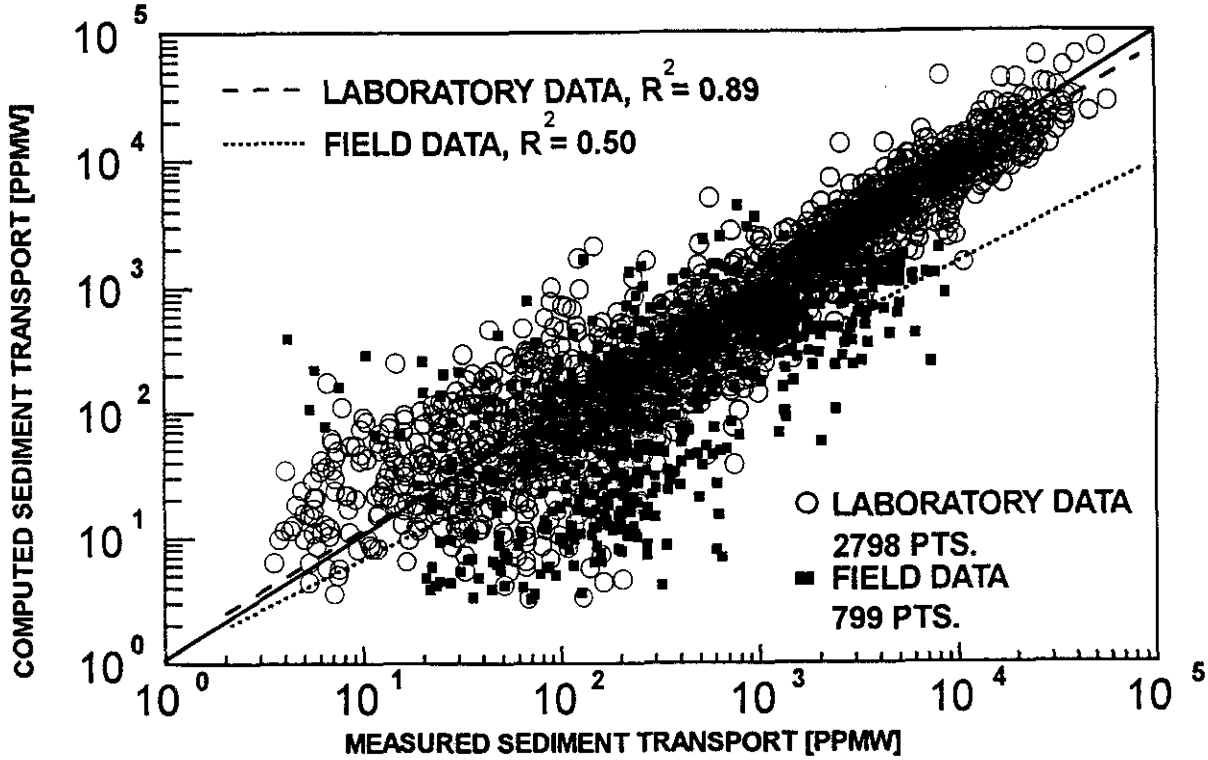

Figure 1. Measured versus computed sediment transport capacity.

Transition between transport equations: An important aspect of the sediment transport capacity algorithm is the smooth transition in estimated transport capacity between size fractions 3 and 4, and size fractions 5 and 6. These are size fractions at which the sediment transport equations change from Laursen to Yang and from Yang to MPM, respectively. Figure 2 shows the computed sediment transport of Laursen versus Yang for sediment sizes between 0.127 and 0.448 [mm], the representative sediment diameters for size fractions 3 and 4. The regression line for the two computed transport rates for laboratory data (829 data points) is close to the line of perfect agreement for high transport values (above 1000 [ppmw]) and slightly below the line of perfect agreement for low sediment transport rates (below 1000 [ppmw]). This indicates that for low sediment transport rates the computed rates after Yang are slightly higher than those computed after Laursen. For field conditions the regression line is parallel offset below the line of perfect agreement with computed transport rates after Yang higher than those after Laursen (204 data points).

Figure 3 shows the computed sediment transport of Yang versus MPM for sediment sizes between 1.297 and 2.594 [mm] for laboratory data (198 data points) and for sediment sizes between 0.841 and 3.364 [mm] for field data (81 data points). The larger sediment size range for the field data was necessary because there were no data in the range indicated for the laboratory data. Regarding the laboratory data, the MPM equation under-predicts the transport in the low sediment transport range (10 to 500 [ppmw]) as compared to the predictions by

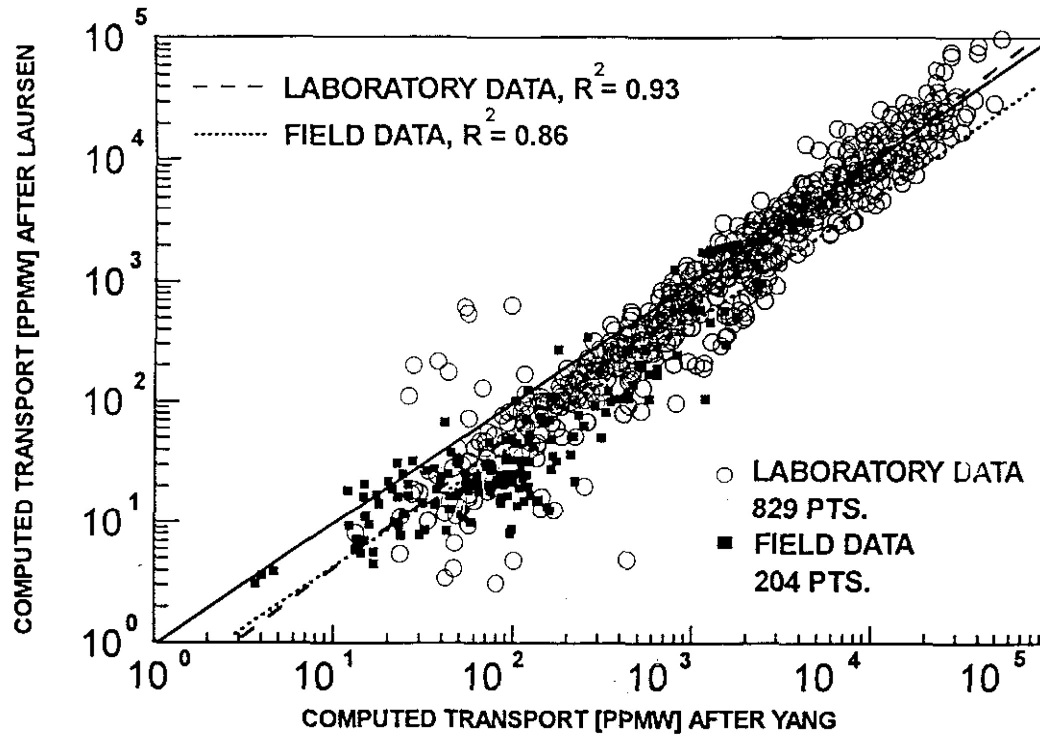

Figure 2. Computed sediment transport by Laursen versus Yang for sediment sizes between 0.127 and 0.448 [mm].

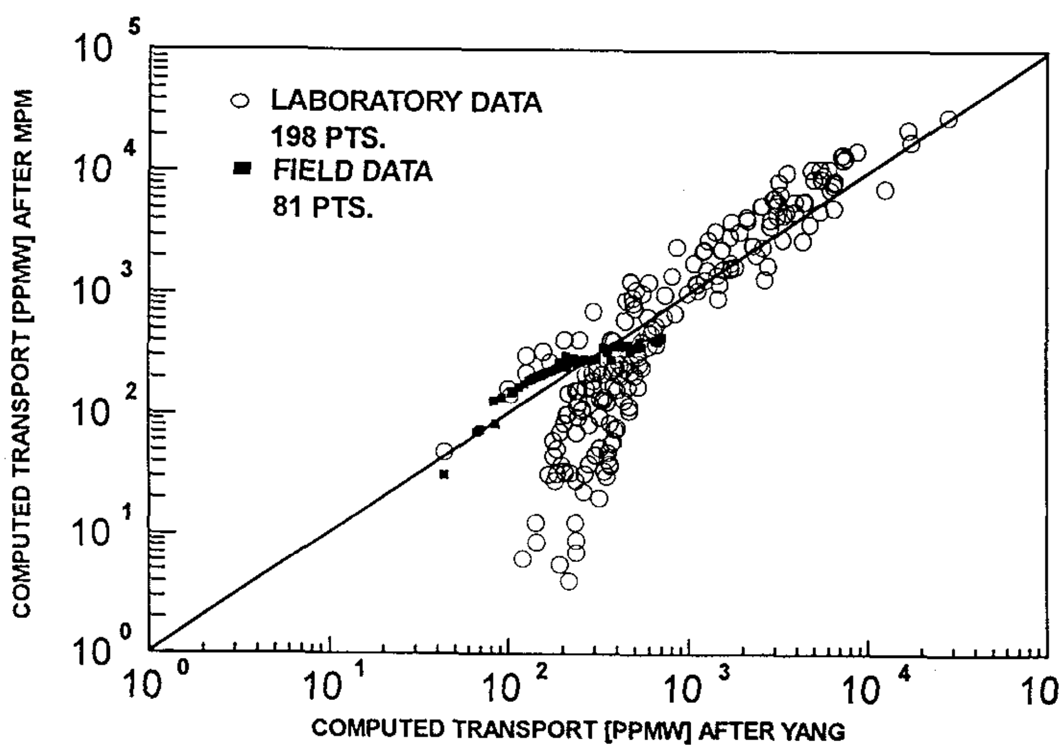

Figure 3. Computed sediment transport by Yang versus MPM for sediment sizes between 0.84 and 2.2 [mm].

Yang's equation. To a large extent this under-prediction is attributed to the sensitivity of the MPM equation to the separation of form and grain roughness in the low transport range. The necessary data to perform the form and grain roughness separation, in particular the D90 of the sediment distribution, was not directly available from the basic data set and was inferred as best as possible from the limited hydraulic and sediment data that was available. In the high sediment transport range (500 [ppmw] and up) the correspondence between the predictions by Yang and MPM is good. The predictions for the field conditions by both equations is relatively good with all data close to the line of perfect agreement.

DISCUSSION AND CONCLUSIONS

A sediment transport capacity algorithm for channels with widely graded sediment size distributions or for channel networks is presented. The algorithm is based on transport estimation by sediment size fraction and a relation between critical flow strength and size of the bed material for initiation of movement. The approach, equations and testing for total sediment transport capacity are presented in this paper. The evaluation of the critical sediment diameter for initiation of motion and the detailed application of the algorithm for evaluation of the distribution of the transported sediment is presented in an companion paper.

The total sediment transport computed by the presented algorithm was tested against a large number of measured data, as well as for a smooth transition in computed transport rates between successive size fraction at which the transport equation changed. The plot of computed versus measured sediment transport rates shows a reasonable agreement over 5 orders of magnitude. The computed values for laboratory conditions were much better reproduced than those for field conditions. The systematic under-prediction of transport rates for field conditions by the proposed algorithm is attributed in part to the correction of the measured field data for unmeasured load, restricted measurements for some data sets to the middle of the channel where transport rates are generally highest, and limitations of the data to perform a reliable form and grain roughness separation. Otherwise the scatter of the data is consistent with the variability of sediment data, particularly in light of the wide range of channel, flow and sediment characteristics of the test data sets (from mountain creeks to river such as the Mississippi).

The transition regions between those successive sediment size fractions for which the transport equation changes show good agreement for high transport rates and a slight over-prediction by Yang's equation for low transport rates. It is believed that the discrepancies are related to the separation of form and grain roughness. Especially the MPM procedure is sensitive to this separation. These transition regions can be improved by determining a common form and grain roughness separation for all three equations. This improvement is being investigated at this time.

The proposed sediment transport algorithm was found to be applicable to channels with widely graded sediment distributions and to channel networks with variable sediment characteristics. The use of a single algorithm assures consistency in computed sediment erosion, transport and deposition patterns throughout the network. The algorithm is best suited for comparative analyses of alternative land and channel management strategies on longterm sediment yields and channel stability in complex networks.

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TEACHING SEDIMENTATION IN THE 21ST CENTURY

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Abstract

The technological developments in the field of erosion and sedimentation and the proliferation of methods to calculate sediment transport provide a wealth of material for the formation of competent graduate students. Graduate teaching of sedimentation in the 21st century will require judgement as to what should be selected and used in the classroom. Several aspects of teaching sedimentation engineering are discussed, including: 1) should teachers emphasize the development of analytical or numerical modeling skills?; 2) should students use existing codes or should they learn to program their own?; 3) what is the proper balance between teaching "accurate" theoretical concepts versus "crude" practical approximations?; 4) should teachers focus on the latest albeit sophisticated methods or should they convey basic knowledge through simple perhaps outdated methods?; 5) should students spend long hours learning how to collect data in the laboratory and/or in the field?; 6) can design really be taught in the classroom?; and 7) how about recent sedimentation-related issues like GIS, remote sensing, wetlands, environment, contamination? Is it possible to integrate it all into a one semester course?

The author expresses his views on graduate teaching of river mechanics and erosion and sedimentation. Classroom experience as to what works best and what students really enjoy will be shared with the audience. Success can be achieved within a regular 45 hour semester by combining theory, useful analytical derivations, computer modeling exercises with laboratory and field measurements leading to practical solutions and appropriate design.

INTRODUCTION

The need for graduate engineering education in sedimentation and river mechanics is becoming an essential part of hydraulics, hydrology and environmental programs. The role played by sediments is not only important to solve problems of reservoir sedimentation and dredging, but plays a significant role in river mechanics, fluvial morphology, bridge crossings, bank protection, water supply, water quality, fish habitat, contaminant transport, etc. At Colorado State University, the Civil Engineering Department offers two graduate courses entitled "Erosion and Sedimentation" and "River Mechanics". Because the first course directly relates to the theme of this Conference, the details of the course objectives and content are expanded upon. The course on erosion and sedimentation serves as prerequisite to the practical applications discussed in river mechanics.

WHAT SHOULD BE TAUGHT

This is perhaps the most difficult question as there may be more answers than people in the audience! There are many different ways to teach the same basic ideas, but the fundamental concepts reoccur under different forms. The details of the author's views are contained in Julien (1995) and the following discussion serves as a preface to instructors with broad guidelines as to what works very well in graduate classrooms. One of the essential concepts to be conveyed is that sediments rarely move just by themselves. It is with the help of a fluid like water, and to a lesser extent air, that sediments are brought into transport. Per se, a strong background in fluid mechanics and basic understanding of open-channel flow constitute ideal prerequisites. It is afterall difficult to understand sediment motion without understanding the interaction between sediment particles and the surrounding fluid. The kinematic concepts of fluid and particle motion in terms of velocity and acceleration are fairly straightforward given the junior level engineering mechanics course on dynamics of particles and rigid bodies. The basic dynamic concepts of force, momentum, energy, pressure and shear stress are usually taught in the undergraduate fluid mechanics courses. At the graduate level, a fluid mechanics course strengthens physical and mathematical understanding of potential flow, inviscid fluids, viscous flows, turbulence and boundary layers. With this prerequisite, sediment transport becomes easier to understand. However, prerequisite concepts usually need to be reviewed and summarized at the beginning of a sediment transport course as it enables non-engineering students to be exposed to concepts that are normally not covered in their programs of study.

Principles of fluid mechanics can then be applied to the motion of single sediment particles. Spherical particles are prone to simple applications and relatively easy integrals that can be useful in determining the basic forces applied on particles, such as buoyancy, lift and drag. The concept of grain versus form resistance can also be studied after separating the shear force from the pressure force. At this level, students have an opportunity to develop analytical skills such as simple surface integrals. Applications to beginning of motion can be examined for simple cases. Viscous forces applied onto single particles are also subject to analytical treatment which leads to separating surface drag from form drag. The classic analysis of the settling velocity of a very small particle by Stokes is a milestone in the field of sedimentation that the students have to look into. Empirical settling velocity relationships for coarse particles are also interesting at this point because this is the breakpoint where theory based on simple hypotheses becomes insufficient to describe the mechanics of settling particles. Turbulence and the effects of particle shape mingle to make the problem beyond the mathematical capabilities of our time. Turbulence is a topic in itself that affects the motion of small particles in suspension. The concepts of mixing length and logarithmic velocity profiles are essential to all engineering applications in rivers and pipes. Knowledge of boundary layers is critical to differentiate between hydraulically rough and hydraulically smooth surfaces. The implications are tremendous and they can explain why gravel-bed rivers have different features than silty rivers. To this point the basic material is not likely to change much in coming decades. Methods are fairly standard but they require analytical skills from the students, with a tendency for the lecture material to become arid and theoretical. Simple practical applications to real problems are most welcome to illustrate the purpose of theoretical deviations.

Sand-bed rivers are extremely difficult to understand because the laminar sublayer thickness is approximately the same size as the grain size. The corresponding turbulent flows are in the transition zone between hydraulically rough and hydraulically smooth boundaries. The relationships for sediment transport in the transition zone can only be difficult to determine because the hydraulics itself is poorly understood. Incipient motion defines the beginning of motion of sediment particles. The concepts of the Shields diagram can be well understood and easily applied for granular material. The case of cohesive material is extremely complex and difficult to treat besides empirical methods. Bedforms are elusive and remain only partially defined. Still today, clear physical explanations for the formation of ripples, dunes, plane bed and antidunes are lacking, but the topic is so important with regard to resistance to flow in sand-bed rivers that the topic cannot be ignored. Methods rapidly become empirical and newer methods become fashion and make earlier contributions obsolete. Perhaps the question is to how many different bedform classification schemes can be presented in the classroom without utter confusion? Bedload is a concept easily grasped, but the calculations of sediment transport rates deserve several clarifications. Many equations are unfortunately not dimensionless and the units as to whether sediment transport is by mass, weight or volume are not always obvious. The analysis of suspended load finds applications in many different fields including advection-diffusion of gases, chemicals and pollutants. The treatment with linear equations is prone to easy solutions, as well as the analysis of vertical sediment concentration profiles in turbulent boundary layers. Hyperconcentrations are becoming increasingly important. Total load involves the important concepts of washload versus bed material load. A quantitative presentation of reliable methods is subjective and fashionable. There are many different equations which are too complex to understand and too empirical to judge whether they are applicable to different situations. The topic can only be mastered through examples and comparisons with field data. There is a wide gap between theoretically sound concepts and empirical methods which fit almost all data available. It is somewhat unfortunate to have to explain methods that cannot be physically reasoned but give the most accurate results. The state-of-the-art in sediment transport equations is perhaps too empirical at this time but it will offer challenges to scientists eager to find better for generations to come. Reservoir sedimentation is in itself easy and complex. The laws for sediment settling are well known but the sediment source from upstream is dependent upon many factors such as watershed characteristics, soil type, topography, precipitation, land use and vegetation. The uncertainties associated with infrequent extreme events will remain tied to hydrologic analyses that contain both deterministic and stochastic components.

TOUGH CHOICES

This section discusses difficult decisions that need to be made prior to teaching sedimentation. Natural preferences certainly dictate the emphasis on various aspects of a given course. It is often preferable to seek balance between various components of a course. The following topics will be discussed in the perspective that it would be nice to do it all, but everything needs to fit within a 45 hour semester course:

1. should teachers emphasize the development of analytical or numerical modeling skills?;
2. should students use existing codes or should they learn to program their own?;
3. what is the proper balance between teaching "accurate" theoretical concepts versus "crude" practical approximations?;
4. should teachers focus on the latest albeit sophisticated methods or should they convey basic knowledge through simple perhaps outdated methods?;
5. should students spend long hours learning how to collect data in the laboratory and/or in the field?;
6. can design really be taught in the classroom?; and
7. how about recent sedimentation-related issues like GIS, remote sensing, wetlands, environment, contamination? Is it possible to integrate it all into a one semester course?

