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Modification of Toffaleti's Procedure for Sediment Transport

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MODIFICATION OF TOFFALETI'S PROCEDURE
FOR SEDIMENT TRANSPORT

BY

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MODIFICATION OF TOFFALETI'S PROCEDURE

FOR SEDIMENT TRANSPORT

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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INTRODUCTION

The study of sediment transported by rivers is required to provide the best approximation of expected amounts of degradation or deposition. Transport quantities are required for engineering analyses associated with safety and productivity.

The design and placement of river training structures to prevent flooding and bank erosion, design and determination of life expectancy of reservoirs and optimization of channel designs all require sedimentation movement evaluations. Estimations of life expectancy and dredging requirements for navigable rivers or channels require calculations of sediment transport. Studies can be used as an indication of soil conservation effectiveness in areas under construction or under tillage.

There are numerous sediment transport procedures available to be used by designers. All transport procedures are restricted to certain optimum sediment sizes, specific gravities or measured data limitations.

Toffaleti's procedure requires field measurements of the river bed material by sediment size fraction to calculate bed material sediment discharges. Because data is available for only the suspended sediment load in many cases, it was proposed that Toffaleti's approach be modified to use measured suspended load data in sediment size fractions rather than measured bed material size fractions. The approach to modifying Toffaleti's procedure is similar to the modified Einstein procedure and provides bed material and total sediment discharges both as size fractions and total loads. A computer program was written utilizing measured suspended load to calculate discharges. The specific objectives of the project were as follows:

1) Modify Toffaleti's procedure for sediment transport calculations to allow the use of suspended load measurements rather than bed material measurements in order to be able to calculate not only bed material load but also the total load and
2) Compare the results for the modified procedure to Toffaleti's existing procedure, the modified Einstein procedure and the Ackers and White procedure.

LITERATURE REVIEW

Sediment transport is broken down into two major categories: wash load and bed material load (3). The wash load is the transported sediment that is not present in the bed material of the river and is usually assumed to include all the silt and clay sediment sizes (7). Because the concentration of particles in these size ranges remains nearly constant throughout the vertical profile of a river, the transported volumes are calculated directly from measurements of the sediment and water discharges.

The bed material load is the material present in the stream bed that is transported. This load is divided into suspended load and bed load. The suspended load is that material that is supported by the stream turbulence. Bed load is the material moved by jumping, rolling or sliding along the bed surface. The lowest two grain diameters of the stream is the area that is generally assumed to carry the bed load. The standard sediment sizes are shown in Table 1 with their respective titles, abbreviations, size ranges and geometric means (10).

Fall velocity is a measure of the tendency of sediment that is suspended in water to fall to the bed. Standard fall velocity is the maximum velocity of a particle falling alone through an undisturbed, continuous

TABLE 1

Sediment Size Classification

CLASS NAME	ABBREV-IATION	SIZE RANGE (mm)	GEOMETIC MEAN (ft)
Very large boulders	VLB	4096-2048	9.502
Large boulders	LB	2048-1024	4.751
Medium boulders	MB	1024-512	2.376
Small boulders	SB	512-256	1.188
Large cobbles	LC	256-128	.594
Small cobbles	SC	128-64	.297
Very coarse gravel	VCG	64-32	.1485
Coarse gravel	CG	32-16	.0742
Medium gravel	MG	16-8	.0371
Fine gravel	FG	8-4	.0186
Very fine gravel	VFG	4-2	.00928
Very coarse sand	VCS	2-1	4.64×10^{-3}
Coarse sand	CS	1-.5	2.32×10^{-3}
Medium sand	MS	.5-.25	1.16×10^{-3}
Fine sand	FS	.25-.125	5.80×10^{-4}
Very fine sand	VFS	.125-.0625	2.89×10^{-4}
Coarse silt		.062-.031	
Medium silt		.031-.016	
Fine silt		.016-.008	
Very fine silt		.008-.004	
Coarse clay		.004-.002	
Medium clay		.002-.001	
Fine clay		.001-.0005	
Very fine clay		.0005-.00024	

volume of distilled water. As the particle size increases and the particle shape approaches spherical, the particle tends to fall through the water at a faster speed. Fall velocities for small particles increase with higher water temperatures, but this effect becomes negligible for large particles.

The measure of the ability of a stream to move a particle is the shear velocity. This term is called a velocity because its units are the same as velocity units. The shear velocity is equal to the square root of the product of the acceleration of gravity, the energy gradient and the hydraulic radius. The shear velocity and fall velocity combine to give an indication of the relative concentration of a sediment size at any point above the river bed as shown in Fig. 1 (11). The plotted value, Z_i, is the concentration exponent for each particle size. The figure indicates that small particle concentrations remain relatively constant through the vertical profile of the river while large particles tend to have higher concentrations near the bed with little to no concentration at a point near the water surface.

Suspended sediment sampling is done either by instantaneous or integrating methods (8). The instantaneous method traps a volume of water-sediment

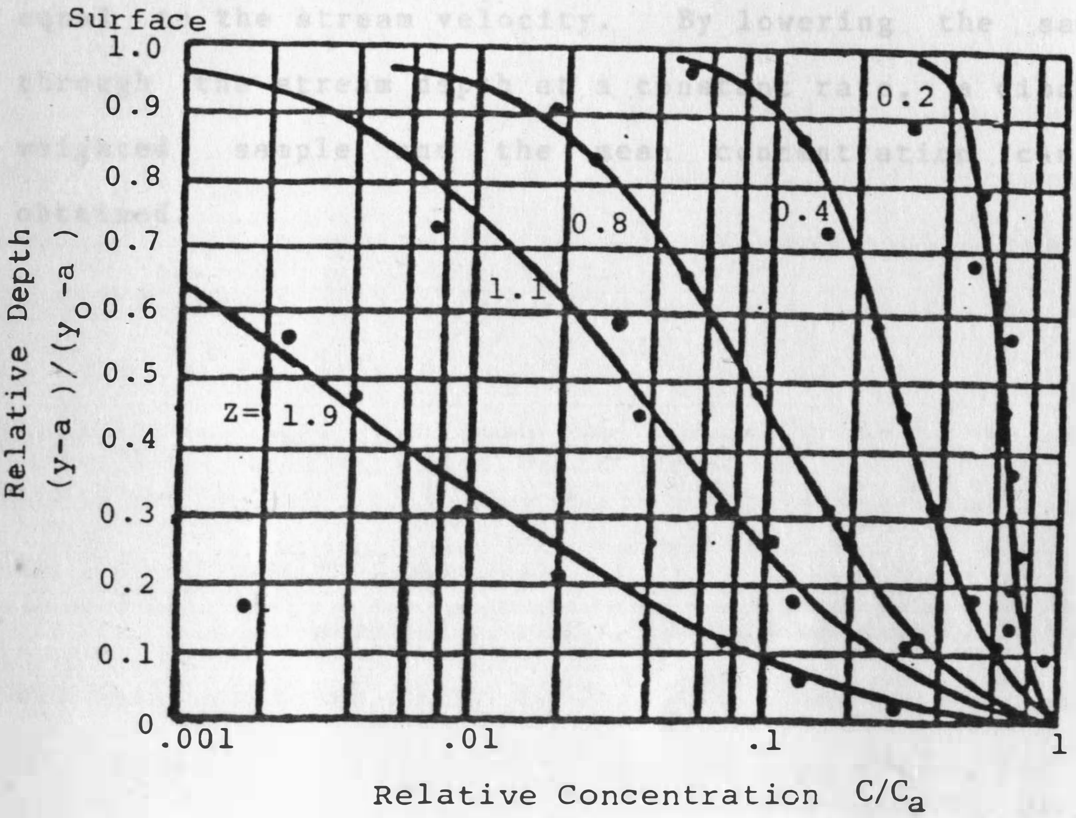

Figure 1. Distribution of Suspended Sediment

mixture passing the sampling point at an instant. Integrating samplers take samples over extended periods of time to average concentration fluctuations. The depth-integrating sampler is designed to have an inlet velocity equal to the stream velocity. By lowering the sampler through the stream depth at a constant rate, a discharge weighted sample and the mean concentration can be obtained.

TOFFALETI'S PROCEDURE

Toffaleti's procedure for sediment transport calculation as presented in 1969 will calculate both the suspended and bed load (10). He recommends limiting this procedure to streams carrying quartz sediment in the sand size range of .062 to 2 mm diameters. The stream is assumed to be equivalent to a two-dimensional stream of width, B, equal to the actual stream and a depth, r, equal to the hydraulic radius of the real stream. The bed material is divided into the standard size fractions listed in Table 1. The discharge calculations are carried out for each size fraction.

The vertical profile of the stream is divided into the four zones shown in Fig. 2. The upper, middle and lower zones carry the suspended load while the bed zone carries the bed load.

The upper zone extends from the water surface to a lower limit of r/2.5. The middle zone extends from an upper limit of r/2.5 to a lower limit of r/11.24. The lower zone extends from r/11.24 to the bed zone upper limit of $2d_{si}$, where d_{si} is the geometric mean of the maximum and minimum limits for each sediment size fraction. The bed zone is the bottom $2d_{si}$ of the stream.

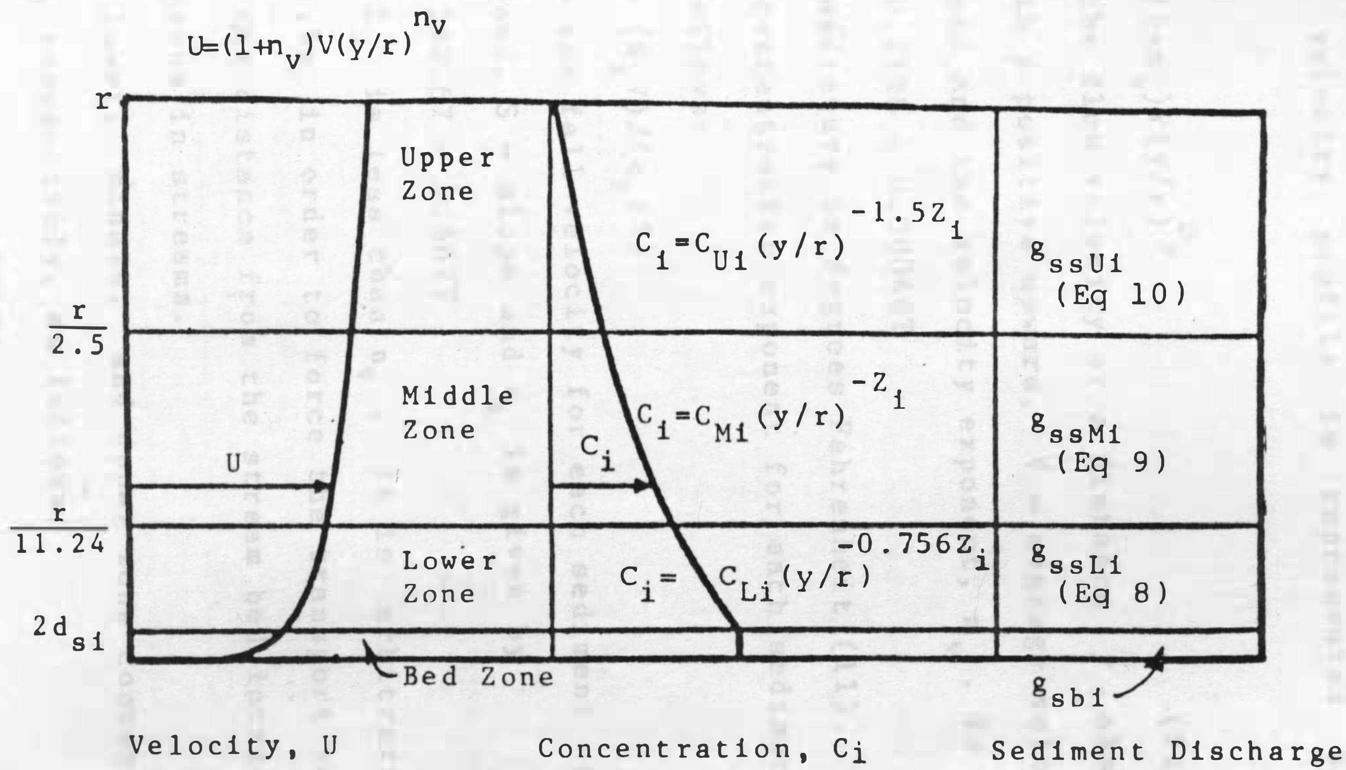

Figure 2. Toffaleti's Velocity, Concentration and Sediment Discharge Relations

The velocity profile is represented by the relationship

$$U = (1+n_v)V(y/r)^{n_v} \qquad \text{(ft/s)} \quad (1)$$

where U = the flow velocity at a distance y above the river bed with y positive upward, V = average velocity in feet per second and the velocity exponent, n_v, is

$$n_v = 0.1198 + 0.00046T \qquad (2)$$

where T = temperature in degrees Fahrenheit (11).