1. Analytical versus numerical skills

Both analytical and numerical skills are desirable to solve sedimentation problems. Although practical problems are rarely solved with a simple integral, analytical skills are very important to promote advances in the field. At the graduate level, many students will have the opportunity to contribute to the future developments of sedimentation engineering through theses and dissertations. For them to have any chance to make long standing contributions, they must develop analytical skills in physics and mathematics. On the other hand, numerical solutions will enable them to solve probably most practical problems and practical knowledge of finite differences with application to sediment transport and aggradation-degradation in rivers is desirable.

Analytical skills are best developed at the beginning of a graduate course, followed with practical applications and numerical models. The converse would be awkward in that it is difficult to get into partial differential equations once empirical tools have been given to the students. The development of analytical skills nicely bridges the gap between fluid mechanics and applications to open-channel flow and sediment transport. Homework problems involving analytical solutions to simplified differential equations are extremely useful early on. Numerical skills can be developed through calculations of backwater profiles, resistance to flow, sediment transport and aggradation and degradation. A long computer problem can be assigned in three parts with the students given one month for each part.

2. Canned codes versus self-programming

Whether students should use existing codes or program their own is an important dilemma. The advantage of existing programs lies in possible direct applications to more complex problems. The major drawback is that students learn to enter data and read the output rather than understand the mechanics of what the code is really doing. The advantage of developing new programs is that students learn to master the intrinsic difficulties of solving hydrodynamic and sediment transport equations. The inconvenience is that it take a long time to seek quite simple applications.

Overall, asking graduate students to develop their own is truly rewarding in that despite simplified applications, programming skills are developed. Students can use any computer language of their choice, they indirectly learn to solve stability, accuracy and convergence problems. Those with non-engineering background find it perhaps most difficult but team work is sometimes possible. At the undergraduate junior/senior level, however, using a simple existing code is preferable.

3. Theory versus practice

Theory versus practice should not be viewed as a conflict but a sound balance between both aspects should be sought. Students shy away from courses that are too theoretical but they are not challenged by courses that are too practical. Theory alone is not convincing and empirical solutions to practical problems are difficult to grasp. Theory strengthens practice and vice-versa. Students are amazed when advanced theoretical concepts can be used to solve real problems. Sometimes, they will not learn the theory until they see how it can solve practical problems. The higher the level of combining advanced theory with solution to difficult problems, the stronger the course.

It is preferable to present the theory first and then illustrate with examples. Once the theory has been covered in class, one can present a case study and ask the audience what would be the solution. The is a level of confidence at problem solving that emanates from guessing right and wrong. In our field of sedimentation, fluid mechanics tends to be theoretical and arid while empirical formulas for bedforms, resistance to flow and sediment transport still lack a strong theoretical background. Students, as well as teachers, have a clearer mind at the beginning of a semester and exhaustion settles in as finals week approaches. It is a nice change of pace within a graduate course to start with more theory at the beginning of a course, followed with examples and applications near the end of the semester.

4. Sophisticated methods versus rule of thumb

Another balance to seek is between sophisticated and elaborate methods that provide precise answers, versus crude "rule of thumb" approximations. It is sometimes possible to simplify the complex formulation to something close to the rule of thumb approach. One can identify the hypotheses needed to simplify the complex formulation and the conditions when the rule of thumb is applicable can be delineated. In doing so, a student can look at a given problem and see if the conditions required for the rule of thumb are satisfied, otherwise the complete solution is required. It is important to give the short formulations as well as the conditions under which they are applicable. It is usually preferable to start with the long formulation and reduce it to the rule of thumb or outdated method. When given the rule of thumb first, some students can hardly go back to the full formulation. It is important to derive equations in the classroom, otherwise students develop the tendency to believe everything written in the book without judgement. In assigning problems, it is sometimes possible to compare the results of rule of thumb approximations with long solutions. One can judge of the improvement gained from the long solution.

The newest methods are not necessarily the best methods and one needs to carefully consider what is being used. It is usually good to have an assortment of methods including some classics and recent ones. Examples showing comparisons with field data are enlightening as they develop a sense of judgement about the expected accuracy in all calculations involving sediments. One must exercise a lot of judgement in selecting appropriate methods because there are many in the literature and none seems unequivocally better than all the others. Some outdated methods offer simplicity and sound physical basis, where recent methods tend to be too empirical to be approached with simple physical meaning.

5. Collecting versus using field/laboratory data:

Should students spend long hours learning how to collect field and/or laboratory data? Hands on experience is extremely valuable. Data collection such as velocity and sediment measurements are developing realistic confidence in the value of field and/or laboratory data. It should be part of every graduate course although constraints in laboratory space and equipment make this difficult to include in a course. It is not the number of laboratory experiments or field trips that counts, but rather the fact that they learn to collect data on their own and that they can reflect on the importance and accuracy of their measurements. In the case where direct field and/or laboratory experiments are not possible, substitute exercises consist of using raw data from a real experiment for the calculations. Also, field trips are quite interesting in that with proper guidance students can see many applications of concepts learned in class.

6. Engineering design

Engineering design can only be taught through a project where a specific problem is given to a group of students for technical solution including the design of the main components. It is usually difficult to teach the concepts and carry out a project at the same time. One must decide between design project, lab/field data acquisition, numerical models, or field trips. It is often rewarding to substitute the actual design on paper with a field trip to a variety of structures including some that are well and others poorly designed. At CSU, the course on River mechanics includes in-class discussions of projects, some that involve rapid decision making in emergency situation and others that can be long-term solutions. In-class discussions are rewarding. Guest speakers discussing the details of a particular structure are very welcome. The experience is most profitable when the students are given blueprints and problem statements prior to the guest lectures.

7. Recent issues

Recent issues such as GIS, remote sensing, wetlands, environment, and contamination are relevant topics that can rarely find enough class time for detailed information. The best way to interest students in these topics is through seminar series, conferences or workshops taking place at a regional level. Student admission is usually reasonable and on an optional basis, students like to be informed about these related activities. Another option is to take full advantage of library services and provide a list of books, periodicals and journals on topics of broad interest. A book report is sometimes sufficient to entice students to extract working knowledge from the library.

CONCLUSION

Is it possible to integrate everything in a 45 hour course? Yes after being somewhat selective of methods prone to suit the needs of the audience interested in sedimentation problems. There are plenty of activities to chose from and the course content can change slightly from year to year depending on the individual interests of the audience. Tailor-made teaching is possible in small classes, but a standard course is preferable when more than about 20 graduate students register. Individual teachers should emphasize the aspects of sedimentation that they are most familiar with as long as the equilibrium between various aspects of the course is maintained. It is easier to teach things we know well, but over the years it is nice to improve the course by adding new components to the course content. Student evaluations and discussions at the end of one course offer interesting ideas as to what would be a nice addition to the past course content.

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BEDLOAD TRANSPORT PATTERNS IN COARSE-GRAINED CHANNELS UNDER VARYING CONDITIONS OF FLOW

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Abstract: Bedload transport rates and patterns are important factors in developing criteria for channel maintenance flows, particularly in steepland channels where the flow conduit is typically formed in very coarse material. To this end, field observations and sediment transport were measured for the main stem of St. Louis Creek, Fraser Experimental Forest, Colorado. Distinct patterns of sediment transport were observed in 4 cobble- and 2 boulder-bed channels under varying conditions of flow ranging from base flow to bankfull discharge. Total unit bedload transport rate was variable but correlated well with changing flows; transport increased as a power function of discharge. Additionally, different size fractions were moved at varying flow levels and up to 3 phases of transport were observed at each of 6 sites. These phases correspond to those observed in other coarse-grained channels, though St. Louis Creek is considerably coarser than what is typically measured. Transport during Phase 0 is very low, but measurable, and occurs between baseflow and 1/3 to 1/2 bankfull discharge; it is characterized by sands moving over a largely stable bed. Phase 1 occurs between 1/2 and 70% of bankfull discharge and is characterized by an increase in the transport rate of sands and small gravels; however, there is no difference in the motion of particles greater than 16 mm between Phase 0 and 1. Phase 2 transport begins at some point between 70% of bankfull and bankfull and involves the full range of particle sizes up to the limits of the bedload sampler. Maintaining the continuity of both Phase 1 and 2 transport appears to be important for preserving the character and function of steepland channels.

INTRODUCTION

Rates of sediment transport in small, steep channels can vary widely both between and within stream systems. Particles moving as bedload can account for a substantial portion of the total sediment transport in these typically coarse-grained channels (Hayward 1980). Movement of this coarser fraction is particularly important for purposes of channel maintenance as the conduit is formed from gravels, cobbles, and boulders. Yet, coarse-grain transport is particularly difficult to forecast, being influenced by a variety of factors, including periodic bank erosion, exogenous inputs of materials into the channel, and intermittent velocity fluctuations, in addition to the very stochastic nature of individual particle motion. In short, we don't have a clear understanding of how bedload is transported or how channels are maintained over varying conditions of flow because of the difficulties of measuring and modeling continually fluctuating velocity and transport over spatially varying bed topography. Additional measurement of bedload over a wider range of flows would be useful for generating and substantiating transport models and for developing channel maintenance criteria.

A bedload sampling project was conducted for the main stem of St. Louis Creek, Colorado during snowmelt runoff seasons in 1992 and 1993. This study differs from others conducted on gravel bed rivers (e.g., Smith et al. 1993, Lisle 1995) in that the bed of St. Louis Creek is much coarser, but is similar to channels many land managers must contend with in assessing potential impacts from proposed land-use practices. From this endeavor bedload rating curves were developed and phases of transport identified for cobble- and boulder-bed channels. A phase may be defined as levels of flow at which samples of comparable particle size and volume are transported and subsequently trapped in a bedload sampler. The idea of phases has been described in other papers on gravel transport (e.g., Jackson and Beschta 1982, Ashworth and Ferguson 1989, Warburton 1992). In this paper, we tie the idea of transport phases with developing channel maintenance criteria. The results presented are part of a larger study on the relationship between flow, transport, and channel maintenance in very coarse-grained channels; they are also tentative because the transport relationships continue to be refined as additional samples are collected at increasingly higher discharges.

Objective: The objective of this paper is to characterize the transport regime in cobble- and boulder-bed streams under varying conditions or phases of flow. This is done by assessing the relationships between discharge and (1) total unit bedload transport rate and (2) fractional unit bedload transport during snowmelt runoff.

STUDY SITE

St. Louis Creek is a single-thread, fourth-order, perennial stream located within the subalpine environment of the Fraser Experimental Forest near Fraser, Colorado (Figure 1). It is characterized by moderate to steep slopes (0.01 to 0.05), with beds composed largely of gravels, cobbles, and boulders derived from Quaternary glacial outwash and tills. Channel banks are largely stable over a wide range of flows and have dense to moderately-dense vegetative cover. Ninety-five percent of the total annual runoff occurs during snowmelt in spring (Alexander et al. 1985). Water from the St. Louis system is diverted at several points; 3 of 6 bedload sampling sites are located in channels from which roughly 40% of the total annual flow is diverted, on average (Ryan 1994). However, water was diverted for only a few days during bedload sampling periods.

Subalpine channels are, at some points, constrained by narrow valley walls which limit the potential for lateral erosion and channel migration; the width of the valley bottom is less than 7 times the width of the bankfull channel (Ryan 1994). Terraces and floodplains are absent or spatially discontinuous because of these physical limitations. Where present, these surfaces are colonized by upland vegetation, specifically subalpine tree species Engleman spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and, to a lesser extent, lodgepole pine (*Pinus contorta*). Channels are typically straight and irregular with steep slopes (3% or greater). They contain sequences of steps formed from boulders and water surface areas punctuated by supercritical flow. These channel are referred to as *constrained* in this study, denoting the relationship of the valley width to channel width. Constrained channels are comparable to Rosgen's type A channels (Rosgen, 1994) or Montgomery and Buffington's (1993) step-pools or cascades.

Other subalpine streams flow through wider valley bottoms where the distance between valley walls is many times the width of the channel. *Unconstrained* channels may erode laterally and some meandering is evident. These channels have more gentle slopes (1-2%) dominated by pools and riffles formed from gravels and cobbles (or pool/riffle/rapids in steeper segments). Additionally, there is a well-developed, though infrequently inundated, floodplain and several terraces may be evident. The valley floor is typically vegetated by willows (*Salix* species) and herbaceous species (i.e., *Carex* species and grasses); small spruce and lodgepole pine may be present in low abundance. Unconstrained channels are comparable to Rosgen's type B channels or Montgomery and Buffington's plane bed or pool-riffle channels. Both constrained and unconstrained channels were sampled in this study.

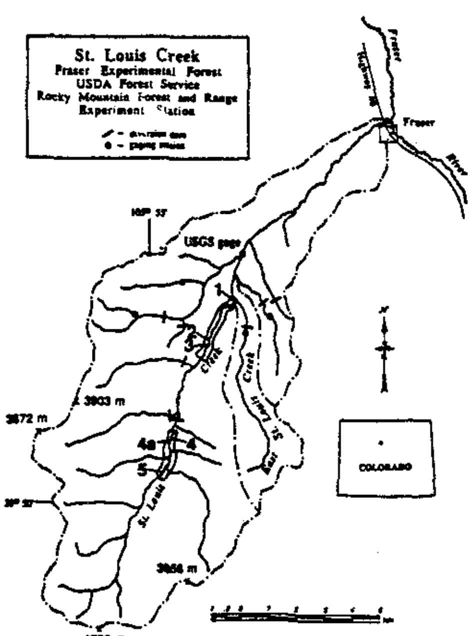

Figure 1. Bedload sampling sites located on St. Louis Creek. Site numbers correspond with Table I.

APPROACH

Flow and bedload were sampled in 1992 and 1993 at 6 sites, including 2 boulder-bed (step-pool) and 4 cobble-bed (pool-riffle) channels (Table I). Sites were selected based on slope, particle size, channel type, and valley floor constraint criteria. Cross-sections in step-pool channels were located downstream of the pool, at the top edge of the step. In pool-riffle channels cross-sections were located in straight or cross-over locations. Bedload transport was measured on a near-daily basis using a hand-held Helley-Smith bedload sampler (Helley and Smith 1971) while wading during low flows and from platforms during higher discharges. The sampler was constructed of 16 gauge steel, with a 76 x 76 mm orifice, 3.22 expansion ratio, and fitted with a 0.25 mm mesh bag (manufactured by GBC steel fabricators, Denver, CO). The particle size limit of the sampler was roughly 70 mm. Samples from 10 to 14 equally-spaced verticals were combined to determine the unit bedload transport rate through the cross-section, expressed in kg $m^{-1} s^{-1}$. Spacing between verticals ranged from 0.6 to 0.7 m, and the sampler was held in place for 1 to 2 minutes at each position. Each composite sample, therefore, represents an average transport rate measured for 20 to 30 minutes at each cross-section. Velocity was measured at each vertical with Price AA and pygmy current meters both near the bed and at the 0.6 depth, assumed to be average for the vertical velocity profile. Discharge was calculated from the average velocity, interval width, and total depth measurements (Buchanan and Somers 1965). Bedload samples were dried, ashed to remove organic matter, and sieved using standard sedimentological methods (Folk 1968). One-half phi internal sieves, ranging from 63 µm to 64 mm, were used to separate samples into grain size classes. These were later combined mathematically into full phi classes for analytical purposes; separate size classes for particles finer than 2mm are not presented here.

Table I. Selected characteristics of 6 sites on St. Louis Creek.

Site #	Bed Topography	Valley Floor Type	Flow Management	Maximum Measured Width (m)	Water Surface Slope* (m/m)	Maximum Average Depth d (m)	Median Particle Size (mm)	Drainage Area (km^2)	Years Sampled
1	Step-Pool	Constrained	Diverted	6.80	0.040	0.57	128	55.6	92 & 93
2	Riffle	Unconstrained	Diverted	8.05	0.020	0.49	76	54.2	92 & 93
3	Riffle	Unconstrained	Diverted	9.80	0.019	0.39	82	54.0	92 & 93
4	Riffle	Unconstrained	Free-Flowing	7.40	0.024	0.38	124	33.8	92 & 93
4a	Riffle	Unconstrained	Free-Flowing	8.50	0.020	0.34	80	33.5	93
5	Step-Pool	Constrained	Free-Flowing	5.30	0.050	0.41	161	21.3	92 & 93

*Water surface slope as measured over the channel reach is reported here and may differ from local water surface slope measured at the cross-section and published in reports elsewhere.

RESULTS AND DISCUSSION

Runoff in 1992 was only moderate, reaching levels 60% of the estimated bankfull (1.5 year return interval) discharge. By contrast, flow levels in 1993 reached or exceeded bankfull on nine days (at USGS gage # 09026500 on St. Louis Creek); the peak mean daily flow has a calculated return frequency of 2.5 years (J. Nankervis, USDA Forest Service, personal communication, 1994). Sampling lasted for 6 weeks in 1992 and 11 weeks in 1993 and included the rising limb, peak, and falling limb of the seasonal hydrograph. Correspondence between transport rates and discharge between the two years was good, with a similar rate of transport measured at comparable discharges at any one site. Therefore, data from 1992 and 1993 are treated and presented as a single dataset.

Total Unit Bedload Transport: Total transport rate increased with increasing discharge at all sites, as may be expected. In developing a sediment rating curve, a power function, compared to a linear or polynomial model, best fit the relationship between flow and total transport (least squares approximation), explaining between 40 and 90% of the variation in unit bedload transport rate (Figure 2). Scatter about the fitted line is similar to that depicted in transport studies from gravel bed rivers (e.g., Lisle 1989, Smith et al. 1993). A hysteresis effect was observed for Site 1 in 1992 when pulses of sand and small gravels were measured on the falling limb of the seasonal hydrograph at discharges less than predicted (Ryan 1994). However, this effect was not observed at any other site in 1992 or 1993.