The concentration exponent for each sediment size, Z_i, is as follows:

$$Z_i = (W_i V)/(c_z rS) \qquad (3)$$

where W_i = the fall velocity for each sediment size in feet per second, S = slope and c_z is given by

$$c_z = 260.67 - 0.667T \qquad (4)$$

If Z_i is less than n_v, it is arbitrarily set equal to $1.5n_v$ in order to force the transport volume to decrease as the distance from the stream bed increases as actually happens in streams.

The lower, middle, and upper zone concentrations are defined, respectively, as follows:

$$C_i = C_{Li}(y/r)^{-0.756Z_i} \qquad \text{(pcf)} \quad (5)$$

$$C_i = C_{Mi}(y/r)^{-Z_i} \qquad \text{(pcf)} \quad (6)$$

$$C_i = C_{Ui}(y/r)^{-1.5Z_i} \qquad \text{(pcf)} \quad (7)$$

where C_i = the concentration per sediment size at a point y above the stream bed, C_{Ui} = the upper zone concentration, C_{Mi} = the middle zone concentration, C_{Li} = the lower zone concentration.

Each zone has a sediment discharge per unit width, that is the result of the integration of the velocity and concentration product and conversion factors, listed as follows from lower to upper zone:

$$g_{ssLi} = M_i \left[\frac{\left(\frac{r}{11.24}\right)^{1+n_v-0.756Z_i} - (2d_{si})^{1+n_v-0.756Z_i}}{1+n_v-0.756Z_i} \right] \qquad \text{(tons/day/ft)} \quad (8)$$

$$g_{ssMi} = M_i \left[\frac{\left(\frac{r}{11.24}\right)^{0.244Z_i} \left[\left(\frac{r}{2.5}\right)^{1+n_v-Z_i} - \left(\frac{r}{11.24}\right)^{1+n_v-Z_i}\right]}{1+n_v-Z_i} \right] \qquad \text{(tons/day/ft)} \quad (9)$$

$$g_{ssUi} = M_i \left[\frac{\left(\frac{r}{11.24}\right)^{0.244Z_i} \left(\frac{r}{2.5}\right)^{0.5Z_i} \left[(r)^{1+n_v-1.5Z_i} - \left(\frac{r}{2.5}\right)^{1+n_v-1.5Z_i}\right]}{1+n_v-1.5Z_i} \right] \qquad \text{(tons/day/ft)} \quad (10)$$

where M_i = the transport coefficient.

Toffaleti starts his transport volume procedure with the nucleus discharge which is the value for the lower zone sediment transport as calculated from the equation

$$g_{ssLi} = \frac{0.600 p_i}{\left(\frac{T_t A k_4}{V^2}\right)^{5/3} \left(\frac{d_{si}}{0.00058}\right)^{5/3}} \text{ (tons/day/ft)} \quad (11)$$

where p_i = the percentage of each sediment size found in sample, k_4 = a correction factor primarily for flume data shown in Fig. 4, A = the function $(10^5\ )^{1/3}/10U_*'$ shown in Fig. 4 and T_t = the temperature coefficient defined as

$$T_t = 1.10(0.051 + 0.0009T) \quad (12)$$

The grain roughness shear velocity, U_*', can be calculated from Fig. 3. The d_{65} grain size is the diameter where 65 percent of the sediment sampled is smaller. The grain roughness shear velocity, U_*', and the kinematic viscosity, ν, can then be used to find A and k_4 from Fig. 4.

Once this lower zone nucleus load is calculated, the transport coefficient, M_i, can be found from Eq. 8 where

$$M_i = 43.2 p_i C_{Li}(1+n_v) V r^{0.756 Z_i - n_v} \quad (13)$$

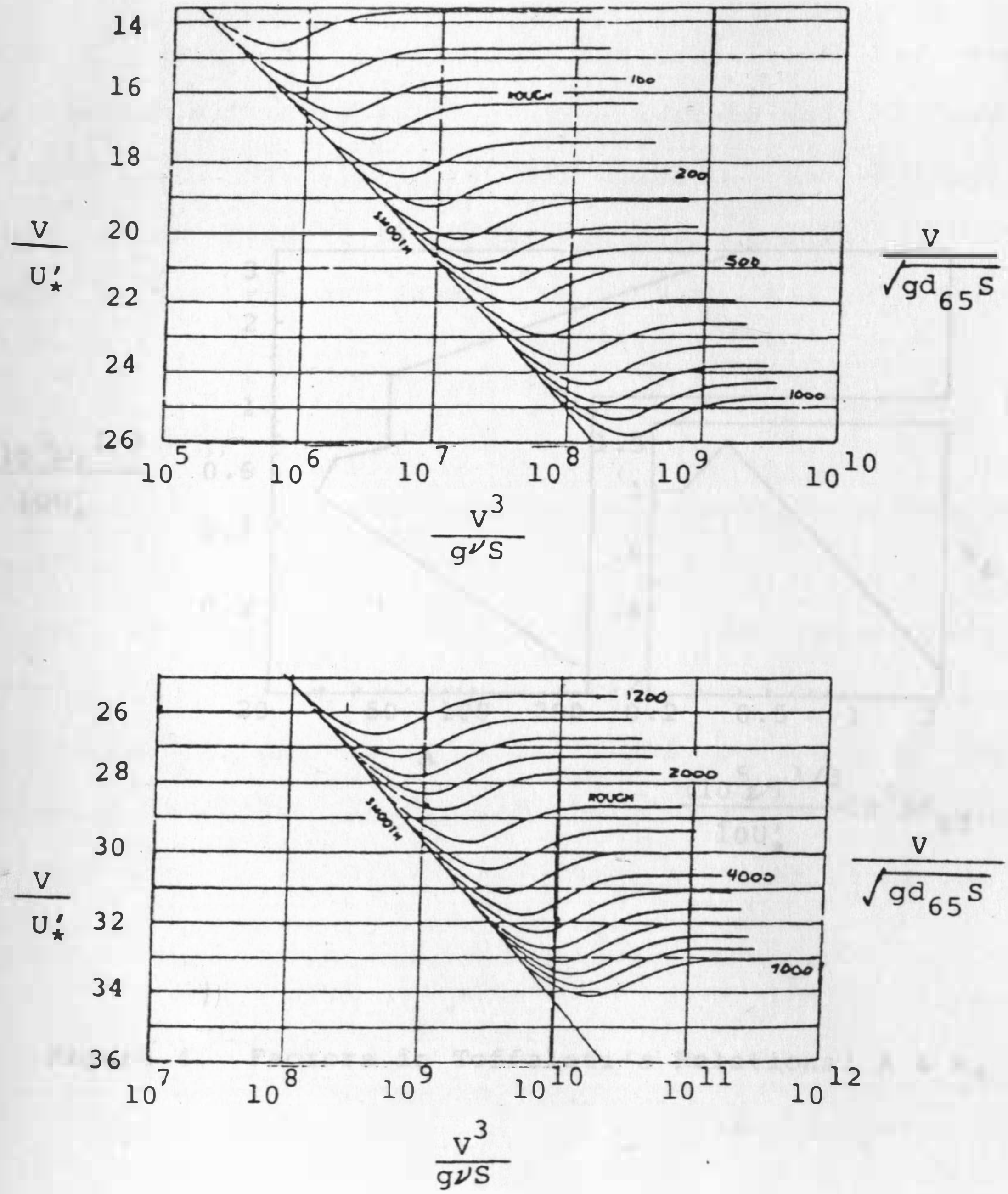

Figure 3. Graphical Solutions to U'_*

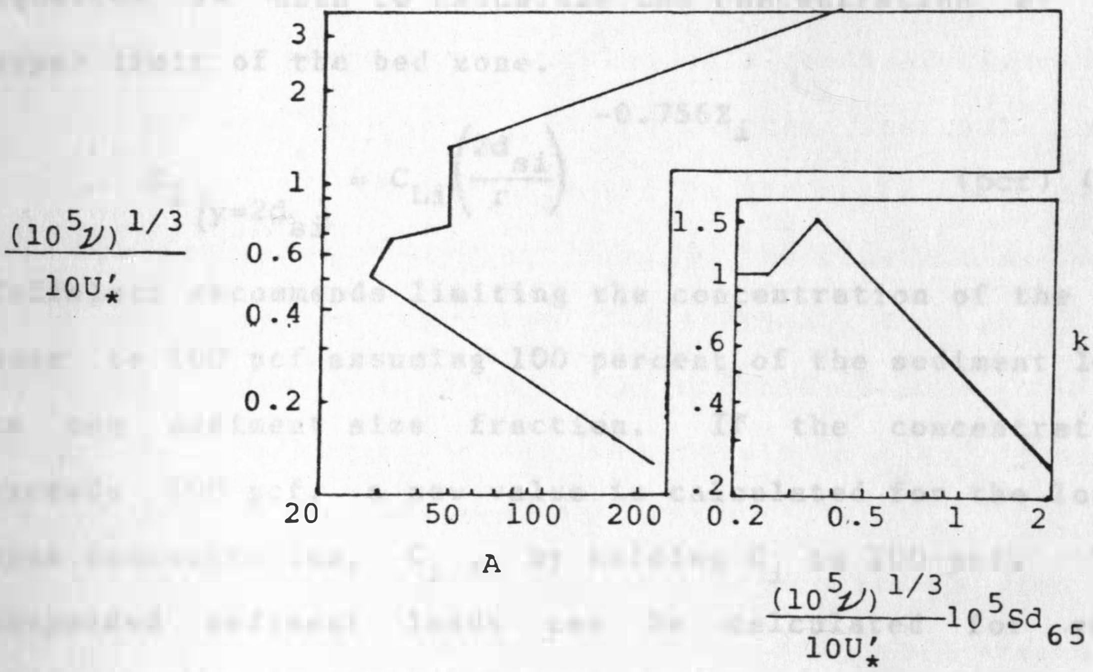

Figure 4. Factors in Toffaleti's Relations: A & k_4

Because there is a possibility the calculated bed load will become extremely large, a test must be made to insure a reasonable transport concentration. The following equation is used to calculate the concentration at the upper limit of the bed zone.

$$C_{i\,(y=2d_{si})} = C_{Li}\left(\frac{2d_{si}}{r}\right)^{-0.756Z_i} \quad \text{(pcf)} \quad (14)$$

Toffaleti recommends limiting the concentration of the bed zone to 100 pcf assuming 100 percent of the sediment load is one sediment size fraction. If the concentration exceeds 100 pcf, a new value is calculated for the lower zone concentration, C_i, by holding C_i to 100 pcf. The suspended sediment loads can be calculated for each sediment size in the middle and upper zones by using Eq. 9 and 10.

The bed load is calculated from the following equation:

$$g_{sbi} = M_i(2d_{si})^{1+n_v-0.756Z_i} \quad \text{(tons/day/ft)} \quad (15)$$

The total transported sediment load for each sediment size is the sum of the sediment loads in all four zones for each sediment size

$$g_{si} = g_{sbi} + g_{ssLi} + g_{ssMi} + g_{ssUi} \quad \text{(tons/day/ft)} \quad (16)$$

MODIFIED EINSTEIN PROCEDURE

In 1950, H. A. Einstein presented a complex procedure for computing suspended sediment discharge that requires several graphs and formulas (2). The procedure required an average cross section of a reach of channel, a slope through a reach and an average particle size distribution of the bed material in the reach as a basis for the transport analysis. Because the Einstein approach does not compute the suspended sediment discharge for sediment sizes not found in appreciable amounts in the stream bed, a suspended sediment sample is also required to calculate total sediment load.

Einstein's procedure is based on integration of the product of theoretical velocity and the suspended sediment concentration through a representative vertical section of an average cross section. The bottom section of the concentration curve is equated to a computed bed zone concentration, where the bed zone is the lowest two grain diameters of the stream. The rate of movement and the concentration in the bed zone are based on a dimensionless expression of the probability that a given particle will move from its position on the stream bed. The sediment discharge is calculated separately for each particle size found in the bed material.

In 1955, B. R. Colby and C. H. Hembree presented a modification of Einstein's procedure to calculate the total sediment discharge. The case study presented was for the Niobrara River near Cody, Nebraska. The study was designed to modify the existing Einstein procedure as follows:

1) Calculate the total sediment discharge including the wash load.
2) Give an approximate size distribution of the sediment discharged.
3) Use measurements of wash and suspended load from a depth-integrated sampler.

The modified Einstein procedure presented by Colby and Hembree requires the following basic data:

1) Stream flow measurements of the average velocity, average depth and stream width.
2) Average concentration of the stream flow measured by depth-integrated sampler.
3) Analysis of the suspended sediment by size fraction of sediment that was included in the average concentration.
4) Average depth of the verticals where the suspended sediment samples were collected.
5) Analysis of the bed material by size fraction.

6) Water temperature.

Different methods were used to calculate the discharge of small particles and large particles. A ratio was computed by dividing the integrated products of theoretical velocity and theoretical concentration from the stream surface to the bed zone by the same integrated products from the stream surface to the lower limit of the sampled zone. This ratio was multiplied by the actual measured discharge for each sediment size to give a total discharge.

For larger sediment sizes, the modified Einstein procedure uses different methods for computing the concentration coefficient, the shear velocity with respect to sediment particles and the intensity of bed load transport. These three factors were changed to reduce the calculated discharge because Colby and Hembree felt Einstein's values were larger than actual field measurements justified.

When the calculated total discharge from this procedure was compared with total discharge measurements, the range of variation was 66 to 146 percent. Colby and Hembree considered this range to be reasonable for sediment calculations.

ACKERS AND WHITE PROCEDURE

In 1973, P. Ackers and W. R. White presented a sediment transport procedure that relates the transport of fine materials to gross shear and the transport of coarse sediment to net grain shear (1). This method was developed in terms of three dimensionless groups: a dimensionless grain diameter, sediment mobility and transport parameters.

Coarse sediment is considered to be transported as a bed process. Fine sediment is suspended by the stream turbulence. The sediment mobility for an intermediate grain size is a percentage of the product of the coarse and fine sediment mobility numbers. The dimensionless grain diameter is a form of the particle Reynolds number that indicates the extent of influence viscous forces have on the motion of a particular grain. Sediment transport is based on the stream power concept, in coarse sediments using the product of net grain shear and stream velocity as the power per unit area of bed and for fine sediments using the stream power.

This procedure requires the d_{35} particle size of the bed material, average velocity, depth of flow and shear velocity to calculate transport bed load volumes.

It works well for sand and gravel sizes. Results are total bed material loads, not size fractions.

MODIFICATION TO TOFFALETI'S PROCEDURE

In order to modify Toffaleti's procedure, an approach similar to that taken in the modification of Einstein's procedure was used. The measurement of the suspended and wash load rather than the bed material used by Toffaleti allows calculation of the total load in addition to the suspended and bed loads. Because the concentration of small particle sizes remains relatively constant throughout the vertical profile of a stream, the concentration of silts and clays is assumed to equal the measured value through the entire stream depth.

A sample that is collected by using a depth-integrated sampler gives a concentration reading for the entire stream depth excluding the last approximately one-half foot above the bed. Because a large portion of the transported load for the larger sediment sizes is included in this lower region, a direct calculation based on constant concentration across the total depth will not give a valid estimate of total transport.

The average velocity of the measured area is used to calculate the measured sediment discharge and water discharge. To obtain the average velocity of the measured zone, the area to the left of the curve on Fig. 5 above point a_o, where a_o is the lower limit of the measured

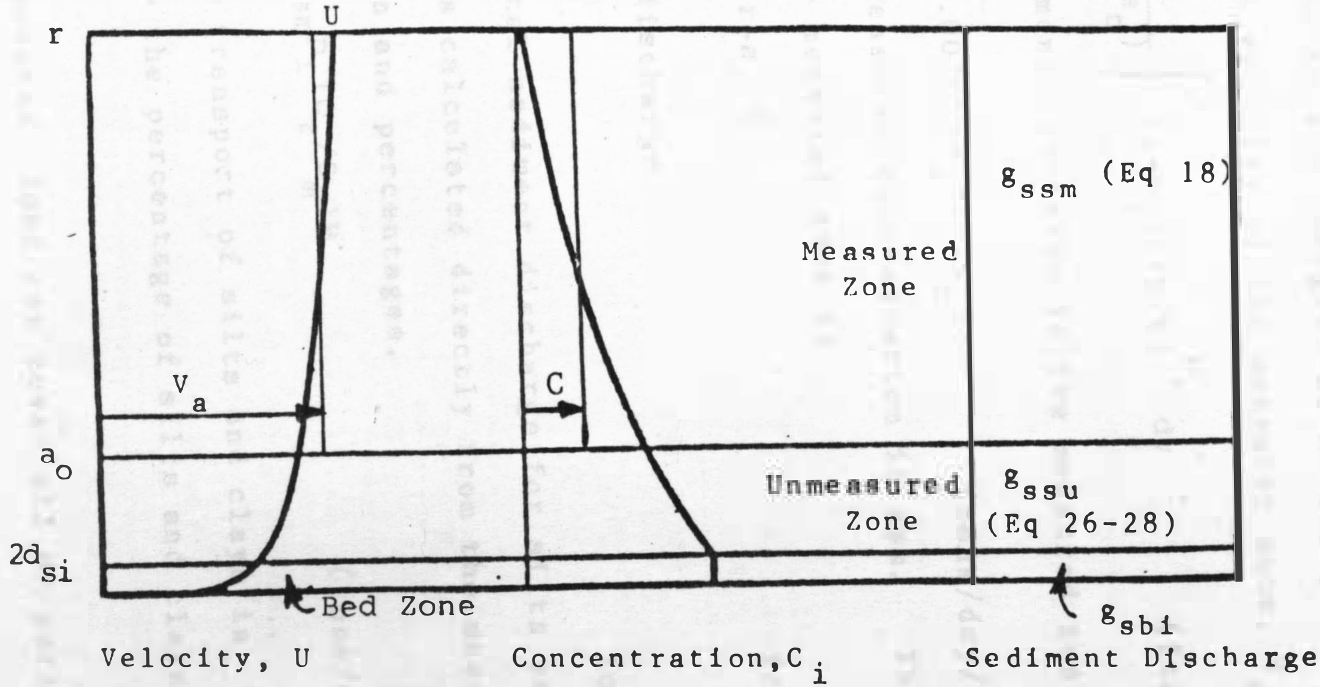

Figure 5. Modified Toffaleti's Velocity, Concentration and Sediment Discharge Relations

zone, is set equal to the integral of U from point a_o to r (6). The average velocity of the measured zone, V_a , is

$$V_a = \frac{1}{(r-a_o)} \int_{a_o}^{r} (1+n_v) V (y/r)^{n_v} dy \qquad (ft/s) \quad (17)$$

The sediment discharge in the measured zone is

$$g_{ssm} = 0.002695 V_a C (r-a_o) \qquad (tons/day/ft) \quad (18)$$

where C is the measured concentration in ppm. The water discharge in the measured zone is

$$Q_m = V_a (r-a_o) B \qquad (cfs) \quad (19)$$

and the total discharge

$$Q_t = VBr \qquad (cfs) \quad (20)$$

The total sediment discharge for silts and clays for the river is calculated directly from the measurements of concentration and percentages.

$$G_w = g_{ssm} p_i (Q_t/Q_m) B \qquad (tons/day) \quad (21)$$

where G_w = the transport of silts and clays in tons per day and p_i = the percentage of silts and clays in the measured zone.

The measured load can cover all or part of the three zones for suspended load that Toffaleti has defined. Because the measured load is taken to be the known quantity instead of the nucleus discharge Toffaleti uses, Eqs. 8, 9, and 10 for lower, middle and upper zones must be combined to find the transport coefficient, M_i, for each sediment size fraction. There are three alternatives for this equation because the upper limit of the unmeasured depth may be in any one the three suspended sediment zones depending on stream depth and sampling depth. The three equations are listed below with the unmeasured depth in the lower, middle and upper zones respectively.

$$g_{ssmi} = M_i \left[\frac{g_{ssUi}}{M_i} + \frac{g_{ssMi}}{M_i} + \frac{\left(\frac{r}{11.24}\right)^{1+n_v-0.756Z_i} - (a_o)^{1+n_v-0.756Z_i}}{1+n_v-0.756Z_i} \right] \quad \text{(tons/day/ft)} \qquad (22)$$

$$g_{ssmi} = M_i \left[\frac{g_{ssUi}}{M_i} + \frac{\left(\frac{r}{11.24}\right)^{0.244Z_i} \left[\left(\frac{r}{2.5}\right)^{1+n_v-Z_i} - (a_o)^{1+n_v-Z_i} \right]}{1+n_v-Z_i} \right] \quad \text{(tons/day/ft)} \qquad (23)$$

$$g_{ssmi} = M_i \left[\frac{\left(\frac{r}{11.24}\right)^{0.244Z_i} \left(\frac{r}{2.5}\right)^{0.5Z_i} \left[(r)^{1+n_v-1.5Z_i} - (a_o)^{1+n_v-1.5Z_i} \right]}{1+n_v-1.5Z_i} \right] \quad \text{(tons/day/ft)} \qquad (24)$$

Once the transport coefficient is calculated, a test must be made similar to Toffaleti's to prevent an unrealistically large bed zone concentration. If adjustment is necessary,the measured load is held constant while the concentration exponent, Z_i , is reduced to force the concentration of the i^{th} sediment size to meet the maximum limit of 100 pcf that Toffaleti suggested. The limitation of each sediment load to 100 pcf will lower the concentration coefficient and force the bed load concentration shown in Fig. 5 toward a lower concentration.

Equation 3 defines Z_i as a result of fall velocity, average stream velocity, temperature , stream depth and slope. Fall velocity is the term most likely to be large because it is defined as the terminal velocity of a particle falling alone through an undisturbed sample of distilled water. In an actual stream the fall velocity would be reduced by the presence of a large amount of sediment and turbulence.

The 100 pcf limit is obtained, if necessary, by reducing the concentration exponent using the following equation:

$$Z_i = -0.756\log(100/C_{Li})/\log(2d_{si}/r) \quad (25)$$

Once the new concentration exponent is calculated a new transport coefficient is determined from the measured load. The concentration is retested against the 100 pcf limit and the procedure repeated until the test is passed.

The unmeasured load is the sediment transported in the remaining area between point a_o and the bed zone upper limit. Because point a_o can be either in the lower, middle or upper zone, the following three equations are required to define the unmeasured load in order from lower to upper zone.

$$g_{ssuLi} = M_i \left[\frac{(a_o)^{1+n_v-0.756Z_i} - (2d_{si})^{1+n_v-0.756Z_i}}{1+n_v-0.756Z_i} \right] \quad \text{(tons/day/ft)} \quad (26)$$

$$g_{ssuMi} = M_i \left[\frac{g_{ssLi}}{M_i} + \frac{\left(\frac{r}{11.24}\right)^{0.244Z_i} \left[(a_o)^{1+n_v-Z_i} - \left(\frac{r}{11.24}\right)^{1+n_v-Z_i} \right]}{1+n_v-Z_i} \right] \quad \text{(tons/day/ft)} \quad (27)$$

$$g_{ssuUi} = M_i \left[\frac{g_{ssLi}}{M_i} + \frac{g_{ssMi}}{M_i} + \frac{\left(\frac{r}{11.24}\right)^{0.244Z_i} \left(\frac{r}{2.5}\right)^{0.5Z_i} \left[(a_o)^{1+n_v-1.5Z_i} - \left(\frac{r}{2.5}\right)^{1+n_v-1.5Z_i} \right]}{1+n_v-1.5Z_i} \right]$$

(tons/day/ft) (28)

The bed load is calculated with Eq. 15 just as in Toffaleti's procedure. The total load for each sediment size is the sum of the measured load, the unmeasured load and the bed load.

$$g_{si} = g_{ssmi} + g_{ssui} + g_{sbi} \qquad \text{(tons/day/ft) (29)}$$

THE COMPUTER PROGRAM

The computer program is listed in Appendix C. The basic data required for the analysis is as follows:

1) Average velocity, average depth and stream width.
2) Average concentration of the stream flow measured by a depth-integrated sampler.
3) Analysis of the suspended sediment by size fraction of sediment that was included in the average concentration.
4) Average depth of sample.

5) Water temperature.

6) Sediment shape factor and specific gravity.

The required data is basically the same as that required for the modified Einstein procedure with the advantage of not requiring measured size fractions of the bed material.

The fall velocity is calculated using a shape factor of 0.7 for an average sand particle and a specific gravity of 2.65 for quartz using the procedures developed by Prasuhn and Knofcyznki (4). Both the shape factor and specific gravity can be changed by the user. The kinematic viscosity is calculated from the temperature in degrees Fahrenheit. The sediment transport calculations are carried out in the order outlined in the analysis of the modification.

RESULTS AND DISCUSSION

Twenty-five data sets listed in Appendix B were used to test the modified Toffaleti program (5). The shape factor and specific gravity used to calculate the fall velocity were assumed to be 0.7 and 2.65 respectively. The bottom one-half foot of the stream was used for the unmeasured depth, therefore, a_o equalled 0.5 feet in all data sets. These three factors were not included in the data sets. The results for all the procedures tested are listed in Appendix D.