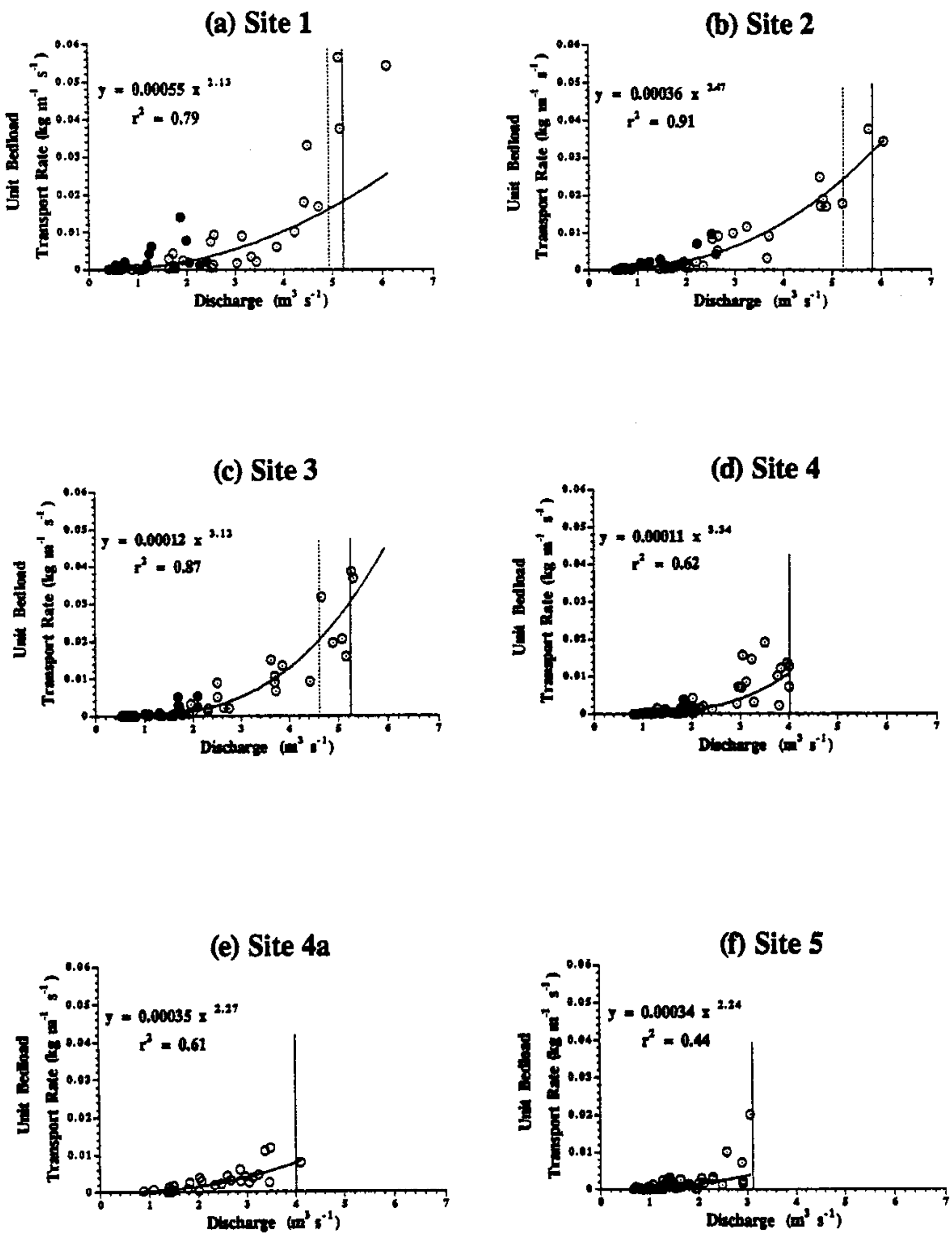

Figure 2a-f. Unit bedload transport rates and discharges for 6 sites on St. Louis Creek. Solid symbols are data from 1992, open symbols are from 1993. Dashed vertical line is 1.5 year return interval flow calculated through regression analysis with discharge from USGS gage on St. Louis Creek. Solid vertical line is bankfull flow based on morphologic features and discharge measured in field.

Model slope coefficients ranged from 2.13 to 3.34, which is within the range developed for gravel bed streams. There was no distinction between coefficients for constrained and unconstrained sites, though slightly smaller coefficients were calculated for the two constrained sites in both years of sampling. However, because 1 or 2 data points can strongly influence the slope of the fitted function, identifying differences in rating curves by channel type will require additional data and testing. At this point, it appears that rating curves fitted for unconstrained sites could be used to estimate transport rates in constrained sites, at least as a first approximation.

Return frequency of the measured flows was estimated for sites 1, 2, and 3 through regression analysis with discharge data from the USGS gage on St. Louis Creek, where the return frequency for a number of flow levels has been previously establish using Log Pearson type III method (Benson, 1968) on instantaneous peak flows (Ryan 1994). There was a linear correspondence between the two discharges; r^2's were 0.95, 0.94, and 0.94, respectively. The 1.5 year return interval flow (approximating bankfull) was estimated from this regression and is plotted in Figure 2 as a dashed vertical line. Measured discharges at sites 4, 4a, and 5 and the USGS gage varied temporally, with peak flows occurring later at the sampling sites than at the gage in the lower basin. Because the regression was poor, an estimate of the 1.5 year flow could not be adequately determined. Bankfull flows were instead estimated using field criteria and measured discharge. This second method of defining bankfull flow involved directly measuring velocity and cross-sectional area when water levels were observed at the edge of the banks; the field-determined bankfull discharge was plotted (solid vertical line) for comparison with the empirically determined bankfull discharge at the lower sites. Note the field-determined discharge was greater than the 1.5 year discharge and has a return frequency of approximately once in 2 years.

Transport rates measured in 1993 were substantially greater than those measured in 1992, as may be expected given the differing levels of flow. Generally, transport rates were very low in 1992, increasing only marginally at the higher discharges. The 1992 flow season is representative of peaks achieved during a heavily diverted flow year when flow levels may only reach 40 to 60% of the bankfull discharge. Coincidentally, this level of flow just reached the top of surfaces within the bankfull channel at sites 2 and 3. These features are thought to have developed in response to 35 years of reduced flows due to diversion (Ryan 1994). By contrast, flow levels in 1993 covered these surfaces by 20 to 40 cm. Flows at this level represent those of the free-flowing regime, occurring with a roughly 2 year return frequency. The highest bedload transport rates were 2 to 5 times greater than those measured in 1992, and are representative of rates achieved on the order of several days per year, on average.

Fractional Bedload Transport Patterns: Phases of bedload transport were identified by plotting the fractional transport rate against discharge to determine flow levels at which grains of differing size classes were transported (Figure 3). Each phase represents a range of flows where similar volumes and sizes of sediment are moved, as evidenced by samples collected with the Helley-Smith. The point of flow (or threshold) which divides the phases occurs with substantial changes in the volume or size of grains moved, as described below. The thresholds, at this stage of analysis, are approximate and may be refined (though only slightly) as more samples with larger grains are collected at higher discharges and allow a more statistically rigorous assessment.

Phase 0 transport consists primarily of sand grains (< 2mm) moving over a stable channel surface. The source of the finer grains is probably material settled out from previous transport events in pools, eddies, channel margins, and around large obstructions, such as boulders and woody debris. Phase 0 transport occurs between 0.5 and 2 m^3s^{-1} which is readily achieved in low flow years and while diverting flow. Maintaining phase 0 transport is not a significant concern in terms of channel maintenance because of the relative frequency with which it occurs and the relative infrequency with which gravels are entrained from the channel surface during this phase.

Phase 1 transport begins as flow increases and a subsequent increase in the transport rate of the finer fraction occurs. Mean transport rates of sand grains and small gravels during phase 1 are significantly (α = 0.01) greater than in phase 0, based on an analysis of variance (ANOVA). While a few larger particles may be moved during phase 1, the rates are very low compared to the rate of sand grain transport. An ANOVA showed no significant difference in transport rates of particles greater than 16 mm between phase 0 and phase 1 transport. Though few coarse grains are moved, phase 1 transport is still important in terms of channel maintenance, particularly for continuous transfer of finer grains through cobble and boulder bed channels; there is potential for aggradation of channel beds, bars, and gravel surfaces by sand and small gravels in absence of this range of flows. Phase 1 transport is in effect by 1/2 the bankfull discharge (or roughly 60% of the 1.5 year return interval discharge), but is observed as early as 1/3 bankfull.

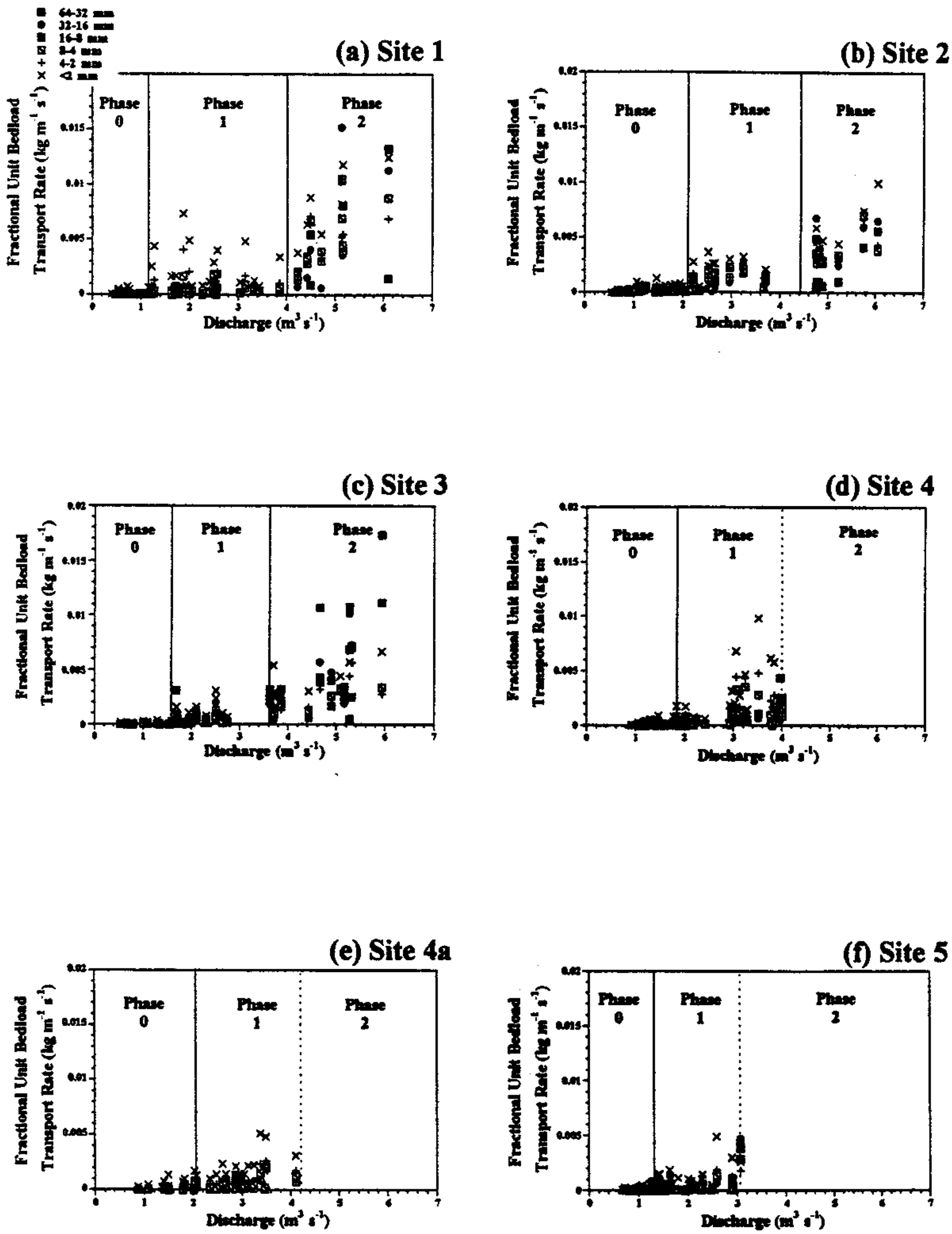

Figure 3a-f. Fractional transport rates and phases of transport identified for 6 sites on St. Louis Creek. Phase 0 transport consists primarily of sands moving over a largely stable bed. Both sands and small gravels are transported during phase 1, but particles greater than 16 mm are largely absent from samples; total transport rates are greater than phase 0 transport. All size fractions, up to the limits of the sampler orifice, are included in samples collected during phase 2. Phase 2 transport probably wasn't achieved at sites 4, 4a, and 5; beginning of this phase approximated by dotted line.

The Phase 2 regime is characterized by an increase in the transport rate of all size fractions, including gravels and small cobbles. An order of magnitude increase in the average transport rate of particles greater than 16 mm separates phase 1 from phase 2. However, phase 2 transport is highly variable because the transport rates for one size fraction can vary severalfold at any given discharge. Still, the *potential* for transport of coarse grains is greatest during phase 2, making this range of flow vital for maintaining the flow conduit. The beginning of this phase was observed at 70% of the bankfull discharge, defined by field observation, at the lower sites. However, while phase 2 transport was readily achieved at sites 1, 2, and 3 it was not observed at sites 4, 4a, and 5. It appears that the threshold of phase 2 transport was just reached at the upper sites in 1993 because a few coarser grains were trapped at the higher discharges. This suggests that the beginning of phase 2 varies somewhat, corresponding with the bankfull discharge at the upper sites and substantially less than bankfull at the lower sites. More samples will be collected at bankfull and greater discharges at the upper sites to better define the point when phase 2 transport begins; this is work in progress. At this point we conclude that phase 2 transport may begin at some point between 70 and 100% of bankfull discharge (as defined in the field).

There is some uncertainty as to what happens to bedload movement once flow greatly exceeds the channel banks; specifically, do transport rates continue to increase, involving increasingly coarser particles, or does it level off. Not only are flows significantly greater than bankfull infrequently achieved, but sampling under these conditions is a particularly onerous task and few samples have been collected. Still, effort should be made to quantify transport at discharges greater than bankfull to provide insight into the transport regime at these less-frequently-achieved flows. Intuitively, there may be "phase 3" transport but it has not been observed on St. Louis Creek. Phase 3 has been described by Warburton (1992) for boulder beds in a proglacial meltwater stream, and it generally involves the break up of bed clusters (steps) and transport of cobbles and boulders during large floods. However, flows in subalpine channels rarely exceed their banks, and the 100 year flood may only achieve levels twice bankfull (Andrews 1984, Ryan 1994); hence, the term "flood" has different connotations in subalpine channels than in other environs (Jarrett 1990). Additionally, Phase 3 transport, as described by Warburton, probably could not be measured directly using methods described in our study, given the limits of the sampling procedure and safety issues. It is better measured through sequential surveys of boulder location before and after a substantial flood. In this regard, detailed baseline surveys of large roughness elements and the position of bed steps have been established at these 6 sites and are monitored for widespread bed disruption.

SUMMARY AND CONCLUSIONS: COARSE GRAIN TRANSPORT AND CHANNEL MAINTENANCE FLOWS

Intuitively, continued redistribution of the full range of transportable bed material is necessary for maintaining the existing condition of alluvial channels. This study (and others) suggests that bedload transport occurs in phases under varying conditions of flow. Phase 0 transport, defined by low transport rates for all size fractions, is readily achieved but is generally ineffective at moving grains larger than sand. Instead, most of the coarse bedload is moved through a site during phase 2 when many grain sizes, up to the limits of the sampler, are represented in the "catch." Phase 2 transport can occur at discharges as low as 70% of bankfull, based on evidence presented here. However, both phase 1 and 2 are necessary for channel maintenance. Phase 1, occurring at roughly 1/2 bankfull, moves and redistributes particles loosened during higher flows, and is important in keeping bed gravels clear of excessive accumulations of fines. Land-use practices which alter the flow regime during either phase 1 or 2 are likely to impact the morphological and functional characteristics of the channel.

ACKNOWLEDGMENTS

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BEDLOAD TRANSPORTED IN GRAVELBED STREAMS IN WYOMING

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__Abstract__: Research in the Rocky Mountain subalpine zone indicates vegetation management (timber harvest) reduces evapotranspirational water loss, resulting in increased streamflow. The Medicine Bow/Routt National Forest, in cooperation with the Rocky Mountain Forest and Range Experiment Station, initiated the Coon Creek study in 1982. The project is an operational-scale, paired-watershed study; Coon Creek is the treatment watershed and the control is East Fork Encampment River. The treatment, or timber-harvest phase, began in the summer of 1990 and was completed in 1993.

A major objective of the project is to monitor the effect of treatment on the water and sediment and compare the observed responses to those predicted; based on small-scale, watershed studies elsewhere. This paper addresses part of the flow/sediment relationships. Suspended and bedload sediment were measured using United States Geographical Survey (USGS) samplers DH-48 and Helley-Smith, respectively. Weir ponds trapped some of the suspended and all of the bedload in transport past the gaging site. Comparison between sizes of sediment trapped by the weir ponds versus sediment captured in the Helley-Smith indicates the 76 mm Helley-Smith sampler to be an effective tool for measuring bedload in coarse-bedded streams.

INTRODUCTION

Coon Creek is a 1613 ha drainage located in southcentral Wyoming on the Hayden District of the Medicine Bow National Forest. It drains to the west at elevations ranging from 3347 to 2682 m. Adjacent to Coon Creek is the East Fork of the Encampment River, a 911 ha control watershed. The East Fork drains to the southwest ranging in elevation from 3075 to 2282 m. These catchments are being monitored as part of a paired watershed experiment demonstrating the large-scale effect of clearcuting on water and sediment yield (Troendle and King 1985, Bevenger and Troendle 1987). The climate of the area is generally influenced by frontal systems and orographic storms during winter months, and by orographic and convectional storms during summer months. Mean-annual precipitation is 89 cm, approximately 70 percent of which comes in the form of snow. Streamflow from April to July is dominated by snowmelt. Stormflow response to summer thunderstorms averages about 3 percent of the total precipitation (Bevenger and Troendle 1987). Average, annual water yield is 40.9 cm for Coon Creek. Forest cover consists of spruce-fir stands along stream courses, on north slopes, and at upper slope positions. Lodgepole pine grows on all low-to mid-elevation southerly, or high-energy, exposed slopes. Alpine tundra is above timberline, at approximately 3200 m elevation.

OBJECTIVES

There are several objectives to the Coon Creek pilot project. The primary objective is to document the ability to predict the effect of a water augmentation treatment on water yield. A second objective is to evaluate the impact of the forest fragmentation practices designed to optimize water yield on specific wildlife populations. The third objective is to monitor bedload and suspended sediment movement before and after timber harvest. This paper will deal with aspects of the third objective; primarily the particle size distribution of material in transport, and the efficiency of the Helley-Smith bedload sampler in trapping these materials.

METHODS

This project is a paired, watershed experiment with three phases; a calibration or pre-treatment period, a treatment period, and a post-treatment period. The pre-treatment period was from 1982 to 1990. Treatment, or harvesting, occurred on the Coon Creek watershed from 1990 to 1993. We are currently in the post-treatment phase. Suspended sediment and bedload export from both watersheds was estimated two ways during all three phases.

First, annual sediment export (primarily bedload) was estimated from accumulations in the weir ponds. Using a grid survey, the change in mean elevation of the pond bottom, pre- and post-excavation, was multiplied by the pond area to estimate the measured volume of sediment transported that year (Troendle and Olsen 1994). The grid points used to survey pond elevations were also used to sample the size distribution of accumulated material.

Second, bedload movement was sampled at two locations in each watershed; on the wooden sill at the lip of the weir pond and at a cross section located 45 - 60 m above the weir ponds. Bedload samples were collected 35 times per site during 1993 using a 76 mm Helley-Smith sampler (Helley and Smith 1971) and USGS techniques (Edwards and Glysson 1988). The pond samples were compared with the size distribution of material caught in the Helley-Smith sampler, allowing an evaluation of how well the point samples of bedload transport at the cross section and wooden sill approximate the accumulated material in the weir ponds. The material available for transport near each of the cross sections was measured in a variety of ways.

A sample of bed material, representing a modification of the traditional pebble count (Wolman 1954) was done at Coon Creek, East Fork, and at East St. Louis Creek on the Fraser Experiment Forest (FEF) in Fraser, Colorado. Seventeen cross sections were surveyed at each stream, eight above, eight below, and one at the bedload cross section. At Coon Creek and East Fork the downstream distance between successive cross sections was 0.45 m while the interval at East St. Louis Creek was 0.25 m. At each cross section, 20 equidistant points were located between left and right bankfull. At each of the 20 points, particles under the base of a stadia rod were selected and the intermediate axis was measured and recorded. The count consisted of 340 particles systematically located above and below the bedload/discharge cross section.

The particle size distribution of material in the pavement, subpavement, and a point bar had been sampled in 1989. A bottomless 55-gallon drum was cut to a height of 0.6 m. It was then placed in the appropriate location and forced down, well into the subpavement, and the material removed layer by layer. The material on top was considered pavement and the material from 2.5 - 15 cm depth was considered subpavement. The nearest bar to the bedload cross section was similarly sampled. Because 1990-1992 were low-flow years; we assume the pavement and subpavement data from 1989 represent the conditions present in 1993. All estimates of particle size are reported as weight-per-size class except for the pebble count (surface material) which is reported as counts per size class.

RESULTS AND DISCUSSION

Bedload transport was sampled 35 times at Coon Creek over the 1993 snowmelt runoff period during both the rising and falling limbs of the hydrograph (figure 1). Sampling at East Fork Encampment River occurred over the same time period, except for the first day when only Coon Creek was sampled. Based on inflow and outflow data (not presented), it is estimated that only 10-15 percent of suspended sediment being transported is retained in the weir pond, implying the material accumulated in the pond is, by and large, the bedload component. Visual comparison of the particle size of the bedload captured with the Helley-Smith versus the material accumulated in the weir pond, for both Coon Creek and the East Fork, demonstrated good agreement during the 1993 runoff season (figures 2 and 3). Only a small percentage, 5 percent (by weight) or less, of the material trapped in the pond exceeds the size limit (76 mm) of the Helley-Smith sampler. In reality, 85 percent or more of the material moving into the pond is represented by that trapped in the Helley-Smith samples. It is also obvious a large percentage of the surface, pavement, and subpavement material is coarser than the majority of material transported in 1993 (figures 4 and 5). However, it should be noted that particles of all the sizes available to be moved, based on measurements of the bed, pavement, subpavement, and the bars have been delivered to the weir pond over the

13-year study period. Although bedload transport includes the entire range of particle sizes available, transport (by weight) is dominated by particles in the D30 range and smaller. Troendle, et al. (1996) documented the effective discharge for these and other small watersheds are the frequently occurring events (1.5-year return maximum daily mean flow) and these flows are capable of moving a wide range of particle sizes.

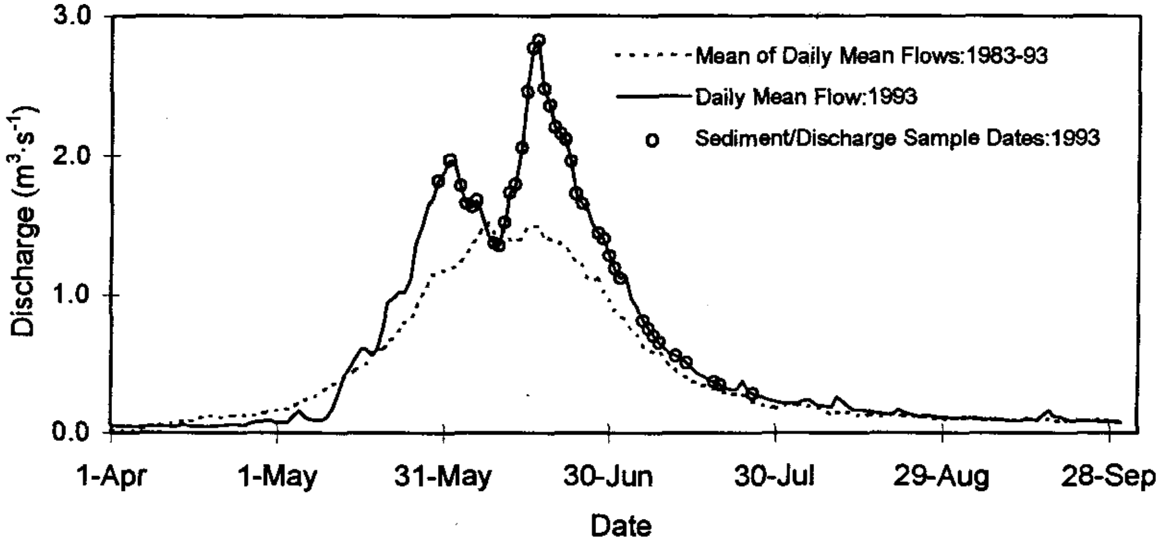

Figure 1. Coon Creek average mean daily flow hydrograph for the period of record plotted against 1993 mean daily flow with 1993 sample dates identified.

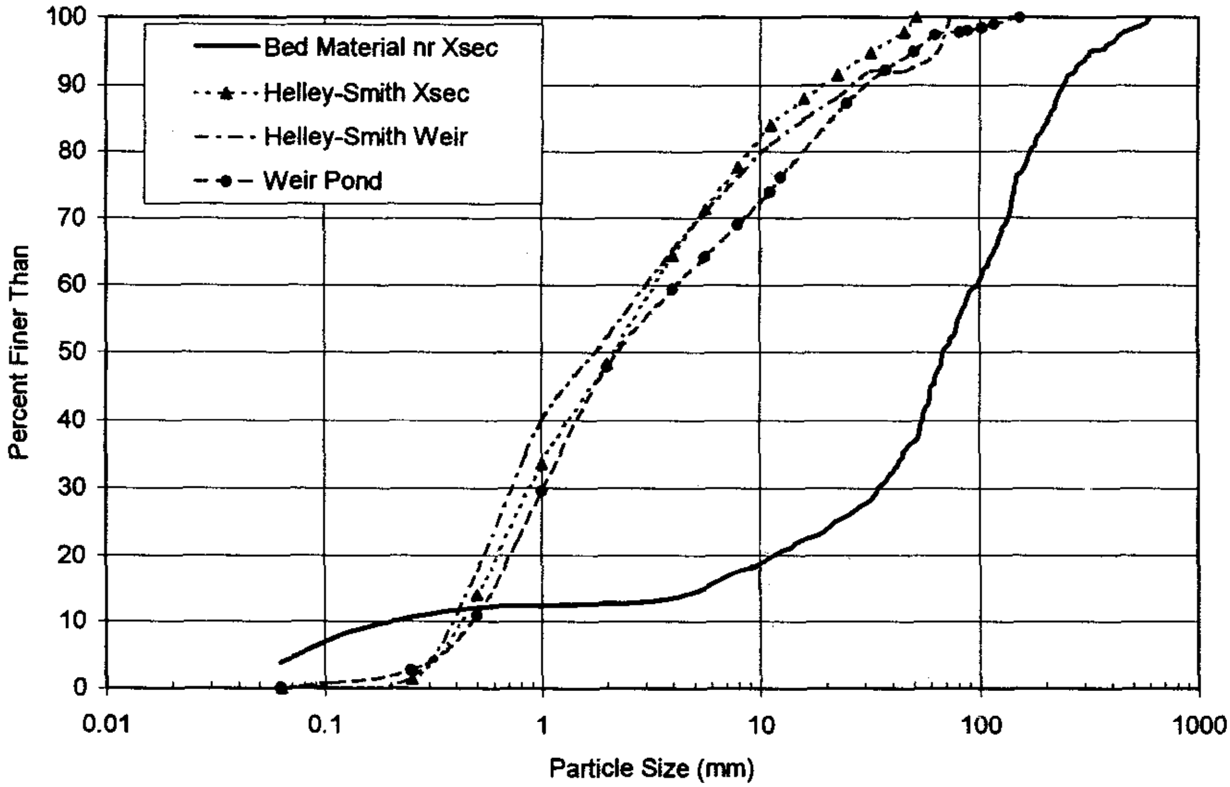

Figure 2. Sediment particle size distribution of Helley-Smith samples, weir pond accumulation and bed material at Coon Creek.

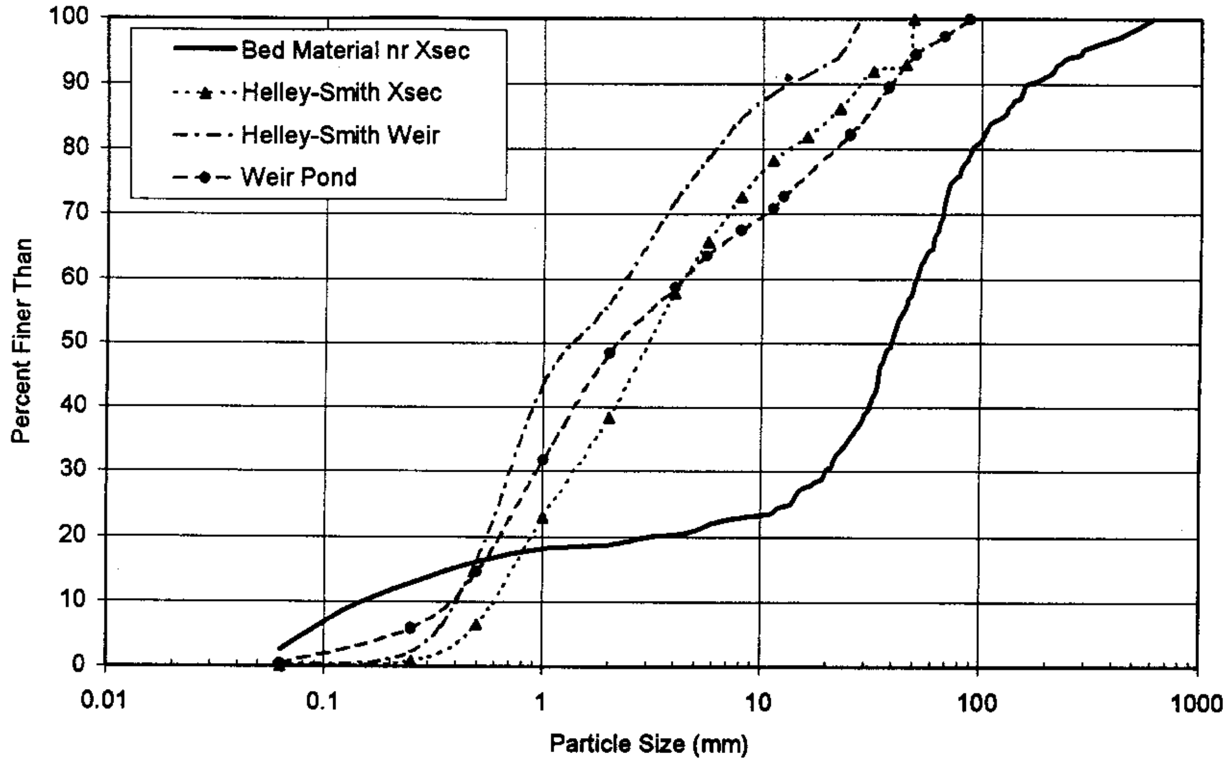

Figure 3. Sediment particle size distribution of Helley-Smith samples, weir pond accumulation and bed material at East Fork Encampment River.

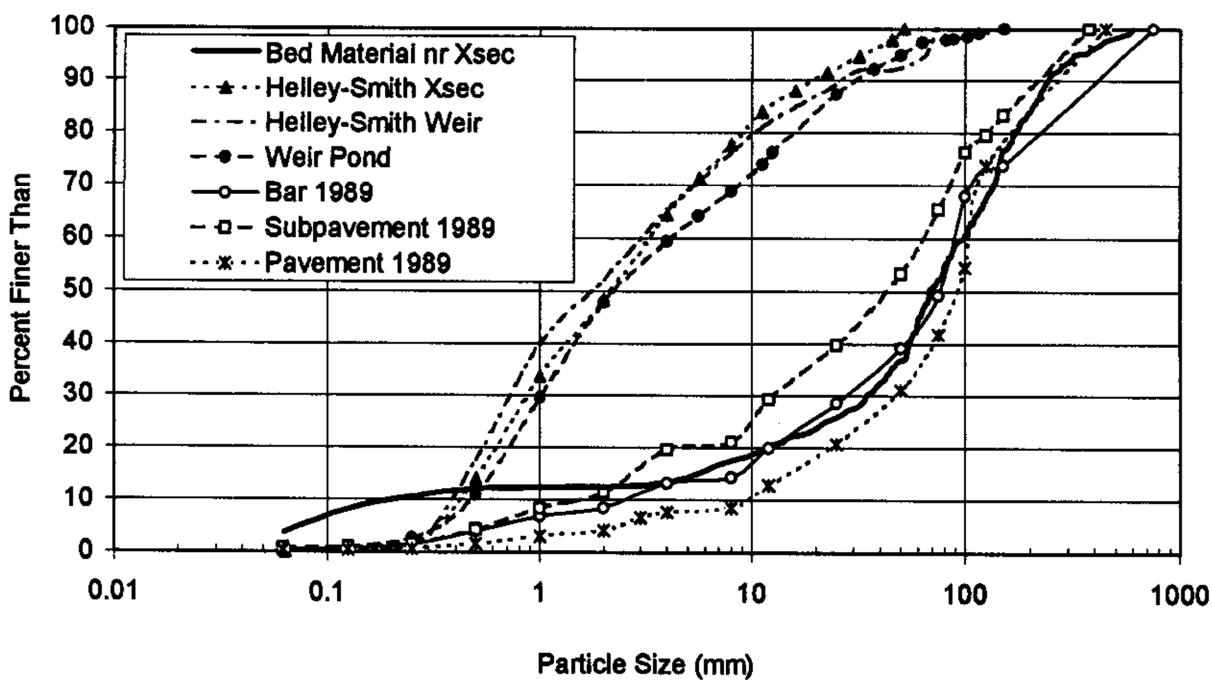

Figure 4. Sediment particle size distribution comparing transported material with in-channel sediment sources, Coon Creek.

As noted earlier, the Coon Creek pilot study represents an operational application of research techniques developed at FEF (Bevenger and Troendle 1987). Sediment accumulations in weir ponds have been measured at Fraser on several watersheds of differing size for many years. East St. Louis Creek is a 803 ha control watershed, this sediment has been monitored since 1964. East St. Louis Creek is very close in size to the East Fork Encampment River; 803 and 911 ha, respectively. The particle size distribution from East Fork Encampment River (figure 5) is similar to East St. Louis Creek (figure 6), for bed material, Helley-Smith samples, and weir pond accumulations. Like Coon Creek and East Fork Encampment River, material in transport at East St. Louis Creek is much finer than the material comprising the bed surface.

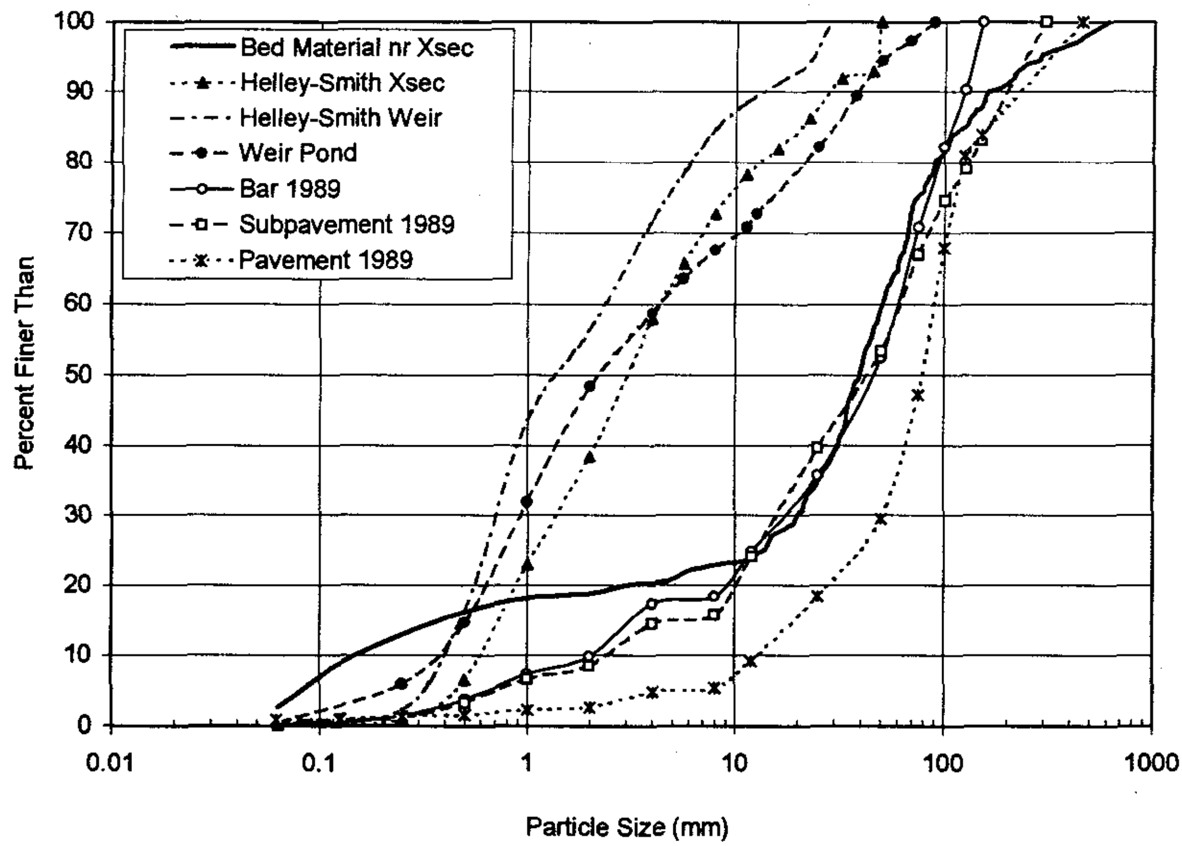

Figure 5. Sediment particle size distribution comparing transported material with in-channel sediment sources, East Fork Encampment River.

SUMMARY

Based on comparison of particles trapped in settling ponds and with the the Helley-Smith sampler, sediment sampling at stream cross sections using tools such as the 76 mm Helley-Smith sampler can yield reasonable indices of the dominant particle sizes being transported. Even when used in coarse cobble-bedded channels, very little difference was seen between particle size distribution in Helley-Smith samples from the natural bed and weir sill, and accumulations in the weir pond.

Most of the bedload is <15 mm in size but particles, up to at least 250 mm in size, do move on a frequent basis.

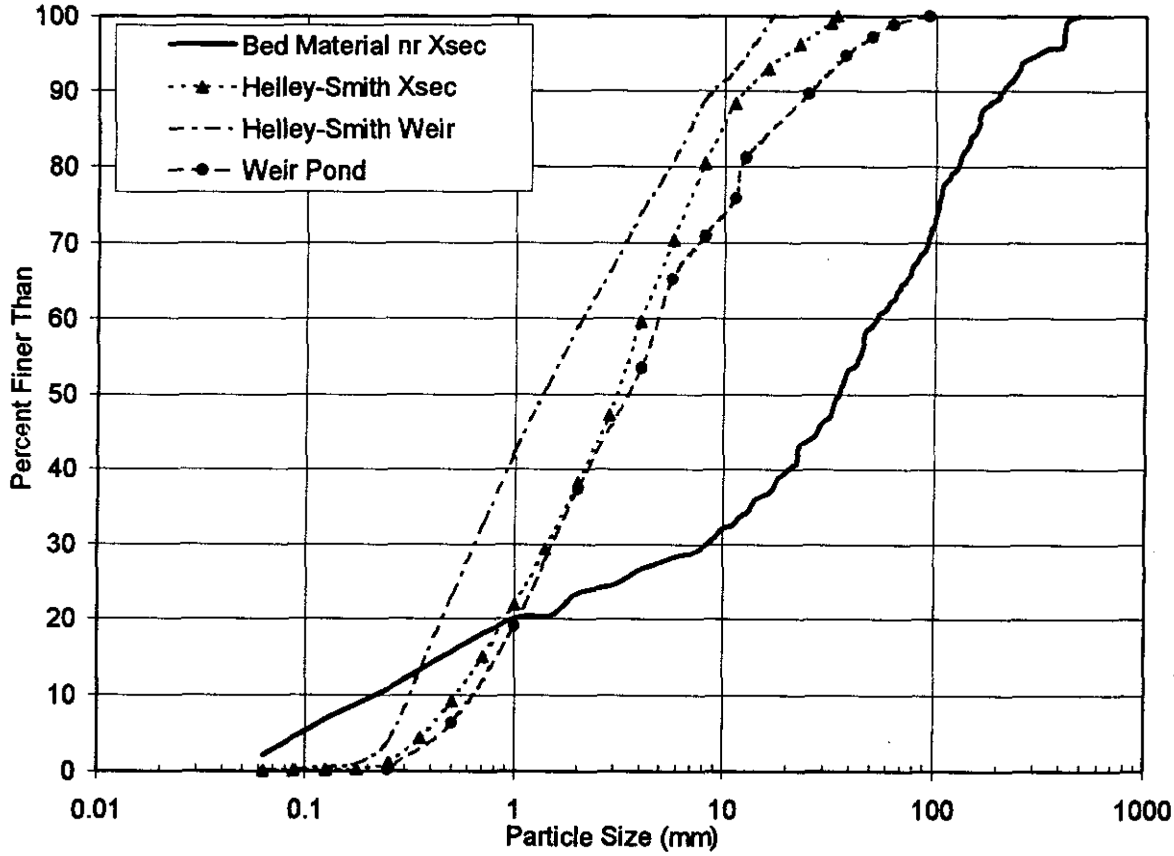

Figure 6. Sediment particle size distribution of Helley-Smith samples, weir pond accumulation and bed material at East St. Louis Creek FEF.