Because transport volumes calculated using procedures requiring sediment measurements from two different sources are independent of each other, inaccuracies in sampling cause discrepancies between methods. Data set 6 has a very low transport rate. The modified Toffaleti procedure predicts a transport rate of nine tons per day while the other methods predict rates over 100 tons/day. The samples of suspended and wash loads contained only three percent of the sediment in the bed material load size range. The modified Toffaleti procedure probably provides the most reasonable value because much of the sediment discharge is measured. Data sets 15 and 17 have discrepancies between the measured bed material and the measured suspended load in size fractions. The percentages of very fine sand and fine sand for the suspended loads are less than 10 in each set while the medium sands are 26 percent and 19 percent respectively. The expected trend after inspecting the bed material measurements would be a decreasing percentage for the medium sands. This contradiction in measurements causes a large difference between the calculated transports for the Ackers and White and Toffaleti procedures, which use the bed material measurements, and the modified Toffaleti procedure, which uses the suspended sediment measurements.

The bed material loads calculated by the Ackers and White method and the Toffaleti method are compared in Fig. 6. Both these procedures use measurements of bed material. Bed material load ratios for these two methods are two or less for all data sets. These ratios show good agreement between methods. In transport calculations large variations between procedures are not unusual. Vanoni shows a comparison of 13 transport procedures for the Niobrara River where ratios were as large as 50 (11).

Figure 7 shows the comparison of bed material load by the modified Toffaleti and the Ackers and White procedures. Measurements of suspended material are used for the modified Toffaleti method and measurements of the

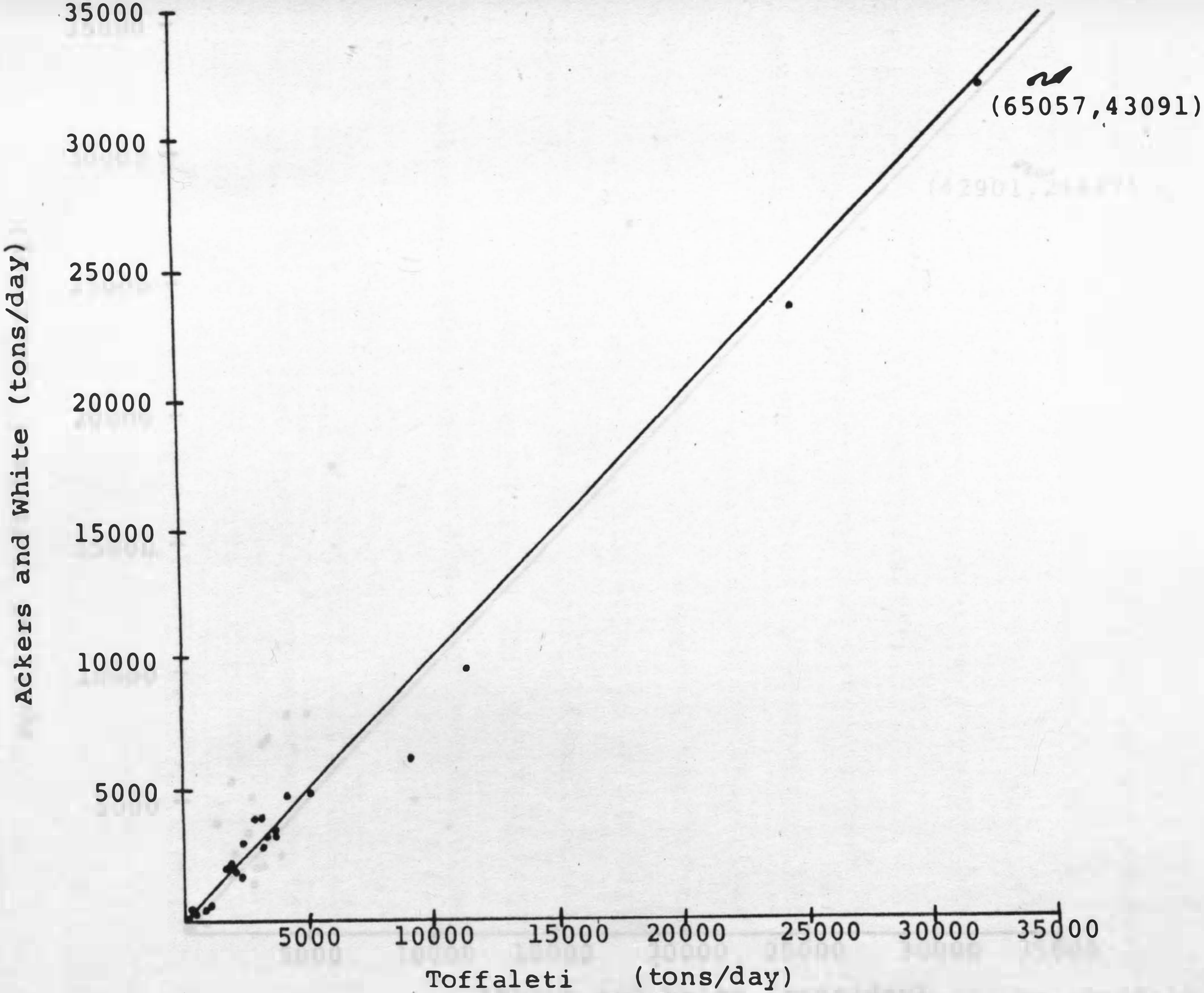

Figure 6. Bed Material Load Comparison -- Ackers and White vs Toffaleti

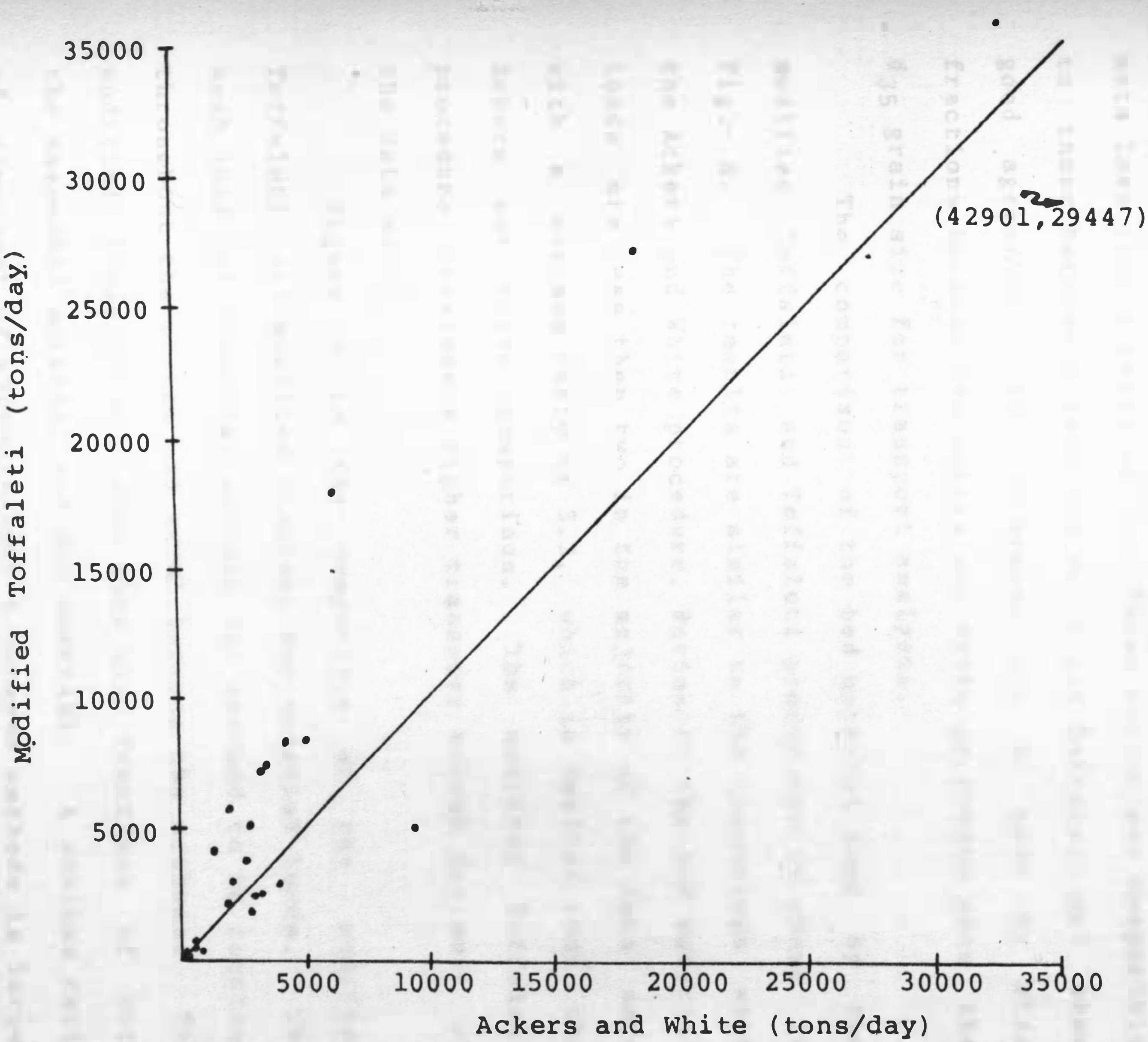

Figure 7. Bed Material Load Comparison -- Modified Toffaleti vs Ackers and White

bed material are used for Ackers and White. Although the modified Toffaleti procedure calculates the larger transport in a majority of the data sets, the maximum ratio between the two procedures is 3.5 with most data sets less than a ratio of 2. These ratios are comparible to those between Ackers and White and Toffaleti and show good agreement. No comparison can be made by size fractions because the Ackers and White procedure uses the d_{35} grain size for transport analysis.

The comparison of the bed material load by the modified Toffaleti and Toffaleti procedures is shown in Fig. 8. The results are similar to the comparison with the Ackers and White procedure. Ratios of the bed material loads are less than two in the majority of the data sets with a maximum ratio of 3.3, which is smaller than the Ackers and White comparison. The modified Toffaleti procedure provides a higher transport volume for most of the data sets.

Figure 9 is the comparison of the modified Toffaleti and modified Einstein bed material loads. The wash load for these two methods was assumed to be constant throughout the stream and equal between the methods. The modified Einstein procedure uses size fractions of both the suspended material and bed material. A maximum ratio of transport of approximately 8 between methods is larger