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A THEORETICAL STUDY OF DRAG REDUCTION FOR AERATED HEAVY SEDIMENT CONCENTRATION FLUID IN PIPE

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Abstract: In this paper, using fluid mechanics theory, firstly, the stratified flow for aerated water in pipe has been studied. The laws of velocity distributions and resistance variations for the stratified flow have been obtained. Then, the velocity distributions and resistance laws of the flow for aerated heavy sediment concentration fluid in pipe have been researched. We also present the resistance laws for no-aerated heavy sediment concentration fluid. At the same flow rate of the heavy sediment concentration fluid, we present a definition of the rate of drag reduction, and compare the resistance laws by aeration with ones by no-aeration. One has obtained the conclusions by the theoretical research, the flow resistance of heavy sediment concentration fluid in pipe can be decreased remarkably by aeration in the wall region.

INTRODUCTION

Research Background: Because heavy sediment concentration fluid belongs to Bingham fluid and it has more yield stress and plastic viscosity, when the fluid flows in pipe, the flow is often the structure flow with the more plug, and the resistance coefficient is more. So, it is more important to research how to reduce the flow resistance of heavy sediment concentration fluid in pipe.

Although the flow resistance in pipe can be reduced obviously by aeration, owing to the complexity of the problem itself, there is not any systematic theoretical research reports about the problem (Hou, H., 1987). The experiment methods are used by many scholars when they study the drag reduction of flow for heavy sediment concentration fluid in pipe, so the calculating formulas are semi-empirical.

Research Method: Because the key area to determine the resistance value is the region near to the wall while fluid is flowing in pipe, i. e. the wall region, the variable laws of the resistance values by aeration in the wall region have only been researched. The resistance feature includes the drag reduction for less viscosity, for thicker boundary layer, and for softer boundary layer, but the drag reduction for less viscosity is primary, the drag reduction for less viscosity is only calculated in this paper.

DRAG REDUCTION OF AERATED WATER FLOW IN PIPE

Velocity Distributions of Gas-Liquid Stratified Flow in Pipe: In the oil engineering, the principle of the liquid-ring oil transport technique is that the oil in the wall region is displaced by the liquid with less viscosity, e. g. water, therefore, the resistance of oil transport is decreased. It is known to all, the viscosity of air is much less than water's, only equals to the 1/56 of water's. So, if the water in the wall region can be displaced by air, the resistance can be decreased remarkably, the more rate of drag reduction is obtained.

As shown as Fig. 1, water is flowing in the center of pipe, air is flowing in the wall rigion. In this paper, we neglect the wave action of interface between water and air, and the expand action of air. After analysing the above flow, we can obtain the velocity equations

$$u = -\frac{1}{4\mu_a}|p'|(R^{*2}-R^2) + \frac{1}{4\mu_1}|p'|(R^{*2}-r^2) \qquad (0<r<R^*) \tag{1a}$$

$$u = -\frac{1}{4\mu_a}|p'|(r^2-R^2) \qquad (R^*<r<R) \tag{1b}$$

So, the flow rate of water is

$$Q = \int_0^{R^*} 2\pi r u dr \tag{2}$$

By combining Eqs. (1) and (2), we obtain

$$Q = \frac{1}{4\mu_a}|p'|(R^2-R^{*2})\pi R^{*2} + \frac{1}{8\mu_1}|p'|\pi R^{*4} \tag{3}$$

While no-aeration in the pipe, let $R^* \to R$, then one obtains

$$Q_0 = \frac{1}{8\mu_1}|p'_0|\pi R^4 \tag{4}$$

The Rate of Drag Reduction by Aeration: The definition of the rate of drag reduction by aeration is the ratio of the resistance fall by aeration to the resistance while no-aeration at the same flow rate of water (let $Q = Q_0$), i. e.

$$DR = \frac{|p'_0| - |p'|}{|P'_0|} \tag{5}$$

By combing the last three Eqs. , We obtain

$$DR = 1 - \frac{1}{2R_\mu(1-R_r^2)R_r^2+R_r^4} \tag{6}$$

Here, $R_\mu = \frac{\mu_1}{\mu_a}$, $R_r = \frac{R^*}{R}$.

Let $\frac{d(DR)}{dR_r} = 0$, from Eq. (6) and $R_\mu=56$, One obtains $R_r=0$ or $R_r=0.7103$.

While $R_r=0$, $DR \to -\infty$, no-meaning. While $R_r=0.7103$, DR arrives maximum, $DR_{max}=96.46\%$. Let DR=0, from Eq. (6) and $R_\mu=56$, one obtains $R_r=0.095$ or 1. So, while $0 < R_r < 0.095$, $DR < 0$, it is the resistance increasing region; while $0.095 < R_r < 1$, $DR > 0$, it is the resistance decreasing region. The variation law between R_r and DR is shown as Fig. 2. From Fig. 2, we can see that if it is aerated in the wall region, in spite of a little air, the more rate of drag reduction can be obtained. For example, while $R_r=0.99$, the thickness of air is only the 1% of the radius, but the

DR can arrive 68.2%. On the other hand, the more rate of drag reduction can be obtained in the wide region of air thickness, e. g. while $0.15 < R_r < 0.99$, DR > 60 %.

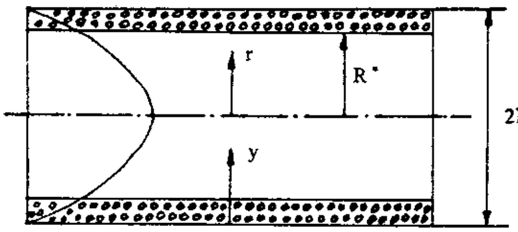

Fig. 1 Stratified Flow in Pipe

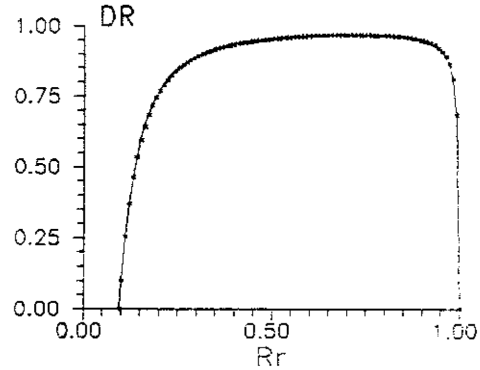

Fig. 2 Variation Law between R_r and DR

DRAG REDUCTION OF AERATED HEAVY SEDIMENT CONCENTRATION FLUID FLOW IN PIPE

Velocity Distributions of Aerated Heavy Sediment Concentration Fluid Flow in Pipe: As shown as Fig. 3, heavy sediment concentration fluid belongs to Bingham fluid. Air is distributed in the wall region of pipe. While $0 < r < R_0$, it belongs to plug flow region; while $R_0 < r < R^*$, it is Bingham shear flow region; while $R^* < r < R$, it is Newton shear flow region. Velocity distributions in these regions are

$$u = \frac{\tau_w}{2\mu_a R}(R^2 - r^2) \qquad (R^* < r < R) \tag{7a}$$

$$u = \frac{1}{\eta}\left(\tau_0 r - \frac{\tau_w}{R}\frac{1}{2}r^2\right) + \frac{\tau_w}{2\mu_a R}(R^2 - R^{*2}) - \frac{1}{\eta}\left(\tau_0 R^* - \frac{\tau_w}{R}\frac{1}{2}R^{*2}\right) \qquad (R_0 < r < R^*) \tag{7b}$$

$$u = \frac{1}{\eta}\left[\tau_0(R_0 - R^*) - \frac{\tau_w}{2R}(R_0^2 - R^{*2})\right] + \frac{\tau_w}{2\mu_a R}(R^2 - R^{*2}) \qquad (0 < r < R_0) \tag{7c}$$

From Eq. (7), the flow rate of heavy sediment concentration fluid can be obtained.

$$Q = \int_0^{R_0} 2\pi u r dr + \int_{R_0}^{R^*} 2\pi u r dr$$

$$= \pi R_o^2 \left[\frac{\tau_o}{\eta} (R_o - R^*) - \frac{\tau_w}{2\eta R}(R_o^2 - R^{*2}) + \frac{\tau_w}{2\mu_a R}(R^2 - R^{*2})\right]$$

$$+ \frac{2\pi}{\eta}\left[\frac{\tau_o}{3}(R^{*3} - R_o^3) - \frac{\tau_w}{8R}(R^{*4} - R_o^4)\right]$$

$$+ \pi\left[\frac{\tau_w}{2\mu_a R}(R^2 - R^{*2}) - \frac{1}{\eta}\left(\tau_o R^* - \frac{\tau_w}{2R} R^{*2}\right)\right](R^{*2} - R_o^2) \quad (8)$$

For no-aeration, while $0 < r < R_{oo}$, it belongs to plug flow region; while $R_{oo} < r < R$, it belongs to Bingham shear region. Velocity distribution is

$$u = \frac{1}{\eta}\left[\tau_o (r - R) - \frac{\tau_{wo}}{2R}(r^2 - R^2)\right] \qquad (R_{oo} < r < R) \quad (9a)$$

$$u = \frac{1}{\eta}\left[\tau_o (R_{oo} - R) - \frac{\tau_{wo}}{2R}(R_{oo}^2 - R^2)\right] \qquad (0 < r < R_{oo}) \quad (9b)$$

So, the flow rate for no-aeration is

$$Q_o = \int_0^{R_{oo}} 2\pi u r dr + \int_{R_{oo}}^{R} 2\pi u r dr$$

$$= \pi R_{oo}^2 \left[\frac{\tau_o}{\eta}(R_{oo} - R) - \frac{\tau_{wo}}{2\eta R}(R_{oo}^2 - R^2)\right]$$

$$+ \frac{2\pi}{\eta}\left[\frac{\tau_o}{3}(R^3 - R_{oo}^3) - \frac{\tau_{wo}}{8R}(R^4 - R_{oo}^4)\right]$$

$$+ \frac{\pi R}{\eta}\left(\frac{\tau_{wo}}{2} - \tau_o\right)(R^2 - R_{oo}^2) \quad (10)$$

because of

$$\tau_o = \frac{R_o}{R}\tau_w \quad (11)$$

$$\tau_o = \frac{R_{oo}}{R}\tau_{wo} \quad (12)$$

Let $\frac{R_o}{R} = i_o$, $\frac{R^*}{R} = i^*$, and $\frac{R_{oo}}{R} = i_{oo}$, So, we obtain

$$\frac{\tau_o}{\tau_w} = i_o, \quad \frac{\tau_o}{\tau_{wo}} = i_{oo}, \quad \text{and } \frac{i_{oo}}{i_o} = \frac{\tau_w}{\tau_{wo}}.$$

From Eq. (8), one can get

$$Q = \frac{\pi R^3 \tau_o}{12 \eta i_o} [i_o^4 + (3 - \frac{6\eta}{\mu_a}) i^{*4} - 4 i_o i^{*3} + \frac{6\eta}{\mu_a} i^{*2}] \tag{13}$$

From Eq. (10), one can get

$$Q_o = \frac{\pi R^3 \tau_o}{12 \eta i_{oo}} (i_{oo}^4 - 4 i_{oo} + 3) \tag{14}$$

The rate of drag reduction by aeration for heavy sediment concentration fluid is the ratio of the resistance fall by aeration to the resistance for no-aeration at the same flow rate of heavy sediment concentration fluid. Let $Q = Q_o$, from the last two equations, we can obtain the values of i_o and i_{oo}. So, the rate of drag reduction is

$$DR = \frac{\tau_{wo} - \tau_w}{\tau_{wo}} = 1 - \frac{\tau_w}{\tau_{wo}} = 1 - \frac{i_{oo}}{i_o} \tag{15}$$

Example: $Q=0.1 m^3/s$, $R=0.1 m$, $\tau_o=0.06 pa$, $\eta=0.064 pa\cdot s$, $\mu_a=17.9\times10^{-6} pa\cdot s$, $i^*=0.99$.

Calculating result: DR=0.9926. So, for the laminar flow of heavy sediment concentration fluid, drag reduction can be done by aeration in the wall region, and the rate of drag reduction is very high. As shown as the example, the thickness of air is only 1% of the radius, the rate of drag reduction goes up to 99.26%.

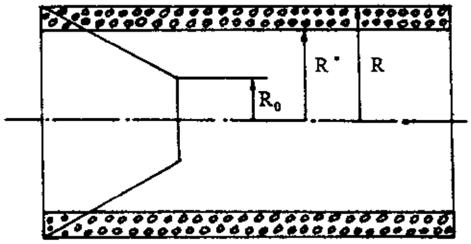

Fig. 3 Stratified Flow for Heavy Sediment Concentration Fluid in Pipe

CONCLUSIONS

We has obtained the conclusions by the theoretical research, the flow resistance of heavy sediment concentration fluid in pipe can be decreased remarkably by aeration in the wall region. Because the flow rate of heavy sediment concentration fluid is constant, there is a optimum aeration quantity. When the aeration quantity is equal to the optimum one, the rate of drag reduction is the most, for water-air system, the most rate of drag reduction is 96. 46%. The optimum aeration quantity is relative to the fluid properties, the diameter of pipe, and the flow rate etc. The optimum aeration quantity is very less generally. When the aeration quantity is less than the optimum one, owing to the less aeration quantity, the aeration boundary layer is thiner, although the resistance can be decreased, the rate of drag reduction is less than the most one; when the aeration quantity is more than the optimum one, owing to the more aeration quantity, the volume in which the heavy sediment concentration fluid flows is decreased, although the resistance can be decreased, the rate of drag reduction is less than the most one.

NOMENCLATURE

$|p'|$ —absolute value of pressure gradient while aeration, pa/m;

$|p'_o|$ —absolute value of pressure gradient whlie no-aeration, pa/m;

Q — flow rate of water or heavy sediment concentration fluid whlie aeration, m^3/s;

Q_o — flow rate of water or heavy sediment concentration fluid while no-aeration, m^3/s;

r — radial coordinate, m;

R — radius of pipe, m;

R^* — radius of the interface between air and water or heavy sediment conc entration fluid, m;

R_o — radius of plug while aeration, m;

R_{oo} — radius of plug while no-aeration, m;

u — velocity, m/s;

μ_a — viscosity of air, pa · s;

μ_1 — viscosity of water; pa · s;

η — viscosity of heavy sediment concentration fluid, pa · s;

τ_o — yield point of heavy sediment concentration fluid, pa;

τ_w — wall shear stress while aeration, pa;

τ_{wo} — wall shear stress while no-aeration, pa.

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SEDIMENT TRANSPORT MODELING USING "EXCEL" IN THE LOWER VIRGIN RIVER, CLARK COUNTY, NEVADA

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__Abstract__: The potential construction of a water resource development project on the lower Virgin River located about 60 miles northeast of Las Vegas, Nevada, consists of a diversion dam and reservoir and an off-channel storage dam and reservoir.

During the design of the diversion dam and reservoir, it became apparent that sediment transport in the river is a major concern and must be understood prior to actual design of the project facilities. A sediment and flow relationship was derived for a short-term gaging station at the project site and for an upstream long-term gaging station. These regression analyses indicated that the average suspended sediment load at the project site was about 20-25 percent of the load at the upstream long-term gage indicating the river is aggrading at an annual rate of about 2,000 acre-feet.

In order to better understand the sediment transport regime, we created and applied a computer model to this reach. The results of the application of the computer model will assist in determining the design and feasibility of operational strategies for the diversion dam. For example, it is of utmost importance to know whether sluicing the sediment through the dam is feasible or not, and at what magnitude of river flow will this aggrading reach degrade and to what extent?

INTRODUCTION

In October, 1989, the Las Vegas Valley Water District (District) filed for surface-water rights from the Virgin River, located about 60 miles northeast of the city of Las Vegas, Nevada. In January, 1994, the applications were successfully defended by the Southern Nevada Water Authority (Authority) , the entity responsible for acquiring new water in southern Nevada, in a water right hearing which resulted in the granting of the applications by the Nevada State Engineer.

The diversion project the Authority presented in support of the water right applications was an in-river diversion dam and reservoir of 300 acres surface area with the main storage reservoir located off channel. Concern over the potential sediment load into the in-channel reservoir led to a sediment analysis to determine if sluicing or some other mechanism would be required to keep the reservoir operational.

Purpose and Scope: The Virgin River was originally named El Rio del Fiero by early Spanish explorers in recognition of the red to brown color of the water caused by the large suspended sediment load transported by the river. The purpose of this paper is to define the amount of sediment transported by the river and to determine the impact of the sediment on certain potential diversion works. The scope of the study was limited to using published data and no attempt was made to estimate bed load.

Availability of Data: The U.S. Geological Survey (USGS) has operated a river flow gaging station near the upper end of the lower Virgin River Valley at Littlefield, Arizona since 1930 and during the course of time has collected about 299 suspended load samples. Data downstream from Littlefield is sparse, but there are seven years of flow and sediment data at the proposed diversion dam also collected by the USGS.

DESCRIPTION OF STUDY AREA

Location and Physiographic Setting: The lower Virgin River Valley is located in southern Nevada, mainly in Clark and Lincoln Counties, and extends into Mohave County, Arizona, and Washington County, Utah as shown in Figure 1. The Virgin River begins its course from precipitation falling on the high plateaus of Utah. Great masses of sandstone are exposed in Utah and Arizona and these are the source areas for most of sediment for the Virgin River. The lower valley is bounded by near continuous mountain blocks and its terminus is Lake Mead on the Colorado River about 35 miles downstream from the Littlefield gage.

Precipitation varies widely throughout the area with the lowlands receiving 3 to 6 inches per year (National Weather Service data base) from winter rainstorms and summer convective storm. Total water falling on Virgin Peak, the highest peak in the area, may average 15 inches annually (Glancy and Van Denburg, 1969)

Hydrologic Setting: Precipitation in Utah provides the majority of water to the lower Virgin River Valley with lessor amounts entering the system from Arizona and Nevada. Most of this water originates as melting snow although summer and winter rains can be significant sources in some years. Summer convective storms are always significant contributors and are probably one of the main mechanism of sediment transport from the mountain blocks to the channels of the river and its tributaries.

Figure 1 shows two sites ta Virgin River; the Littlefield, Arizona gaging station and the project site, about 28.5 miles downstream, where the diversion dam is proposed. The long-term record at the Littlefield gage shows the average annual flow to be about 175,000 af, and based on the work of Brothers et al (1993) the long-term average is about 154,000 afy. There are numerous diversions and other flows to the

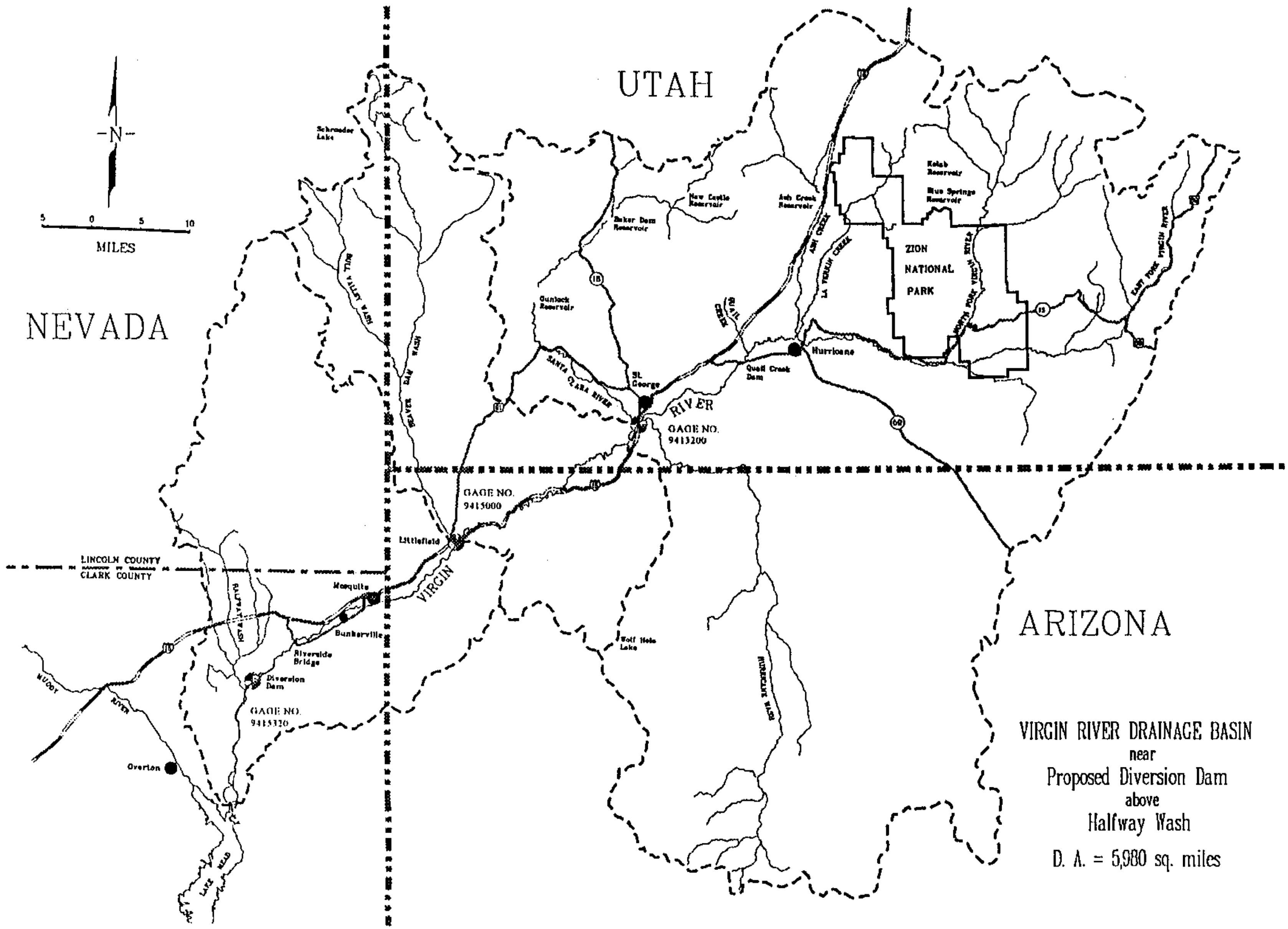

FIGURE 1. VIRGIN RIVER WATERSHED BOUNDARY MAP

river system between the two gages that are defined in Brothers et al (1993) and Katzer and Brothers (1995).

Modification of the River System: Like most western rivers the Virgin River has had its share of development and modification. Irrigation, which of course native Americans had been doing at select sites on the flood plain long before the arrival of settlers in the west, began in the late 1800s. At first small earth and rock diversion dams were constructed after the spring flows had passed to divert the water onto fields adjacent to the river. Then with time more permanent diversion dams were constructed, including the construction of reservoirs until now there are at least six structures in the river system that have clearly altered the flow and sediment regime.

Another factor that has changed the character of the lower river is the introduction and spread of salt cedar, an exotic planted in the west for wind breaks and soil stabilization. The salt cedar out competes most other native plants, has incredible drought tolerance, and spreads very fast. Much of the flood plain, that is non agriculture in the lower Virgin River, is covered with this plant, which is also considered a phreatophyte. Salt cedar stabilizes banks and flood plains by armoring them with a thick heavy growth thus reducing lateral river movement to some extent. The net effect is that only very large floods or high sustained spring flows are able to cause channel migration.

Additionally the construction of Lake Mead, which has inundated several miles of the lower Virgin River, has also flattened the gradient in the last few miles of the free flowing river by creating a large delta with heavy vegetation and multiple river channels.

Floods: Flood peaks above 3,000 cubic feet/second (cfs) are relatively common and occur as a result of convective storms and rapid snowmelt, however severe floods can be caused by winter rains. Ely et al., (1993) cited three classifications of severe storms that produce large floods in the southwest: 1) North Pacific frontal storms, 2) late summer and fall storms associated with Pacific tropical cyclones over northern Mexico in conjunction with a mid-latitude low pressure trough, and 3) local summer convective thunderstorms. The maximum peak in the historic record is 61,000 cfs measured a few miles upstream from the Littlefield gage. This peak occurred on January 1, 1989, as a result of a dam failure from Quail Creek Reservoir located about 20 miles north of St. George Utah. The Authority has a cooperative program with the USGS to evaluate the river geomorphology which will include changes to the sediment Regina resulting from this flood. The maximum natural flood of record measured by the USGS occurred in 1966 and was about 35,000 cfs. Ely documented a flood that occurred about 1100 to 1200 years ago that had an estimated peak of slightly over 60,000 cfs.

SEDIMENT TRANSPORT

River Flow: The daily mean water discharge (Q) records used in this paper were collected for Virgin River at littlefield, Arizona from 1930 through 1992. The daily mean discharges for Halfway Wash, Nevada (28.5 downstream from Littlefield) were taken for seven years; 1978-1983 and 1985. In order to estimate the available water at Halfway Wash for the period of 1930 through 1992, a regression equation was developed based on the seven years of concurrent data at the two locations, and used to predict the daily flow at Halfway Wash from the flow at Littlefield for the period of record (1930-1992). The results of this regression analysis are shown as follows.

$$Q(\text{Halfway Wash}) = 21.13 + 0.81 * Q(\text{Littlefield})$$

There were 84 observations, the coefficient of correlation was 0.98, and the standard error was 72.81.

The hydrology of the river system between the two gages is complex because there are diversions for agriculture with corresponding return flows, there is a large acreage of phreatophytes, some irrigation and spring flow bypasses the Littlefield gage, occasionally surface water enters the river from ephemeral drainages, and there is ground water flow to the river. All these complexities add to the difficulties of interpreting the river flow variation between the two gage sites.

Sediment Discharge: Extensive suspended sediment discharge data were collected at Littlefield, Arizona, for water years of 1951, 1959-1968, and 1986-1991 for a total of 299 samples. The Halfway Wash, Nevada, suspended sediment discharge data were collected from 1979 through 1982 and from 1985 through 1986 for a total of 51 samples. Non-linear regression analysis was applied to these sediment data and their corresponding water discharge values. The results of the regression analysis are summarized in Table 1.

	LITTLEFIELD		HALFWAY WASH	
REGRESSION STATISTICS	**Q < 300 CFS**	**Q > 300 CFS**	**Q <40 CFS**	**Q >40 CFS**
R Square	0.41	0.62	0.71	0.7
Standard Error	0.72	0.43	0.36	0.3
Observations	173	126	7	44
Intercept	-3.45	0.506	-0.68	-0.218
ALOG(Intercept)	0.000335	3.21	0.208	0.605
Exponent of Independent Varaible	2.95	1.45	1.59	1.42

TABLE 1. NON-LINEAR REGRESSION ANLYSES FOR SEDIMENT RATING CURVES OF LITTLEFIELD, ARIZONA AND HALFWAY WASH, NEVADA

The regression equations that are acquired from Table 1 were plotted on the sediment rating curves for Littlefield and Halfway Wash and are presented in Figures 2 and 3 and respectively. The unit weight of the sediment at Littlefield was estimated to be 75 pounds per cubic foot based upon a time weighted average of the suspended sediment size analyses (clay-36%, silt-42%, and sand-22%).

<u>**River Flow-Sediment Discharge Computer Model**</u>: The computer model consist of an EXCEL spreadsheet and a macro program that drove the spreadsheet. The regression equation from the River Flow section was applied to each daily mean water discharge value for Littlefield to simulate the flow at Halfway Wash. Then, the sediment regression equations from the preceding section, for each day, predict the sediment load at Halfway Wash and Littlefield using daily river flows and each daily sediment load is converted to acre-feet. All daily sediment and river flow values are summed up annually and are tabulated in Table 3.

<u>**Application of the River Flow-Sediment Flow Model:**</u> The computer model was applied to 63 year of daily mean river flow values at Littlefield to simulate daily mean flow values at Halfway Wash and sediment loads at Halfway Wash and Littlefield. The largest part of the input data was the 63 years of mean daily water flow at Littlefield which was contained in the model spreadsheet. The rest of the input data and the output data are presented in the Tables 2 and 3.

	CONSTANT	EXPONANT
Halfway Wash river flow Regression	**21.14**	**0.8109**
Littlefield Sediment Load Regrss. Q<300 CFS	**0.000355**	**2.9501**
Littlefield Sediment Load Regrss. Q>300 CFS	**3.21**	**1.4521**
Halfway Wash Sediment Load Regress. Q<40 CFS	**0.208**	**1.599**
Halfway Wash Sediment Load Regress. Q>40 CFS	**0.605**	**1.425**
Specific Weight of Sediment	**75**	**lbs/ft3**

TABLE 2. REGRESSION EQUATION CONSTANTS AND EXPONENTS USED AS INPUT DATA

DISCUSSION OF RESULTS

Log-log scatter diagrams, shown in Figures 2 and 3 were created to determine the distribution of the sediment data with river flow.There is a change of slope in both data sets; for Littlefield it occurs at about 300 cfs and at 40 cfs at Halfway Wash.

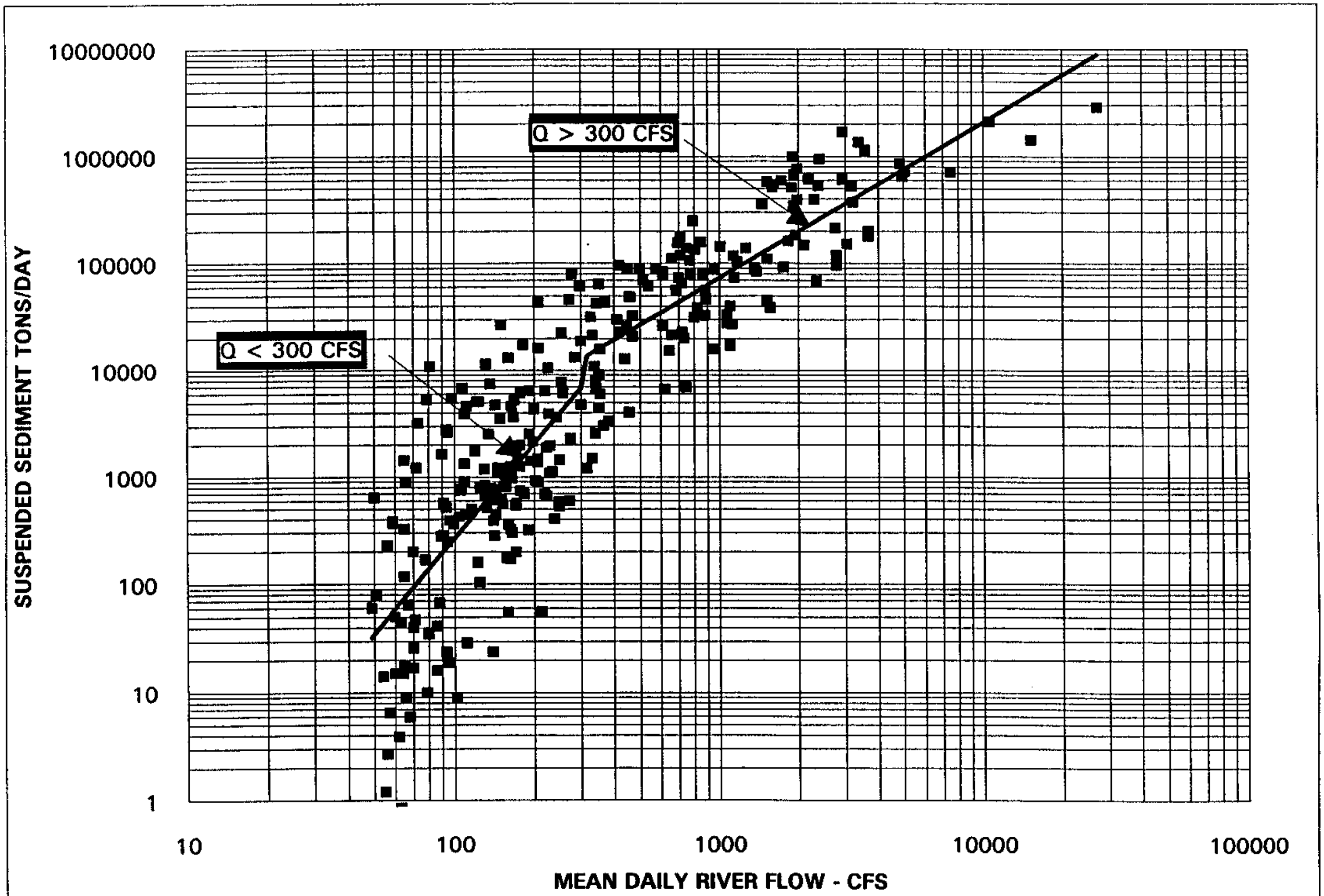

FIGURE 2. SUSPENDED SEDIMENT RATING CURVE OF VIRGIN RIVER AT LITTLEFIELD, ARIZONA

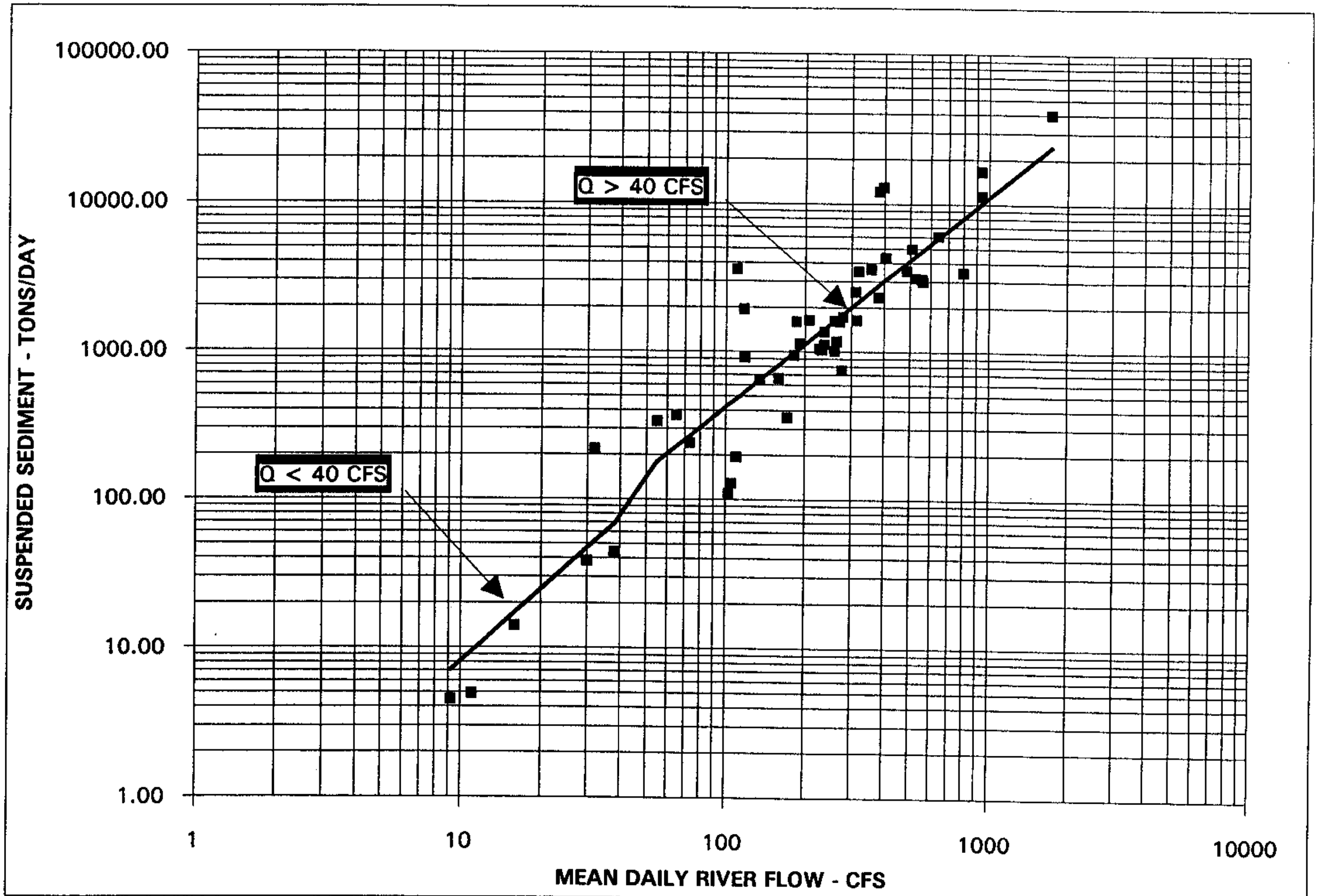

FIGURE 3.SUSPENDED SEDIMENT RATING CURVE OF VIRGIN RIVER AT RIVERSIDE, NEVADA

TABLE 3. RIVER FLOW AND SUSPENDED LOAD DATA FOR LITTLEFIELD AND HALFWAY WASH SITES

LITTLEFIELD RIVER FLOW AF/YR	SUSPENDED SEDIMENT AF/YR	WATER YEAR	HALFWAY WASH RIVER FLOW AF/YR	SUSPENDED SEDIMENT AF/YR
188,085	3,478	1930	167,822	503
119,365	878	1931	112,098	206
381,888	11,432	1932	325,019	1,373
127,394	701	1933	118,609	208
78,008	274	1934	78,561	119
164,777	1,750	1935	148,922	314
130,953	1,295	1936	121,536	252
240,303	3,613	1937	210,167	519
278,618	7,933	1938	241,236	992
154,927	1,932	1939	140,935	342
173,681	2,785	1940	156,184	428
399,979	9,789	1941	339,647	1,223
214,984	2,876	1942	189,636	440
178,122	2,158	1943	159,744	353
182,696	2,184	1944	163,494	360
166,310	1,801	1945	150,165	324
121,242	740	1946	113,620	207
192,248	2,997	1947	171,199	462
116,406	610	1948	109,740	187
155,877	1,515	1949	141,705	285
127,053	761	1950	118,332	211
99,929	644	1951	96,337	177
273,463	5,316	1952	237,098	710
99,489	458	1953	95,980	160
136,493	1,191	1954	125,986	247
135,513	1,703	1955	125,192	307
92,836	386	1956	90,628	146
100,173	537	1957	96,535	163
294,607	5,618	1958	254,201	757
92,862	376	1959	90,607	146
83,449	266	1960	83,015	127
108,522	1,148	1961	103,305	225
142,427	1,597	1962	130,799	281
83,294	423	1963	82,848	135
89,510	521	1964	87,930	148
120,434	1,045	1965	112,965	213
128,454	1,172	1966	119,468	243
187,561	5,306	1967	167,398	698
128,672	852	1968	119,686	215
343,569	7,968	1969	293,905	1,007
96,980	383	1970	93,946	151
99,780	547	1971	96,217	163
126,914	1,737	1972	118,261	296
321,015	6,731	1973	275,616	875
90,476	326	1974	88,672	140
111,209	789	1975	105,484	197
91,198	404	1976	89,299	146
81,439	474	1977	81,344	138
256,558	7,025	1978	223,348	871
308,898	6,215	1979	265,790	809
450,248	12,285	1980	380,453	1,496
163,864	1,328	1981	148,182	288
165,172	1,457	1982	149,242	298
504,585	11,830	1983	424,473	1,470
191,365	1,982	1984	170,525	358
175,313	1,766	1985	157,466	321
143,328	888	1986	131,529	240
130,372	828	1987	121,023	217
190,171	2,009	1988	169,556	374
121,323	1,555	1989	113,685	277
82,100	263	1990	81,879	125
72,589	122	1991	74,167	103
138,436	1,204	1992	127,605	245
170,595	2,543	MEAN-AF	153,651	397

Much of this scatter is attributed to the extreme flashy nature of river and the uncertainties of the bed load and suspended load relationship.