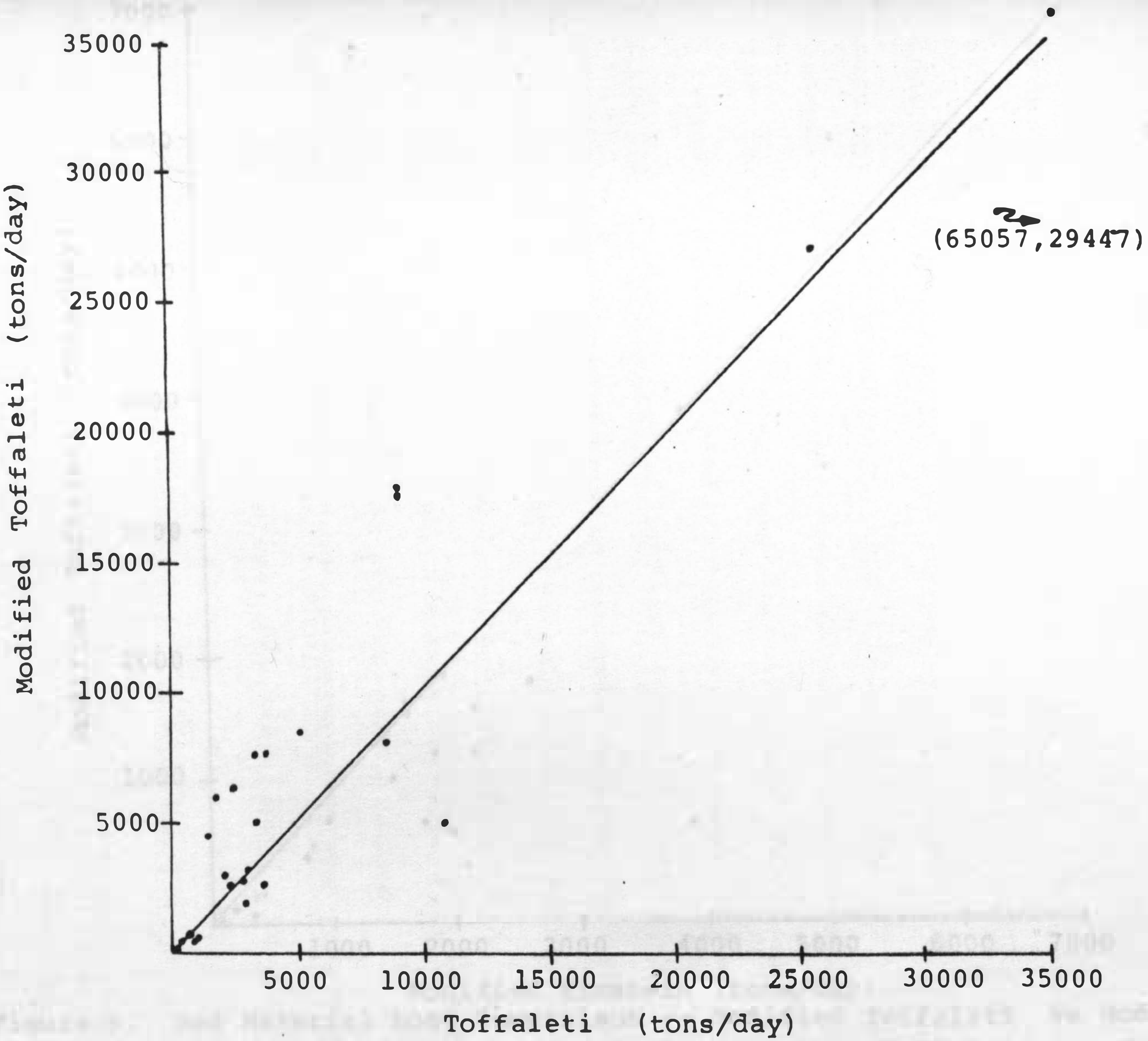

Figure 8. Bed Material Load Comparison -- Modified Toffaleti vs Toffaleti

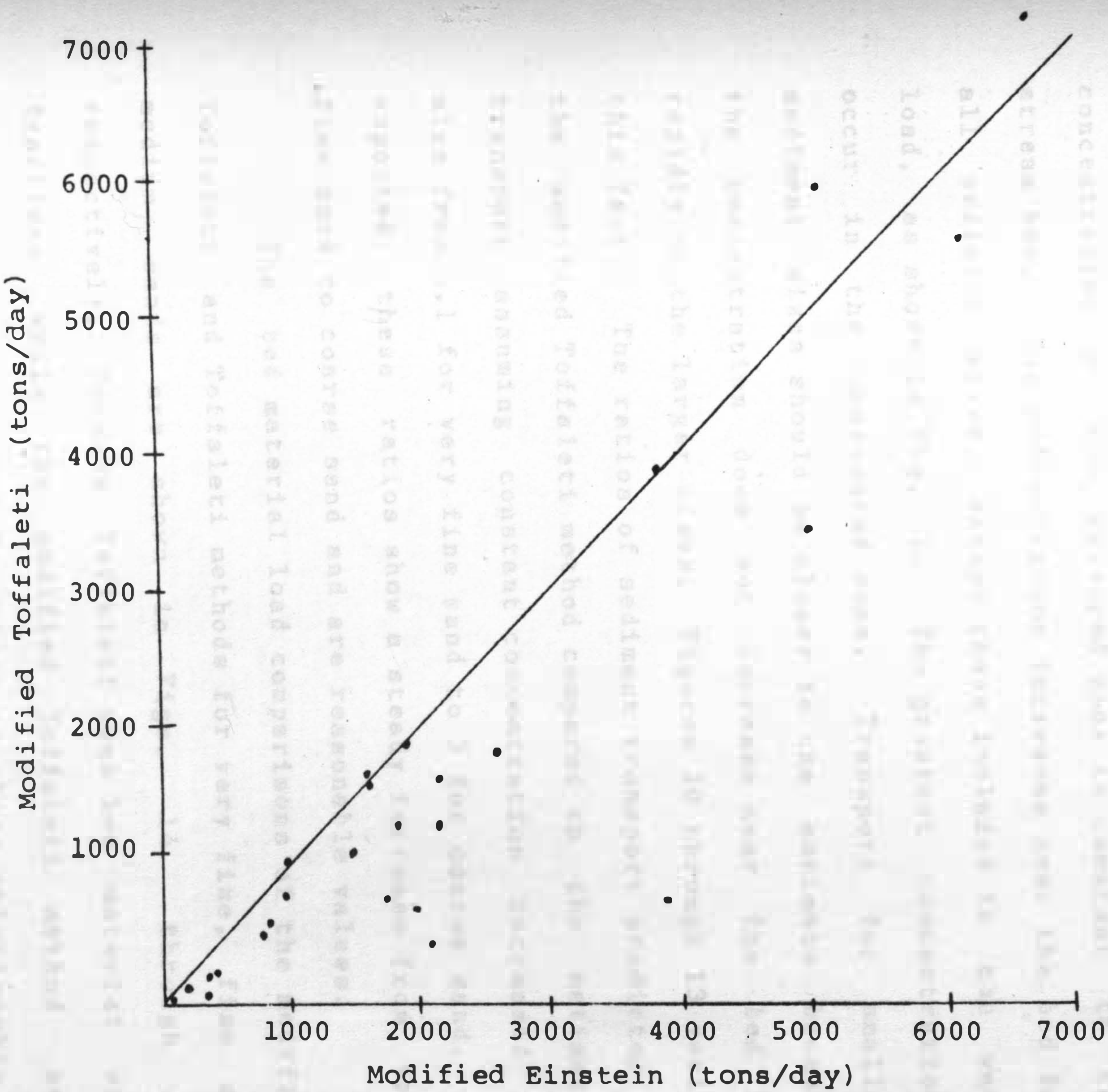

Figure 9. Bed Material Load Comparison -- Modified Toffaleti vs Modified Einstein

than the comparisons with Toffaleti and Ackers and White, but still shows reasonable agreement between methods.

The transport by size fraction should be larger than the estimation made assuming the average concentration of the measured zone is constant to the stream bed. The concentration increases near the bed for all sediment sizes, except those included in the wash load, as shown in Fig. 1. The greatest concentrations occur in the unmeasured zone. Transport for smaller sediment sizes should be closer to the estimate because the concentration does not increase near the bed as rapidly as the larger sizes. Figures 10 through 13 verify this fact. The ratios of sediment transport predicted by the modified Toffaleti method compared to the estimated transport assuming constant concentration increased in size from 1.1 for very fine sand to 3 for coarse sand. As expected, these ratios show a steady increase from very fine sand to coarse sand and are reasonable values.

The bed material load comparisons of the modified Toffaleti and Toffaleti methods for very fine, fine and medium sands are shown in Figs. 14 through 16 respectively. Because Toffaleti uses bed material size fractions while the modified Toffaleti method uses suspended sediment size fractions no close relationship is

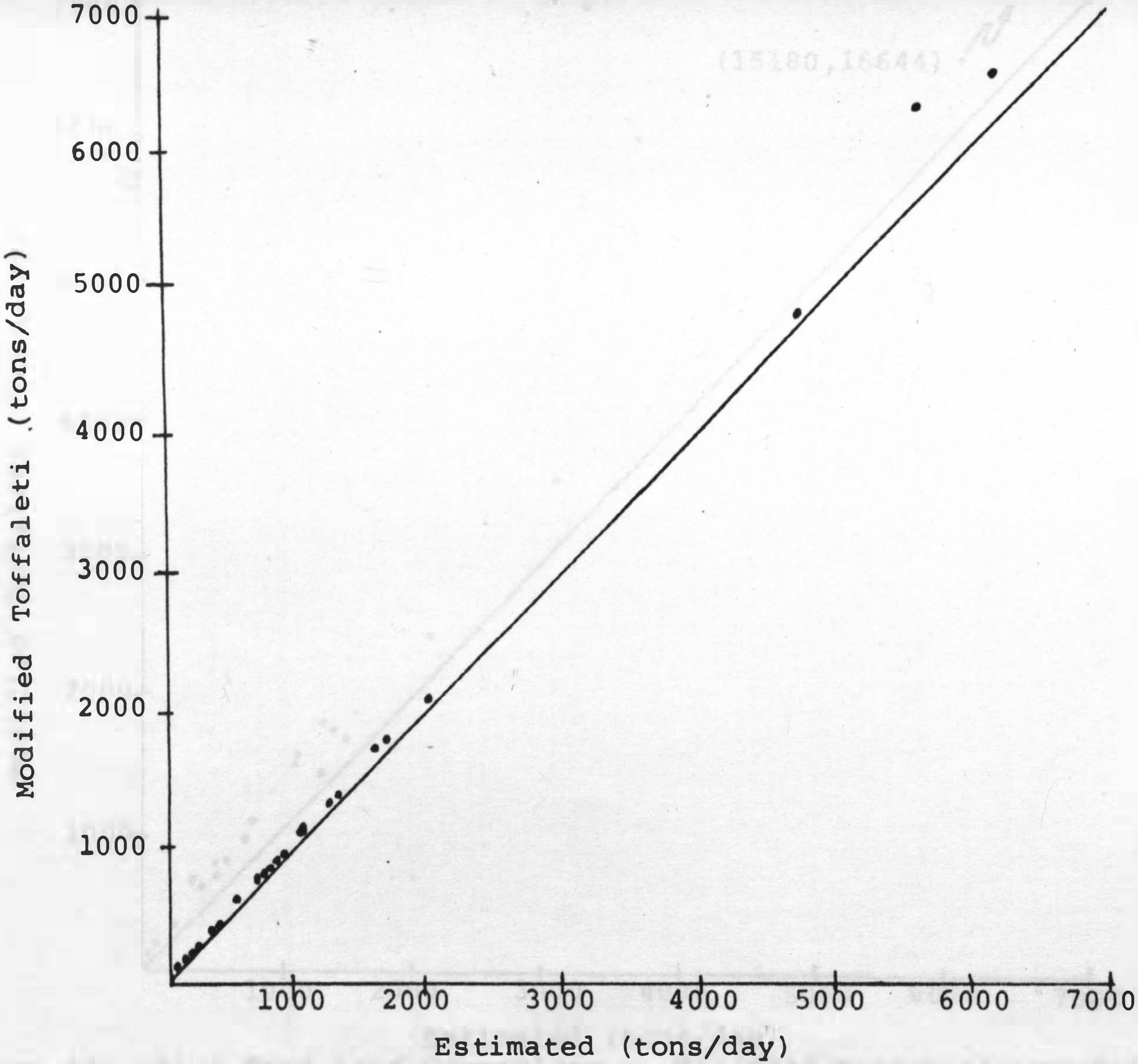

Figure 10. Very Fine Sand Load Comparison -- Modified Toffaleti vs Estimated Assuming Constant Concentration

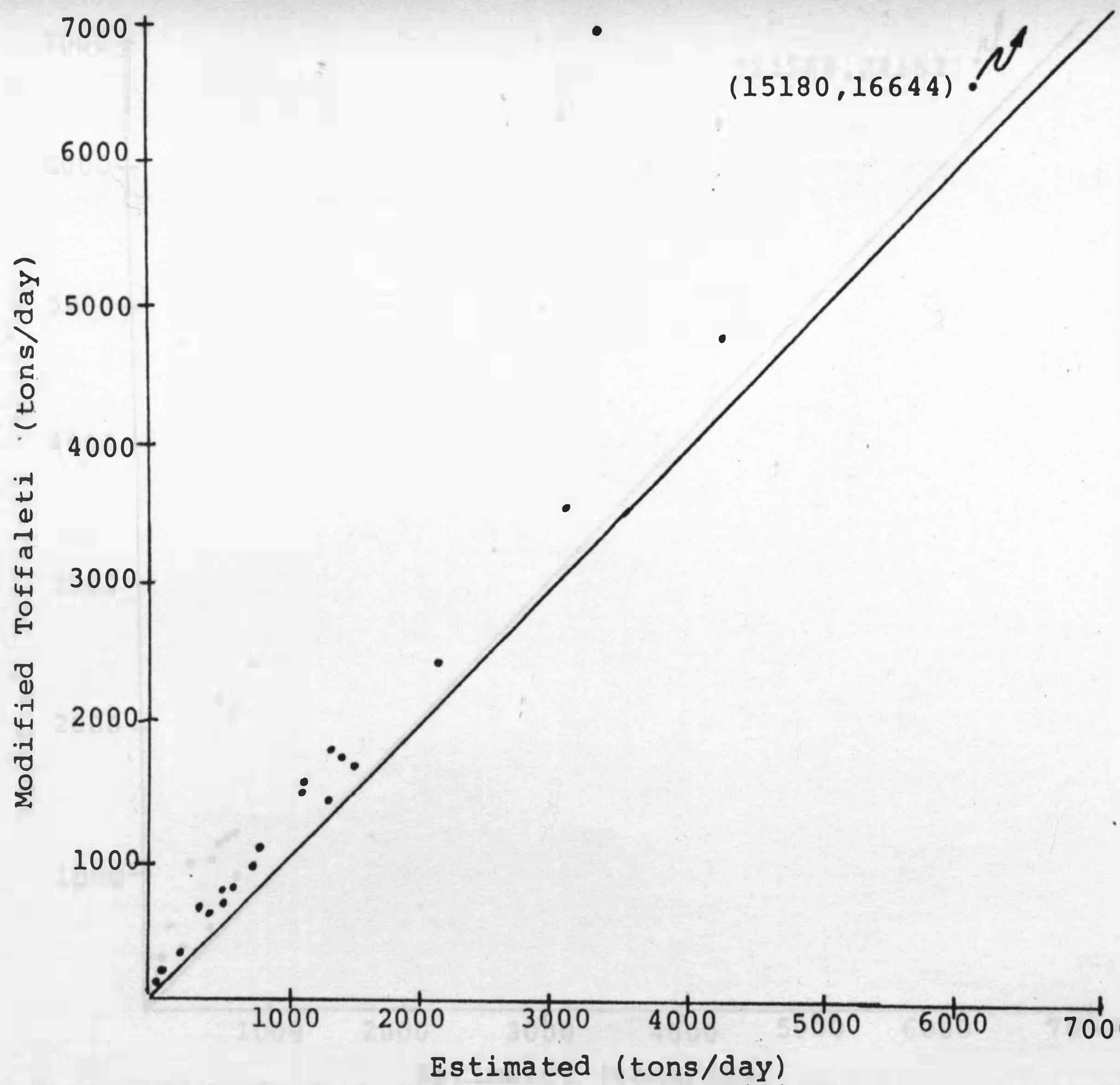

Figure 11. Fine Sand Load Comparison -- Modified Toffaleti vs Estimated Assuming Constant Concentration

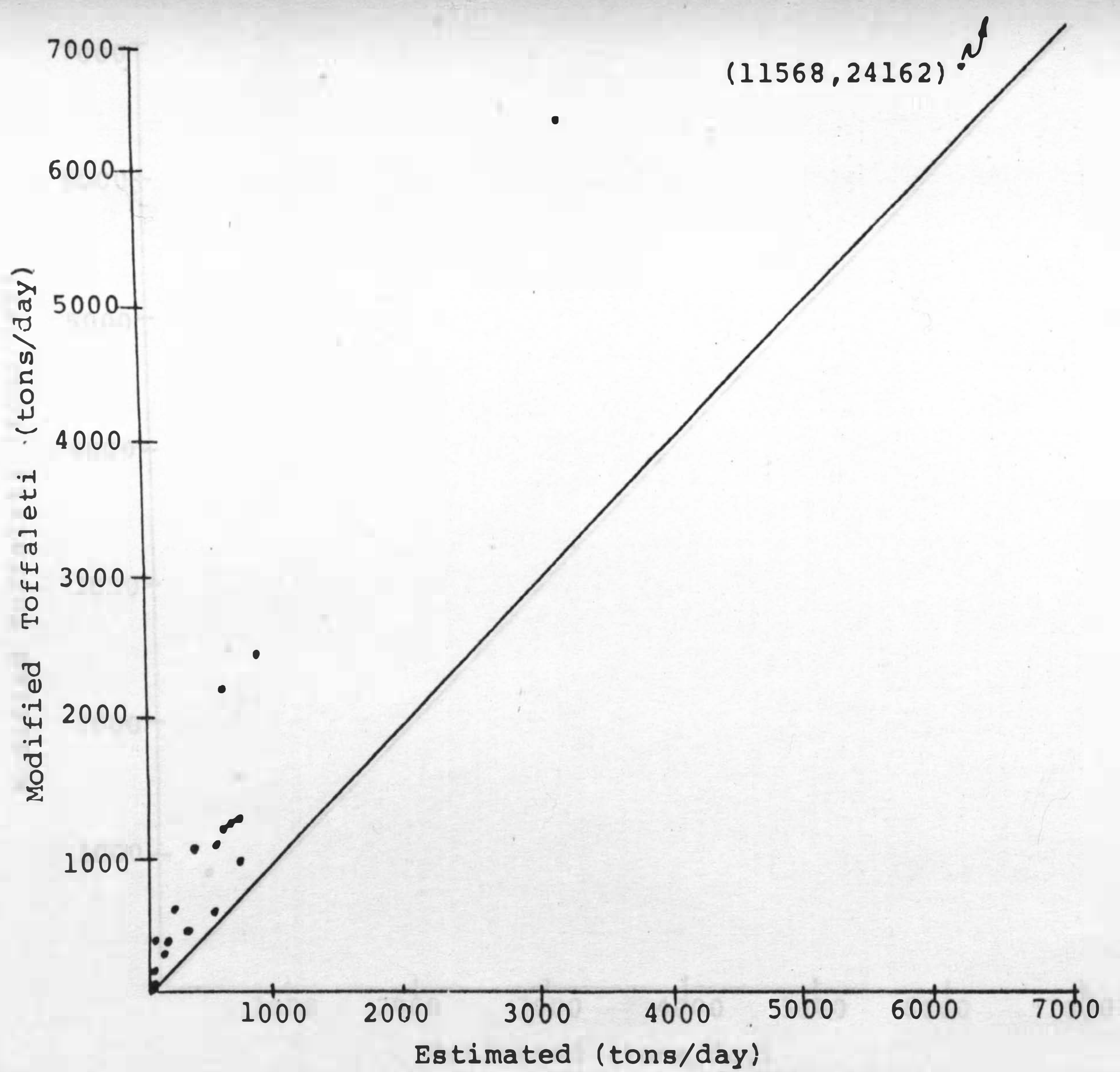

Figure 12. Medium Sand Load Comparison -- Modified Toffaleti vs Estimated Assuming Constant Concentration

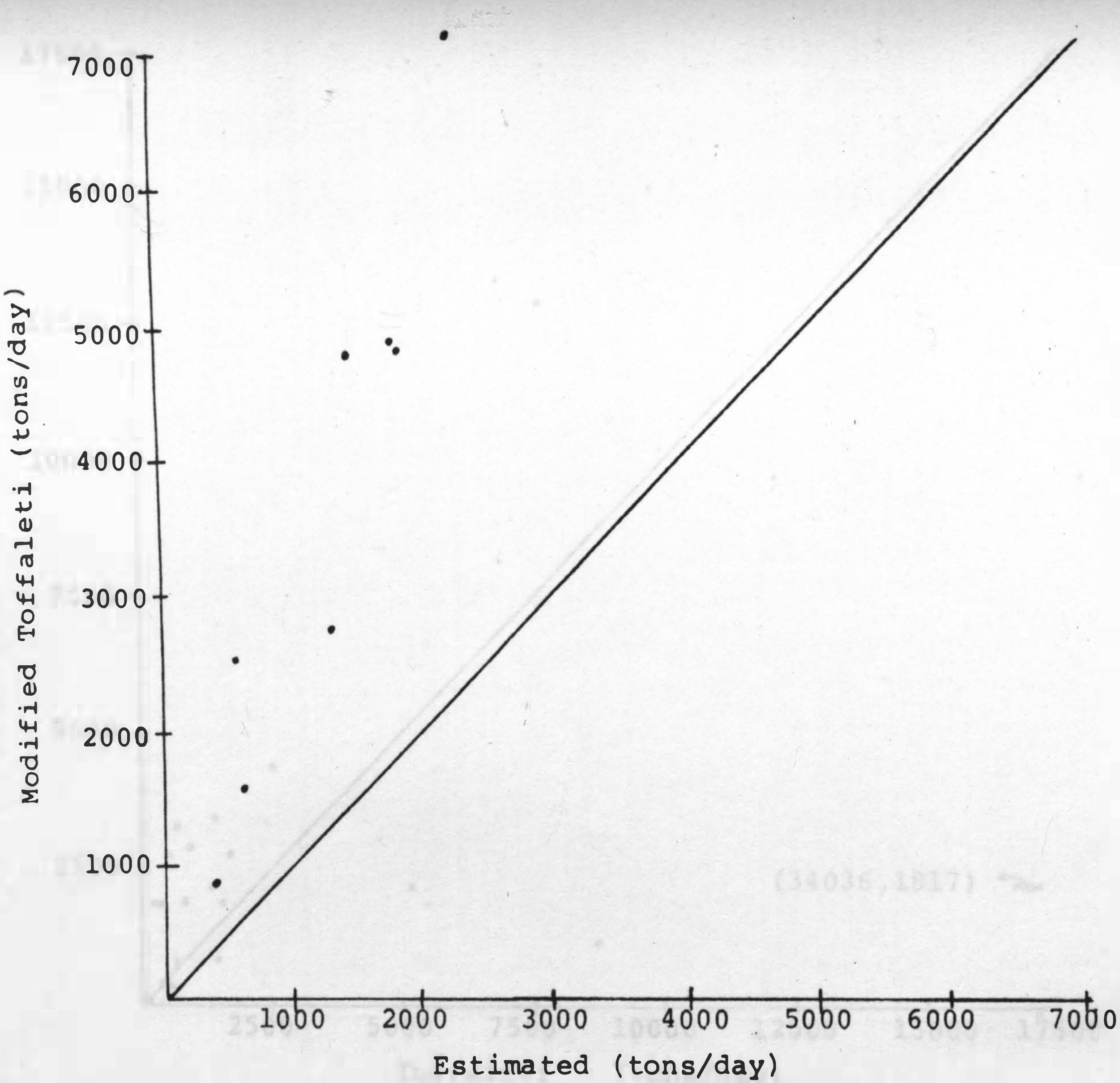

Figure 13. Coarse Sand Load Comparison -- Modified Toffaleti vs Estimated Assuming Constant Concentration