The reach between Littlefield and Halfway Wash, based on the average annual (mean) river flow, is a loosing reach since the average annual flow of the Halfway Wash is about 90 percent of that of Littlefield. The average annual sediment yield of Halfway Wash is approximately 16 percent of Littlefield's sediment yield. Thus, it appears that the river is depositing sediment at an average rate of 2,100 afy. The advantage of this method is that regarding the sluicing operation of the diversion dam is that it provides information on a daily basis. For example, in a high flow year, the highest sediment loads for a day, a week, and a month can be determined. This type of information can assist designers to prevent over or underdesigning of the sluicing infrastructure and more accurately size the pool for the diversion dam.

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SEDIMENT TRANSPORT IN THE YANGTZE BASIN

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Abstract Temporal and spatial variations of suspended and bed load at the main stations on the stem stream of Yangtze River have been analysed using 40 years of data. Above Yichang, the Yangtze River is a mountainous river with a close relationship between sediment yield and sediment transport, and the suspended sediment load increased downstream. Below Yichang, it flows on to an alluvial plain and the sediment concentration and load decreased downstream. In the Yangtze basin, the sediment source is concentrated and the sediment delivery ratio is small. Sediment transport is reduced by the human activities. Variations of sediment concentration and load are irregular and no systematic change was found for the 40 years of record.

INTRODUCTION

The Yangtze River is the longest river in China. It is 6300 km long and has a basin area of 1.8 million km^2 and is rich in water resources. At Datong Station, a control station on the downstream Yangtze, the long – term mean annual runoff is 915 billion m^3, sediment concentration is 0.53 kg m^{-3} and sediment load is 472 Mt(Xiang *et al.*, 1990). While sediment concentration is low on Yangtze River, there is a large discharge and the absolute value of annual sediment transport is still large. This large amount of sediment being transproted results in some problems with flood control, power generation, navigation and water supply for industry and agriculture.

For comprehensive utilization and planning, engineering construction and river regulation in the Yangtze basin, a great number of sediment observations (including sediment yield, transportation and deposition) have been made by the Hydrology Bureau, Yangtze Water Resources Commission including systematic data processing, analysis, and interpretation (Xiang & Zhou, 1993). This paper describes the characteristics of sediment transport in the Yangtze basin.

TRANSPORT OF SUSPENDED LOAD

Suspended Sediment Load The distribution of control stations on the main Yangtze and its tributaries are shown in Fig. 1. In the main Yangtze, the long–term mean annual suspended sediment load at Zhimenda Station on the Jinsha River on the upstream Yangtze is 9. 71 Mt. increasing to 530 Mt. at Yichang Station. Below Yichang it decreases to 472 Mt. at Datong Station, a downstream control. For the tributaries on the Jialing River, Beibei Station has the highest load of 14. 3 Mt followed by Gaochang Station on the Minjiang River with 5. 07 Mt. In the other major tributaries those with high loads are the Wujing River with 32. 2 Mt and the Yalong River with 27. 5 Mt. Before the construction of Danjiangkou Reservoir, sediment transport at Huangzhuang Station on the Hanjiang River was 124 Mt, and after the

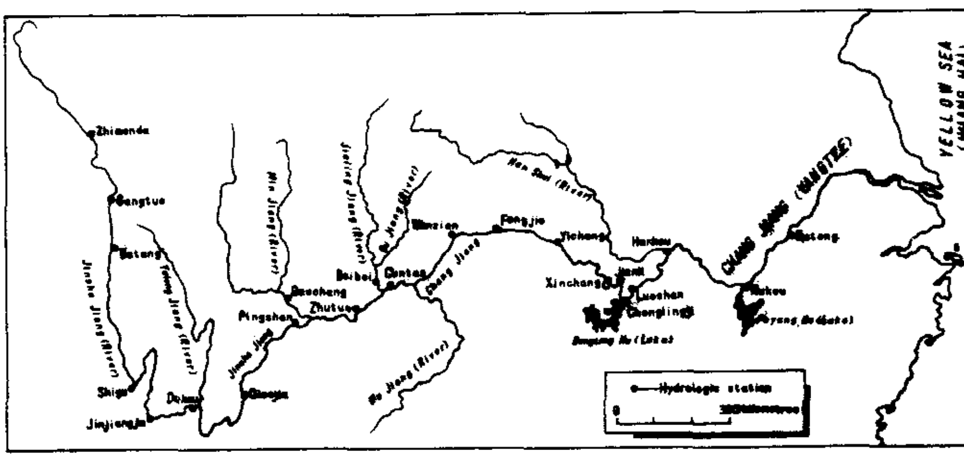

Fig. 1 The Yangtze River and its tributaries showing the major control stations.

construction of the reservoir was 30. 1 Mt. The Jinsha River and Jialing River are the rivers producing the major sediment yield in the upstream Yangtze accounting for 73—90% of the total sediment. The sediment from the other rivers is small, accounting for only 10—27%. Erosion intensity on the downstream Jinsha River is high, and the long—term mean annual sediment transport exceeds 2000 t $km^{-2}year^{-1}$. Its sediment yield is 57% of the total sediment load of the Jinsha River. The Western Han River and the mid—section of the Bailong River are the major sediment contributors on the Jialing River, from which the erosion intensity is high and the mean annual sediment load is greater than 3 000 t $km^{-2}year^{-1}$. The discharge of the Western Han River and Bailong River are not high but their sediment concentration is high and sediment yield is generally around 29% of the total load of the Jialing River, but reaches a maximum of 83%. The sediment transport runoff from Yangtze stem passing through four river mouths into Dongting Lake. These four rivers account for 83% of the total sediment load of the main Yangtze at Dongting Lake over the period 1951—1987. With the systematic cutoff on the Jing River, the diverted discharge at the Ouchi Mouth has decreased, and in recent years the water and sediment volumes of the Yangtze River entering into the lake have decreased significantly. Consequently, the outflow of sediment from the lake has also decreased from 5. 95 Mt. (1956—67) to 3. 82 Mt. (1973—84) after cutoff.

Variation of Suspended Load along the River The variation of suspended sediment concentration and load on Yangtze River is shown in Fig. 2. In the upper Yangtze, upstream of Yichang,Sediment increases with drainage area, however decrease in the mid and lower

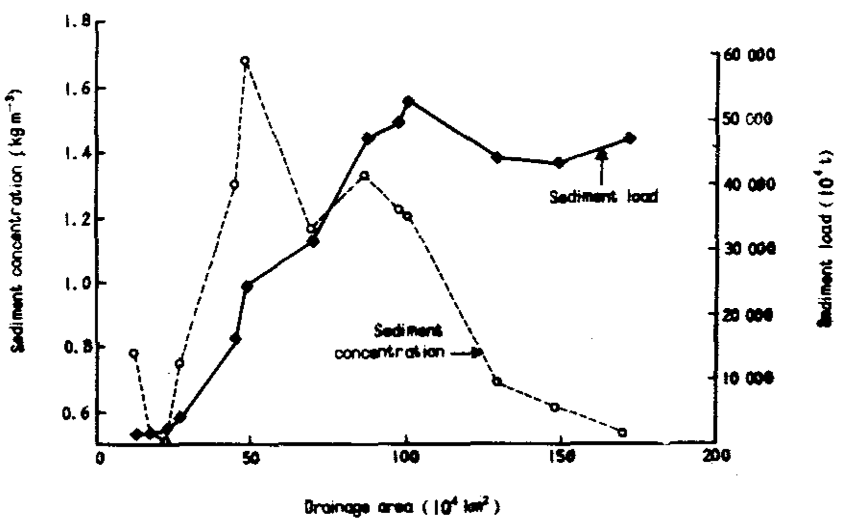

Fig. 2 Suspended sediment concentration and load along the Yangtze stem.

sections from Yichang to Hankou, due to a large amount of deposition in Dongting Lake. Below Datong, sediment load increases slightly. Above Yichang, sediment concentration increases and then decreases, however sediment load continue to increase. Below Yichang, both sediment concentration and load decrease. This is due to by the different characteristics of the river. The Yangtze River above Yichang is a mountainous river with a gravel and bedrock bed, steep slope, high velocity with excess transport capacity and no exchange between suspended and bed load. the load is controlled by erosion of surface soil. Thus, the variation of sediment concentraton and load in this reach is closely related to the sediment yield. Downstream of Yichang the Yangtze is an alluvial river. The variations of sediment concentration and load in this section are significantly affected by regulation, storage and depositon of water and sediment in lakes, especially the Dongting Lake. Three quarters of the sediment from the four tributary rivers which flow into Dongting Lake are deposited in the lake resulting in a decrease in downstream sediment. Danjiangkou Reservoir and Poyang Lake also the affect the regulation, storage and deposition of water and sediment.

Intra – annual Variation of Sediment Concentration and Load The variation of sediment concentration and transport runoff throughout the year is determined by the source of sediment. For the Yangtze stem above Yichang, the sediment comes mainly from the erosion of surface soil by precipitation, so the distribution of suspended sediment concentration throughout a year is closely related to the variation of precipitation and runoff throughout the year. The Yangtze River is a flood dominated river, and the major proportion of runoff is concentrated in the flood season, so the variation of annual hydrographs and sedigraphs is similar. However, there are some differences in the low flow season when runoff is derived from ground water, which has low sediment concentrations and results in low loads. sediment load is the product of runoff and sediment concentration and high loads only occur when there is a co–incidence of both, which results in a concentration of load in the flood season.

In the Yangtze River below Yichang, sediment concentration is also affected by scouring and deposition in the river channel and sedimentation in the lake, as well as precipitation. The minimum concentration occurs in February. The variation of mean monthly concentration along the river is: Yichang 0.042 kg m^{-3}, Xinchang 0.194 kg m^{-3}, Jianli 0.278 kg m^{-3} and Luoshan 0.320 kg m^{-3}. Sediment concentration increases significantly below Yichang.

Inter–annual Variation of Sediment Concentration and Load The inter–annual variation of sediment concentration and load depends on the effect of human activity as well as natural factors, such as precipitation (amount, intensity and regional distribution) and the condition of the underlying surface (geomorphological pattern, lithologic character, soil characteristics). An analysis has been carried out of the inter–annual variation trend for Yichang Station. Other upstream stations on the Yangtze stem are basically similar to Yichang.

Fig. 3 shows the hydrographs and sediment concentration and load at Yichang from 1950–92. The long term mean annual sediment load at Yichang Station is 530 Mt, based on data from the 1950s. The variation of water flow and sediment basically coincide, with some fluctuation in the mean annual value but with no obvious systematic deviation. Based on the existing sediment data, there was no systematic trend of increase or decrease of sediment in the upstream Yangtze. In the early 80s, the high sediment load is related to natural hydrologic phenomena and was not caused by human activity.

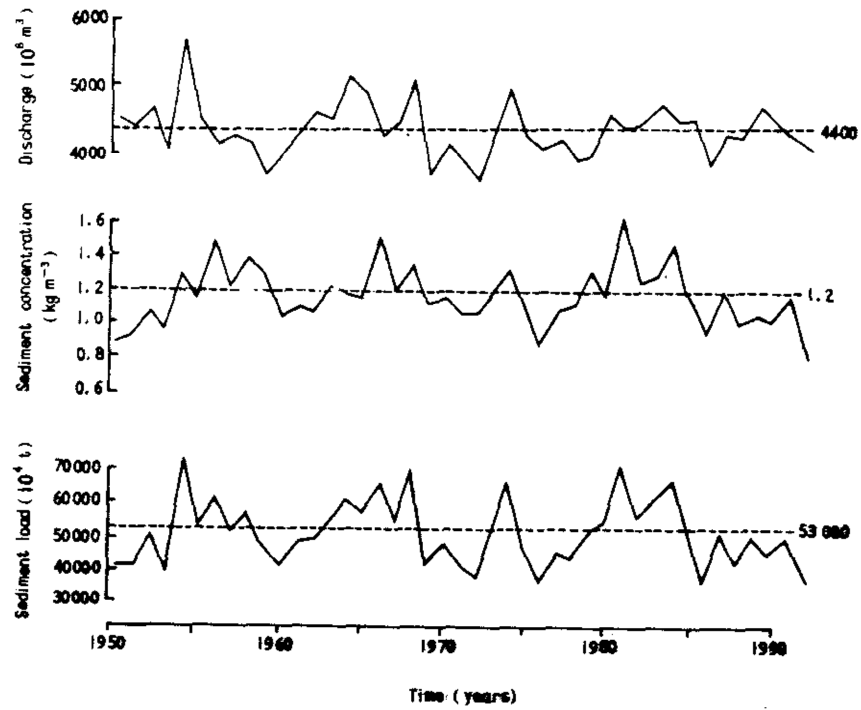

Fig. 3 Discharge, sediment concentration and load for Yichang station on the Yangtze River.

Grain Size Distribution of Suspended Load The variaton of mean annual grain size distribution of suspended load at the control stations on the Yangtze River and its tributaries and described as follows. The grain size at the stations on the Jinsha River is the coarsest, with median grain diameter of 0. 045—0. 046 mm. This is related to the dry climate, loose surface soil and coarsed grained regolith in this region. The median grain diameter at Cuntan is 0. 033 mm, finer than all the stations on the Jinsha River. At Yichang it is reduced to 0. 029 mm. In the reach from Yichang to Luoshan, a part of the water flow and sediment on the Yangtze stem passes through four river mouths into Dongting Lake where the sediment is deposited. However, due to the effect of systematic cutoff on the lower Jing River, the channel has been scoured. These two factors result in the median grain diameters of suspended sediment at Yichang and Luoshan stations being similar. Below Luoshan, the grain size becomes finer.

TRANSPORT OF BED LOAD

Transport of Gravel Bed Load: The long term mean annual gravel bed load, $D>10$ mm, of the upstream Yangtze stem at Cuntan Station is 280x 10^5 t. It decreases downstream in the Zhutuo

—Cuntan reach, but increases gradually in the reach below Cuntan. The sediment load made up of the large or median grain fraction (D>50 mm) decrease slightly downstream in this reach, while the median or small gravel (D<50 mm) increases. In the upstream Yangtze stem, the gravel bed load becomes finer downstream. Median diameter at Zhutuo is 57 mm, and reduces to 26 mm at Yichang.

The gravel load is related to the velocity so the gravel load is concentrated in the flood season. This is shown by comparing the percentages of bed load transport for the period from May—October to that of the whole year at Cuntan (96.8%), Wanxian (99.7%) and Zhutuo stations (99.8%) respectively. The only exceptional is Fanjie station, which is located upstrem of Qutangxia Gorge, where the proportion 22.5%. Here, there is a back water effect in the valley during the flood season resulting in low slope and reduced velocity. After the flood season, the back water disappears, the surface slope of the reach and the velocity increase, thus a major portion of the gravel bed load is transported in the low—water season from November to April.

Transport of Sand Bed Load: There is considerable variation in the sand bed load associated with variations in grain size. Before the construction of Gezhoubar Reservoir, the river bed at Yichang Station was mainly sand and the mean annual sand bed load was 8.45 Mt (if the 1—10 mm material is included it was 8.78 Mt). After dam operations commenced the annual sand bed load reduced considerably to 0.32—1.41 for the period 1981—87 Mt due to a coarsening of the river bed composition. The river bed at Fanjie is mainly gravel but in flood season the back water in Qutangjia Gorge reduces velocity and the bed material becomes finer with an increased proportion of sand with a sand bed load transport of 0.81 Mt. This is significantly smaller than that at Yichang.

The river bed at Cuntan is gravel although 13% is finer than 1.0 mm. As the velocity is low, there is no gravel transport and the overlying gravel protects the sand from transport. The water flow has an effect on the exposed surface sand, transporting it, but it can not be supplemented from the underlying sand so sand transport cannot be maintained. When the velocity is increased (bottom velocity>1.1 ms^{-1}) the gravel starts moving and underlying sand passes into suspension. In the gravel river bed, sand bed load is generally non—existant, only being found as bed load in some individual verticals close to the shore.

CONCLUSIONS

The main source of sediment in the Yangtze River is from the Jinsha and Jialing Rivers. Most of the sediment is from the reach between the confluence of the Yalong River and Jinsha River down to Pingshan, and also from the Western Han River and Bailon River.

Soil erosion associated with human activity in the Yangtze basin is common resulting in increased sediment concentrations and loads compared with natural conditions. However, there is a reduction in sediment due to water and soil conservation and sedimentation in the reservoir. The amount involved is small and so on the Yangtze stem and its larger tributaries, sediment transport has not been significantly affected. From several decades of data, the variation of sediment concentration and load at the stations on Yangtze stem from year to year is irregular. No systemic trend can be shown.

The Yangtze River above Yichang is a mountainous river with a close relationship between sediment yield and sediment transport. The suspended sediment load increases downstream while concentration both increases and decreases. Below Yichang, the Yangtze flows into an alluvial plain and due to the effects of lake sedimentation and the depositon or scouring of the river channel, the suspended sediment concentration and load reduce downstream.

The variaton of grain size distribution of suspended sediment depends on the grain size of the sediment input from the surface of the basin and the depositon or scouring of sediment along the channel. The grain size of suspended sediment on Yangtze stem is coarsest on the Jinsha River and below Pingshan it trends to be finer.

The annual bed load in the upstream Yangtze is 282—324 thousand t. The coarse gravel bed load (D<50 mm) reduces downstream and the finer gravels (D>50 mm) increase. The coarse sand and fine gravel (1—10 mm) bed load is insignificant amounting to 8 thousand t at Cuntan Station.

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EQUILIBRIUM SLOPE AND WIDTH RELATIONS IN THE RIO GRANDE CONVEYANCE CHANNEL UPSTREAM OF ELEPHANT BUTTE RESERVOIR

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Abstract: The Rio Grande Floodway and Conveyance Channel convey water from San Acacia Diversion Dam to Elephant Butte Reservoir. The Conveyance Channel was built in the 1950's in response to a severe drought to provide a more hydraulically efficient means of delivering water through the sediment delta to the reservoir for discharges up to 2000 ft^3/s. Discharges greater than 2000 ft^3/s are released into the Floodway. The Conveyance Channel saved 50,000 to 60,000 ac. ft. annually from 1953 through 1980. Large flows in the Rio Grande since the 1970's have inundated the lower reaches of the Conveyance Channel severely limiting its use. The Conveyance Channel has only been in operation for 15 months since 1980 because the lower 8 miles of the channel has filled with sediment. Sediment accumulation in the Floodway has also limited water delivery to the reservoir.

Sediment transport rates were modeled in the Conveyance channel to determine what affects changes in channel width and slope have on the Conveyance Channel. Equilibrium slope and width relationships for the Conveyance Channel were determined for the dominant discharge and different sediment transport equations. Sensitivity studies were conducted that varied the width and the sediment transport equation to determine the variability in slope to see if the slope of the Conveyance Channel could be flattened.

INTRODUCTION

The Rio Grande carries heavy loads of sediment in the reach between Cochiti Lake and Elephant Butte Reservoir. Most of the sediment originates from the tributaries draining into the Rio Grande. A large volume of sediment has deposited in the upper reaches of Elephant Butte Reservoir because the reservoir level has been high since the 1970's. In the early 1950's in response to a severe and prolonged drought, a Conveyance Channel was built along the western side of the river channel to deliver water to the reservoir. The Conveyance Channel carries water from San Acacia Diversion Dam to Elephant Butte Reservoir (figure 1). Without the Conveyance Channel a large amount of water would have been lost due to seepage, evaporation, and evapotranspiration as the river crosses the delta. The Conveyance Channel saved 45,000 to 60,000 ac.ft. of water annually when the channel was in operation (1953-1980). Diversions to the Conveyance Channel were discontinued in 1980 because of sediment accumulations.

The Conveyance Channel was designed to carry 2000 ft^3/s. A levee was built to contain the river channel and separate the river channel from the Conveyance Channel. The river carries a high sediment load, and if allowed to overflow into the Conveyance Channel it would quickly fill it with sediment. The river channel and its banks have aggraded to such an extent that the river channel and its banks are now 15 ft above the Conveyance Channel. If the levee between the river channel and the Conveyance Channel gives way during a flood, the Conveyance Channel would be buried under the freshly deposited sediments carried by flows from the river channel. The Conveyance channel needs to be protected from the heavy load of sediment carried by the river channel.

Efficient delivery of water to Elephant Butte Reservoir is vital to the United States and Mexico. The State of New Mexico could not have met their water delivery under the Rio Grande Compact without full operation of the Conveyance Channel during the 1953-1980 period. Flows in the Rio Grande have been much

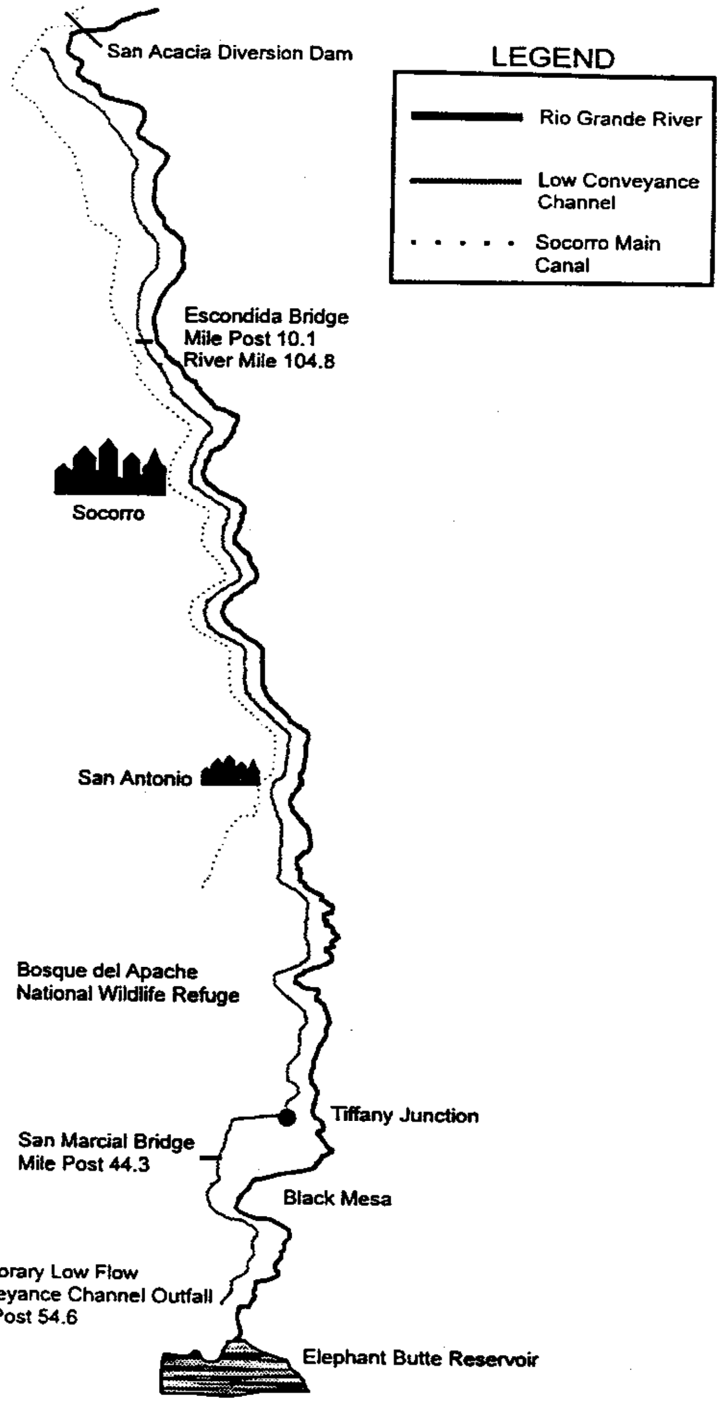

Figure 1 - Configuration of the Conveyance Channel and the Rio Grande near the headwaters of Elephant Butte Reservoir

greater than the previous 20 years resulting in the filling of Elephant Reservoir and inundation of the lower 15 mi. of the Conveyance Channel. Water delivery to the reservoir could be increased in the Conveyance Channel could be operated at a reduced slope.

The purpose of this study is to determine the equilibrium slope of the Conveyance Channel for the dominant discharge. Sensitivity studies were performed to determine the variation in equilibrium slope for different widths and sediment transport equations.

APPROACH

The equilibrium slope of the Conveyance Channel was determined by assuming a rectangular channel section. Different widths were assumed for a fixed Manning's n. The depth and slope were varied until the sediment transported by the different sediment transport equations matched the upstream supply based on the Modified Einstein equation (USBR version). Six different sediment transport equations were utilized for the analysis. These equations included:

a) Velocity Xi (Variation of original Einstein)
b) Engelund and Hansen
c) Ackers-White
d) Toffaleti
e) Laursen
f) Yang

The iteration on slope and depth was performed until the upstream supply was matched for the estimated bed material data. This procedure was also determined by using the HEC-6 model and running a constant hydrograph of 1,500 ft^3/s until equilibrium was reached when the upstream supply coming into the reach was equal to the sediment leaving the reach, and the thalweg elevations did not change from the previous time step.

The theory of minimum energy dissipation rate(Yang, 1976 and Yang and Song, 1986) was applied to the reach to determine the minimum rate of energy dissipation for varying widths under equilibrium conditions. The minimum slope and width based on the theory of minimum energy dissipation rate was compared to the minimum slope and width predicted by the Sam Model (Thomas, et al., 1993). The Sam Model computes a series of slopes and widths based on the sediment transport and resistance equations developed by Brownlie (1981). Stable channel dimensions as defined in the Sam Model refer to a combination of width, depth and slope in which the resulting hydraulic variables will transport the incoming load. A family of slope-width combinations are calculated that satisfy the Brownlie resistance and sediment transport equation. The minimum stream power criteria is applied to the groups of slopes and widths to determine the minimum slope and width based on stream power.

Two different upstream supply relationships were used for the Conveyance Channel. Analysis of double mass curves of accumulated discharge vs. accumulated sediment load revealed a reduction in the upstream supply after 1978. This reduction in sediment supply was probably due to several factors including the completion of Cochiti Reservoir in 1976 and the completion of a dam on the Jemez River, which is tributary to the Rio Grande upstream of Albuquerque near Bernallio. Both of these features lie north of Albuquerque and their effect started to occur around 1980.

The upstream bed material supply was determined from load measurements in the Conveyance Channel from 1968 through 1975 using the Modified Einstein method introduced by the U.S. Bureau of Reclamation (1966). The bed material load includes only particles with diameters greater that 0.062 mm. The sand load equation computed for the Conveyance Channel was $Q_s=0.025*Q^{1.81}$, where Q represents the water discharge and Q_s is the sediment load. For the dominant discharge of 1,500 ft^3/s the total load predicted for that discharge was 14,000 tons/day. No bed material load data were available on the Conveyance Channel after 1985 because the channel was inoperable. An analysis of the total load and bed material load predicted by the Modified Einstein Equation for the Rio Grande river channel at San Acacia showed a definite reduction in sediment supply of at least 50 percent post 1978. Based on the total load predicted by the Modified Einstein Equation for the river channel at San Acacia for the bank full discharge, a reduced load of 7,000 tons per day was used for the Conveyance Channel after 1978. Table 1 shows a summary of total load and sand load data for the river channel at San Acacia for the pre 1978 and post 1978 conditions.

The slope and Manning's 'n' coefficient provided considerable uncertainty since measured data on these parameters were not available. A slope of 0.0005 ft/ft was initially used because it is the prevailing slope of the river in the San Marcial reach. According to Lagasse (1981) the slope of the Rio Grande changes from 0.0009 in the Cochiti to Albuquerque reach to 0.0007 in the Albuquerque to Rio Puerco reach. In the San Marcial reach, according to Pemberton (1966) the slope of the river channel is approximately 0.0005. The Manning's n of the Conveyance Channel according to Pemberton was 0.015. Although this Manning's n value seems to be unusually small, Pemberton's studies (1972) seem to support this value. After conducting sensitivity studies on the Manning's n for the Conveyance Channel, a value of 0.020 appeared to be reasonable.

Table 1-Sand Load and Total Load Relationships for the Rio Grande River Channel at San Acacia based on the Modified Einstein method.

Discharge (ft^3/s)	Sand Load Pre 1978 (tons/day)	Total Load Pre 1978 (tons/day)	Sand Load Post 1980 (tons/day)	Total Load Post 1978(tons/day)
1,000	4,310	10,570	2,600	6,100
2,000	11,300	27,480	5,680	14,562
5,000	40,200	97,200	15,670	45,985
10,000	105,000	252,800	33,755	110,000

MODEL STUDIES

An examination of the predicted supply curves for each sediment transport equation compared to the measured sand load calculated by the Modified Einstein equation shows that Velocity Xi, Toffaleti, and Ackers-White equations greatly over-predict sediment transport rates for larger discharges (Figure 2). The Engelund and Hansen equation under-predicts the incoming load for all discharges. The Colby equation predicted sediment loads that were closed to the incoming sediment load. The Laursen equation is close to the incoming load for the smaller discharges and overpredicts the incoming load for the larger discharges (Figure 2). The Yang equation is parallel to and falls below the incoming load. The loads predicted by the Engelund and Hansen equation are parallel and fall below the incoming load for all discharges. The Yang equation and the Laursen equation were selected as the most reasonable sediment transport equations. The Yang equation predicted equilibrium conditions and the channel was aggrading when it was operational. The Engelund and Hansen equation was not used because it is sensitive in predicting sediment transport for finer size fractions. The Laursen equation was also selected because it was developed from laboratory flume data and small river channels with smaller sand and silt sizes.

The Conveyance Channel was modeled initially as a rectangular channel with a 30 to 100 ft. bottom width and vertical side slopes. The dominant discharge used in the analysis was 1500 ft^3/s with an upstream bed material sediment supply of 14,000 tons/day for the pre- 1978 condition and 7,000 tons/day for the post 1978 conditions. Six different sediment transport equations were used in the analysis to determine the equilibrium slope of the channel for widths of 30 ft., 40 ft., 50 ft., 60 ft., and 100 ft. The slopes predicted by the sediment transport equations that would transport the incoming load are shown in Table 2 for the post 1978 sand load. The range of slopes predicted by the equations shows the importance of selecting the correct channel width for open channel hydraulics computations.

The range of slopes predicted by the sediment transport equations varied by several orders of magnitude. The predicted slopes for the Yang Equation ranged between 0.0006 for the 30 ft. channel and 0.0008 for the 100 ft channel. The Laursen equation shows equilibrium slopes ranging between 0.0006 for the 30 ft channel and 0.00075 for the 100 ft. channel.

The slopes predicted by the Laursen and Yang equations for the single step calculation were compared to the process based model results (Table 3). The slopes predicted by HEC-6 show similar equilibrium slopes for the post 1978 conditions. These slopes are not the same as the results in Table 2 because the bed material will change over time as the material is exchanged in the bed.

The theory of minimum energy dissipation (Yang, 1976, Yang and Song, 1986) was applied to the equilibrium slopes and widths predicted by the Yang equation for the post-1978 conditions in Table 2. The width for which the computed stream power was a minimum was 60 ft with a slope of 0.00067 for the post 1978 conditions. These results were compared to the stable width and slope conditions predicted by the SAM Model using the resistance equation and sediment transport equation by Brownlie (1981). The predicted slope and width at minimum stream power was for a channel width of 104 ft and a slope of 0.00061 for the post 1978 sand load of 7000 tons/day. The widths predicted by the two approaches varied, but the Yang Equation appears to provide a better prediction of the sediment conditions on the Rio Grande Conveyance Channel. A channel width of 60 ft. may be reasonable for future design options, but the equilibrium slope exceeds the valley slope.

CONCLUSIONS

The equilibrium slopes for the Conveyance Channel were determined for different sediment transport equations by varying the slope and depth for a given width until the computed transport rate matched the upstream supply for different sediment transport equations. The predicted slopes for the sediment transport equations varied by many orders of magnitudes.

When the predicted transport rates for the sediment transport equations were compared to the upstream supply estimated by the Modified Einstein equation, the Toffaleti equation, Velocity Xi equation, Engelund and Hansen equation, and Ackers White equation did not match the incoming load. The Laursen and Yang equation appeared to predict the incoming load for the pre-1978 conditions fairly well. Based on this assumption, the predicted equilibrium slopes for widths ranging between 30 ft. and 100 ft varied between 0.0006 and 0.0008 for the post 1978 conditions. The predicted slope and width at minimum unit stream power was 60 ft with a slope of 0.00067 based on the Yang sediment transport equation. The predicted equilibrium slope exceeds the valley slope, and any new channel designed to carry a portion of the discharge of the Rio Grande will have difficulty transporting the incoming load and aggradation of the channel will occur. Sediment removal in the channel will be necessary to remove the accumulated sediment to ensure that the channel will remain operable.

Table 2-Equilibrium Slopes for sediment loads of 7,000 (Post 1978) tons/day in the Rio Grande Conveyance Channel

Width	Yang	Toffaleti	Laursen	Engelund	Velocity-XI	Ackers-White
30'	.0006	0.0003	.00062	.00033	.000073	.00031
40'	.000625	.00033	.00063	.000385	.00009	.000355
50'	.00065	.000358	.00064	.00043	.00011	.0004
60'	.000675	.00039	.000665	.00047	.000125	.00043
100'	.00078	.000535	.00075	.0006	.00018	.000555

Table 3 - Width-Slope Relationships for the Conveyance Channel using HEC-6

Width	Yang	Laursen
30'	0.0008	0.001
60'	0.0006	0.0008

Table 4-Rio Grande Conveyance Channel-Stable Channel Analysis Using the Sam Model for a Discharge of 1,500 ft^3/s

TRIAL	WIDTH	DEPTH	ENERGY SLOPE	N VAL.	VEL
1	54	5.8	0.000682	.033	3.76
2	62	5.3	0.000653	.030	3.85
3	69	4.8	0.000634	.027	3.91
4	77	4.4	0.000621	.025	3.95
5	85	4.0	0.000613	.023	3.98
6	92	3.7	0.000609	.022	4.00
7	100	3.3	0.000607	.020	4.01
8	108	3.1	0.000607	.019	4.01
MIN. ENERGY	108	3.6	0.000609	.018	4.00

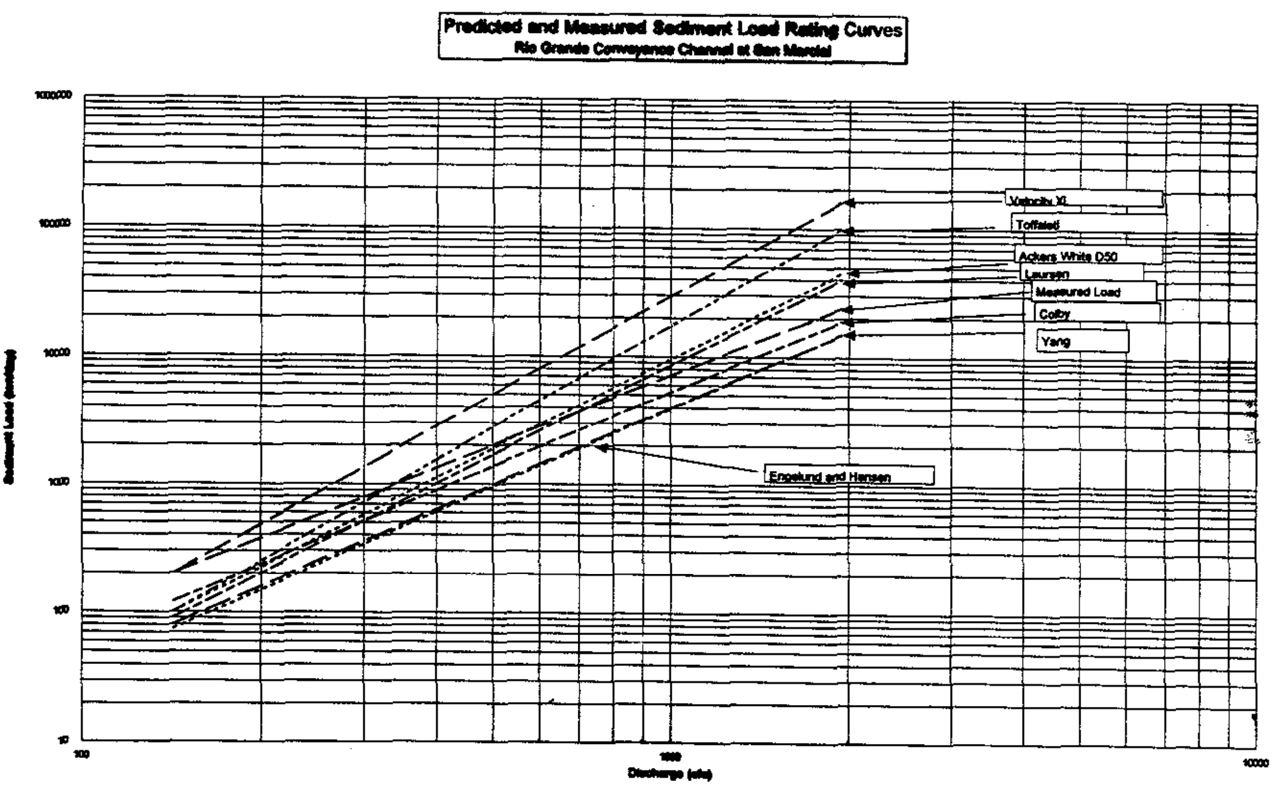

Figure 2 - Predicted and Measured Sand Load Rating Curves for the Rio Grande Conveyance Channel at San Marcial (Pre-1978).

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