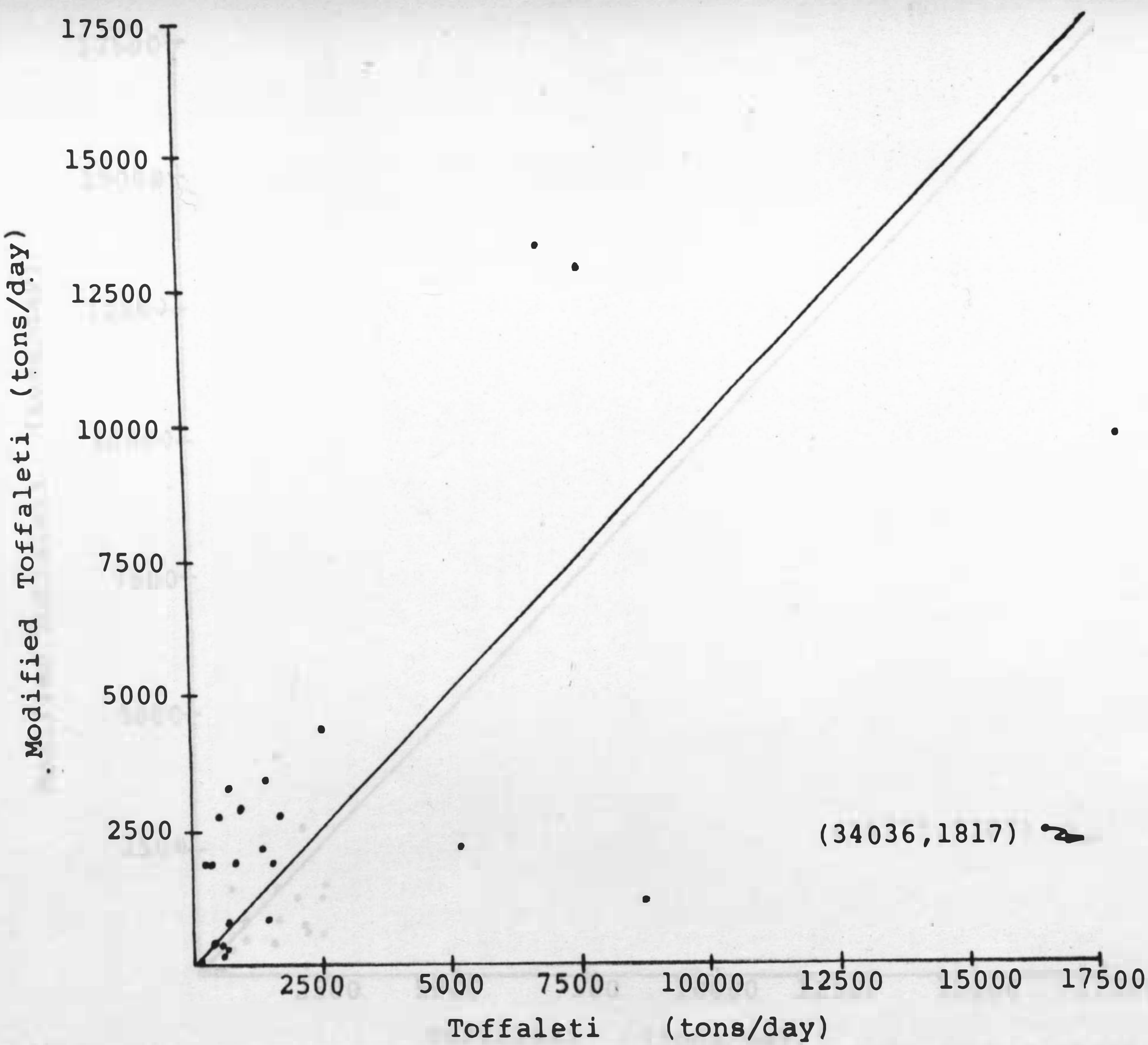

Figure 14. Very Fine Sand Load Comparison -- Modified Toffaleti vs Toffaleti

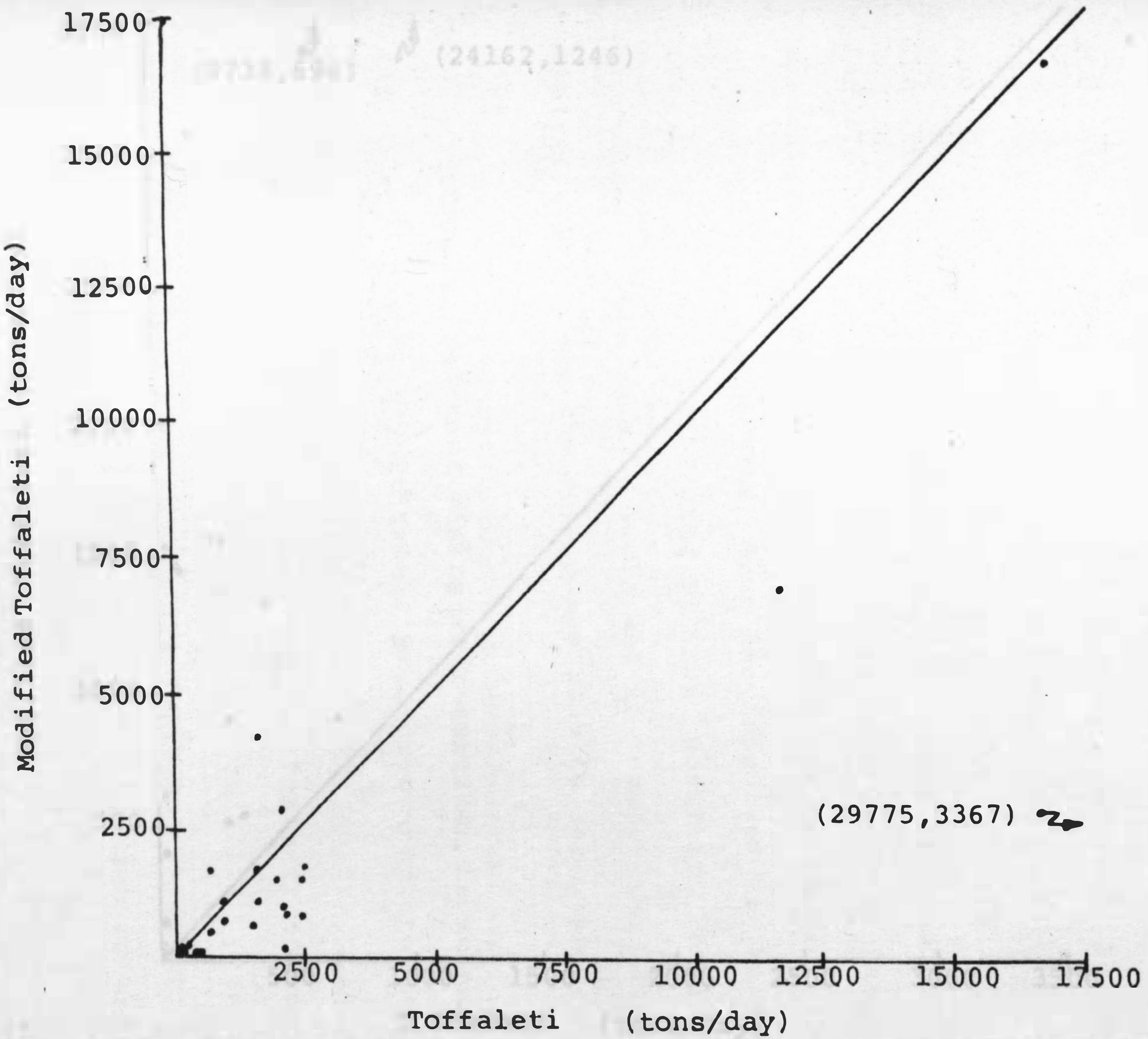

Figure 15. Fine Sand Load Comparison -- Modified Toffaleti vs Toffaleti

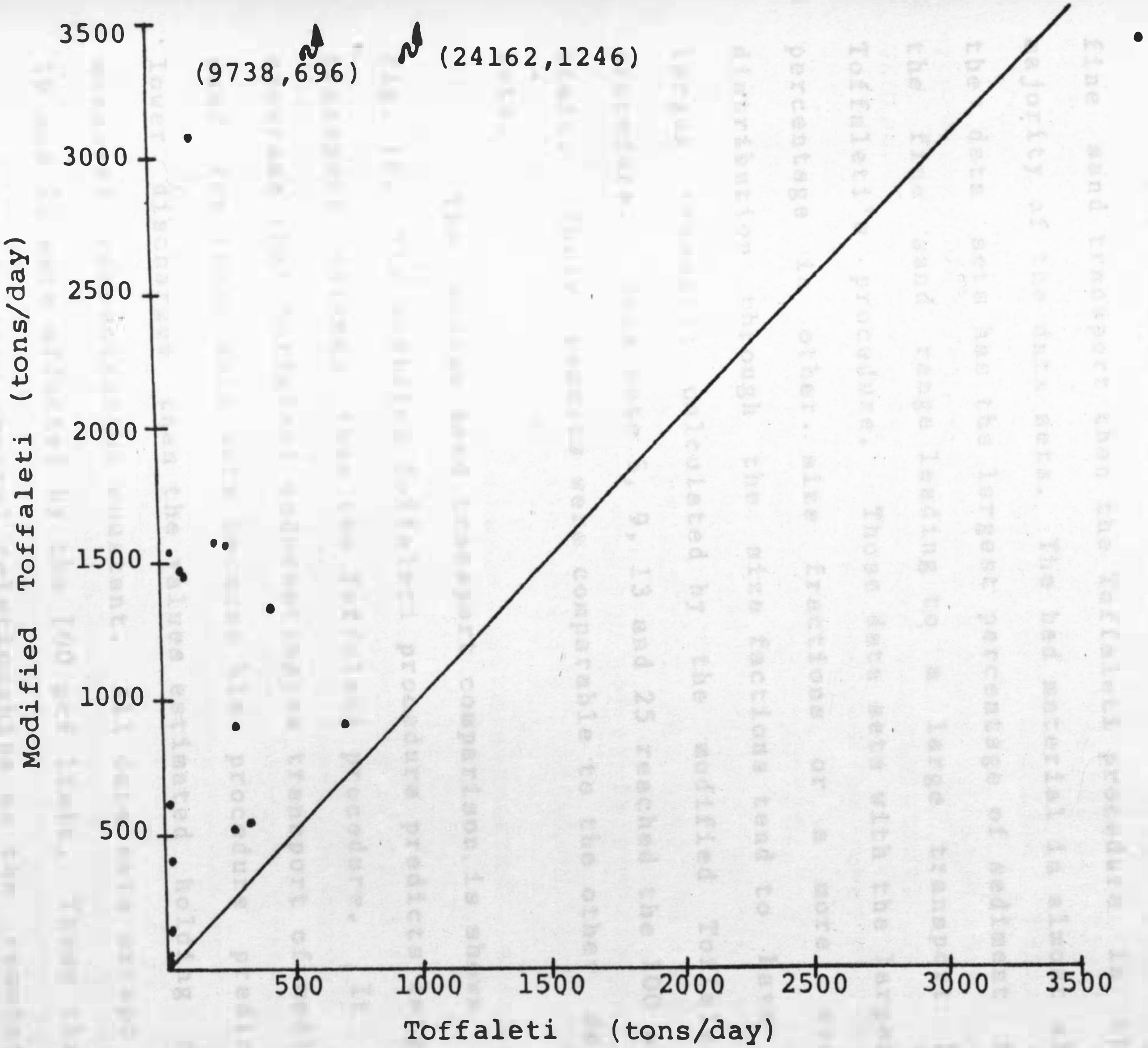

Figure 16. Medium Sand Load Comparison -- Modified Toffaleti vs Toffaleti

expected. The very fine sands have larger transport volumes by the modified Toffaleti method for about half the data sets. None of the data sets are affected by the 100 pcf concentration limit.

The modified Toffaleti procedure calculates less fine sand transport than the Toffaleti procedure in the majority of the data sets. The bed material in almost all the data sets has the largest percentage of sediment in the fine sand range leading to a large transport by Toffaleti's procedure. Those data sets with the largest percentage in other size fractions or a more even distribution through the size factions tend to have a larger transport calculated by the modified Toffaleti procedure. Data sets 5, 9, 13 and 25 reached the 100 pcf limit. Their results were comparable to the other data sets.

The medium sand transport comparison is shown in Fig. 16. The modified Toffaleti procedure predicts larger transport volumes than the Toffaleti procedure. It is apparent that Toffaleti underestimates transport of medium sand for these data sets because his procedure predicts lower discharges than the values estimated holding the measured concentration constant. All data sets except 6, 19 and 21 were affected by the 100 pcf limit. These three sets show the same general relationships as the remaining data sets.

The coarse sand comparison was not plotted. Eleven data sets have coarse sand as both bed material and suspended load in the measured zone. The modified Toffaleti procedure calculates larger volumes than the Toffaleti procedure in every set. The 100 pcf limit is reached for each set with the modified Toffaleti procedure. Toffaleti predicts a discharge less than that estimated with the measured zone concentration, just as for the medium sands. The values by the modified procedure compare well with the measured data.

Toffaleti's recommended 100 pcf concentration limit was selected on the basis of data used to develop and test his procedure. The 100 pcf limit was changed to 80 pcf and 120 pcf in the modified Toffaleti procedure with no significant change in transported sediment volumes.

Figure 17 shows the comparison of total load by the modified Toffaleti and modified Einstein methods. A very close correspondence is seen between transported volumes. Both procedures used suspended and wash load measurements by size fraction. All the data sets have large percentages of the total load as wash load. Because the wash load tends to remain constant in concentration

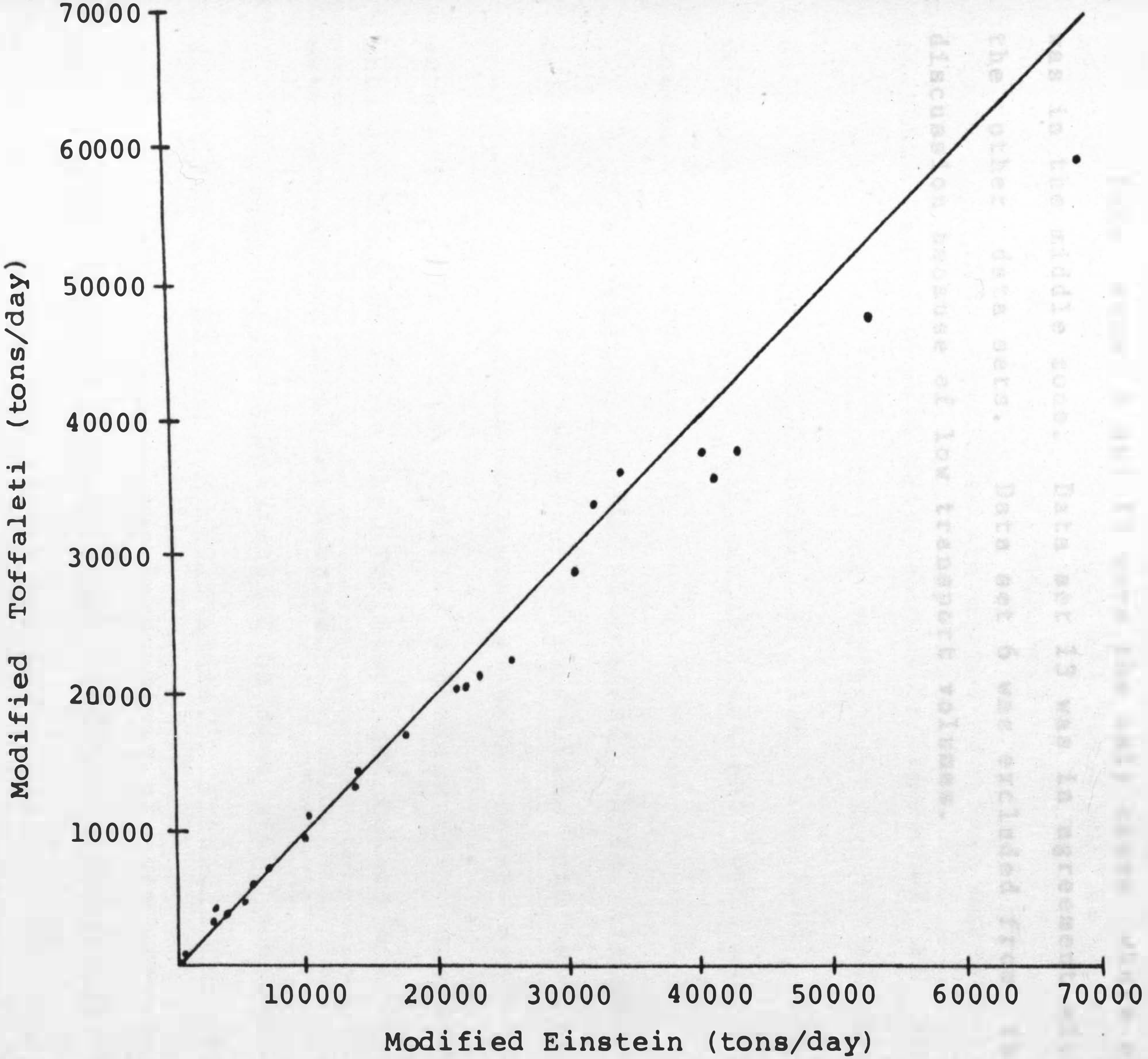

Figure 17. Total Load Comparison -- Modified Toffaleti vs Modified Einstein

throughout the stream depth the results may be closer for these data sets than they would be for a stream with larger transported sediment sizes. The modified Toffaleti procedure tends to have a slightly lower transported sediment volume than the modified Einstein procedure.

Data sets 6 and 13 were the only cases where a_o was in the middle zone. Data set 13 was in agreement with the other data sets. Data set 6 was excluded from the discussion because of low transport volumes.

CONCLUSIONS AND RECOMMENDATIONS

The conclusion of this study is that the modified Toffaleti procedure compares well with the Toffaleti, Ackers and White and modified Einstein procedures. The major advantage of the modified method is that only suspended material measurements are required to predict the total and bed material transports.

The modified Einstein method requires measurement of both the suspended material and bed material in size fractions while the modified Toffaleti method requires only the suspended material in size fractions. Both procedures calculate the total loads and bed material loads.

The Toffaleti and Ackers and White procedures calculate only the bed material load while the modified Toffaleti procedure calculates both total and bed material loads. The modified procedure uses suspended material samples while the Toffaleti and Ackers and White methods used bed material samples.

Additional studies should be done with unmeasured depths in the middle and upper zones. Although for the majority of streams, the lower limit of the measured depth will be in the lower zone, shallow streams may be measured only into the middle and upper zones.

The data sets tested had high percentages of silts and clays and low percentages of large sand sizes. The procedures should be tested with streams carrying larger sand sizes and lower percentages of wash loads.

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APPENDIX A

List of Symbols

LIST OF SYMBOLS

a_o - upper limit of unmeasured zone (ft)

A - Toffaleti's correction factor

B - stream width (ft)

C - concentration (ppm)

C_i - concentration at point y (pcf)

C_{Li} - lower zone concentration (pcf)

C_{Mi} - middle zone concentration (pcf)

C_{Ui} - upper zone concentration (pcf)

c_z - Toffaleti's constant

d_{si} - geometric mean of sediment size fraction (ft)

g - acceleration of gravity (ft/s^2)

g_{sbi} - sediment discharge in the bed zone for the ith sediment size (tons/day/ft)

g_{si} - total transported sediment load for the ith sediment size (tons/day/ft)

g_{ssLi} - sediment discharge in the lower zone for ith sediment size (tons/day/ft)

g_{ssm} - sediment load measured (tons/day/ft)

g_{ssmi} - sediment load measured for the ith sediment size (tons/day/ft)

g_{ssMi} - sediment discharge in the middle zone for ith sediment size (tons/day/ft)

g_{ssUi} - sediment discharge in upper zone for the ith sediment size (tons/day/ft)

g_{ssuLi} - unmeasured sediment load for the ith sediment size, a_o in lower zone (tons/day/ft)

g_{ssuMi} - unmeasured sediment load for the i^{th} sediment size, a_o in middle zone (tons/day/ft)

g_{ssuUi} - unmeasured sediment load for the i^{th} sediment size, a_o in upper zone (tons/day/ft)

G_t - total transport in measured zone (tons/day)

G_w - total transport of silts and clays (tons/day)

k_4 - Toffaleti's correction factor

M_i - transport coefficient for the i^{th} sediment size

n_v - Toffaleti's velocity coefficient

Q_m - measured flow (cfs)

Q_t - total flow (cfs)

r - hydraulic radius (ft)

S - slope

T - temperature in degrees Fahrenheit

T_t - temperature coefficient

U - velocity at y (ft/s)

U_*' - grain roughness shear velocity (ft/s)

V - average velocity (ft/s)

V_a - average measured velocity (ft/s)

W_i - fall velocity for the i^{th} sediment size (ft/s)

y - depth at a point in the stream, positive upward (ft)

Z_i - concentration exponent for the i^{th} sediment size

ν - kinematic viscosity (ft^2/s)

APPENDIX B

Data Sets

Data Sets

Data Set Number	Q (cfs)	B (ft)	V (ft/sec)	r (ft)	S	C (ppm)	Temp (F)	Geom Mean (ft)	Bed %	Suspended %
1	5580	195	3.08	8.2	1/6600	4150	80	0.000036	.01	.71
								0.00029	.24	.23
								0.00058	.67	.04
								0.00116	.08	.02
2	6850	232	2.65	10.1	1/8970	910	80	0.000036	.01	.71
								0.00029	.07	.22
								0.00058	.87	.05
								0.00116	.05	.02
3	5600	200	3.12	8.3	1/6200	524	65	0.000036	.02	.65
								0.00029	.27	.15
								0.00058	.54	.09
								0.00116	.16	.07
								0.00232	.01	.04
4	5200	157	3.43	8.6	1/5700	1560	65	0.000036	.18	.73
								0.00029	.15	.11
								0.00058	.53	.07
								0.00116	.13	.04
								0.00232	.01	.05
5	7320	232	2.89	9.97	1/11200	4180	81.4	0.000036	.01	.98
								0.00029	.07	.01
								0.00058	.87	.01
								0.00116	.05	

Data Set	Q	B	V	r	S	C	Temp	Geom Mean	Bed	Suspended
6	878	71.5	1.98	5.5	1/9280	142	74	0.000036	.01	.97
								0.00029	.00	.02
								0.00058	.76	.01
								0.00116	.23	.01
7	1790	132	2.33	5.7	1/8480	251	74	0.000036	.01	.73
								0.00029	.12	.22
								0.00058	.65	.04
								0.00116	.22	.01
8	6990	227	2.80	10.0	1/8850	2660	85	0.000036	.01	.95
								0.00029	.07	.04
								0.00058	.87	.01
								0.00116	.05	
9	1960	129	2.29	6.3	1/10990	1120	84	0.000036	.01	.91
								0.00029	.12	.06
								0.00058	.65	.02
								0.00116	.22	.01
10	9230	260	2.81	12.1	1/11500	882	79	0.000036	.01	.89
								0.00029	.01	.09
								0.00058	.90	.01
								0.00116	.08	.01
11	1900	129	2.34	6.0	1/8300	968	80	0.000036	.01	.93
								0.00029	.12	.05
								0.00058	.65	.01
								0.00116	.22	.01

Data Set	Q	B	V	r	S	C	Temp	Geom Mean	Bed	Suspended
12	9670	256	2.92	12.0	1/10000	2440	86	0.000036	.01	.96
								0.00029	.01	.03
								0.00058	.90	.01
								0.00116	.08	
13	901	70.5	2.10	5.3	1/11300	3330	86	0.000036	.01	.98
								0.00029	.00	.01
								0.00058	.76	.01
								0.00116	.23	
14	9860	268	3.01	11.8	1/11300	3650	82.4	0.000036	.01	.97
								0.00029	.04	.03
								0.00058	.88	
								0.00116	.07	
15	14100	308	4.24	9.8	1/4570	1290	63	0.000036	.01	.63
								0.00029	.10	.04
								0.00058	.64	.07
								0.00116	.25	.26
16	6200	207	3.31	8.5	1/6300	1923	72	0.000036	.04	.78
								0.00029	.07	.14
								0.00058	.47	.04
								0.00116	.40	.03
								0.00232	.02	.01
17	3870	202	2.74	6.5	1/7600	467	72	0.000036	.01	.62
								0.00029	.03	.09
								0.00058	.43	.08
								0.00116	.50	.19

Data Set	Q	B	V	r	S	C	Temp	Geom Mean	Bed	Suspended
18	5640	193	3.17	8.5	1/3580	1790	77	0.000036	.01	.75
								0.00029	.04	.11
								0.00058	.34	.06
								0.00116	.59	.04
								0.00232	.02	.04
19	13800	313	3.93	10.6	1/5000	1350	64	0.000036	.01	.37
								0.00029	.10	.20
								0.00058	.64	.32
								0.00116	.25	.11
20	5300	196	3.02	8.2	1/6700	2310	67	0.000036	.01	.85
								0.00029	.03	.06
								0.00058	.28	.04
								0.00116	.65	.03
								0.00232	.03	.02
21	5610	183	3.09	8.7	1/3000	680	68	0.000036		.38
								0.00029	.01	.30
								0.00058	.25	.15
								0.00116	.61	.09
								0.00232	.13	.08
22	5360	190	3.10	8.2	1/5510	1090	75	0.000036	.01	.87
								0.00029	.02	.05
								0.00058	.24	.04
								0.00116	.64	.03
								0.00232	.09	.01
23	5290	190	3.10	8.3	1/5500	2660	67	0.000036	.01	.85
								0.00029	.02	.10
								0.00058	.16	.04
								0.00116	.73	.01
								0.00232	.08	

Data Set	Q	B	V	r	S	C	Temp	Geom Mean	Bed	Suspended
24	5540	193	3.15	8.5	1/5000	2330	72	0.000036	.01	.80
								0.00029	.04	.06
								0.00058	.34	.13
								0.00116	.59	.01
								0.00232	.02	
25	12400	356	4.84	6.9	1/8040	1100	64	0.000036	.01	.52
								0.00029	.03	.32
								0.00058	.55	.09
								0.00116	.37	.04
								0.00232	.04	.03

APPENDIX C

Computer Program

```
0020 REM   ****************** MODIFIED TOFFALETI PROGRAM*************
0030 REM
0040 REM    FIRST DATA LINE INPUTS:(IN RESPECTIVE ORDER)
0050 REM        T-TEMPERATURE (DEGREES F)
0060 REM        V-AVERAGE MEASURED VELOCITY(FT/SECOND)
0070 REM        D-HYDRAULIC RADIUS (FEET)
0080 REM        A-UNMEASURED DEPTH (FEET)
0090 REM        B-WIDTH (FEET)
0100 REM        A1-% SILT & CLAY IN MEASURED LOAD
0110 REM        S-SMALLEST SEDIMENT SIZE PRESENT (1=VFS,12=LC)
0120 REM        H-LARGEST SEDIMENT SIZE PRESENT
0130 REM        C-CONCENTRATION (PPM)
0140 REM        @-PRINTOUT REQUIREMENT (2=DETAILED;1=FINAL ONLY)
0150 REM        S1-SLOPE
0160 REM        G5-SPECIFIC GRAVITY
0170 REM        S2-SHAPE FACTOR
0180 REM    SECOND DATA LINE INPUTS:
0190 REM        % OF EACH SEDIMENT IN MEASURED LOAD -
0195 REM        SMALLEST TO LARGEST
0270 DIM  F(160),J(12),K(12),L(40),W(12),Z(40),M(40),Y(12),O(12)
0280 DIM T(60),E$(12),I(60),H(12),E(12,10)
0290 DATA 25
0300 READ R
0310 REM  ******** GEOMETRIC MEANS FROM VFS TO LC  ****************
0320 DATA .000289,.000584,.00116,.00232,.00464,.00928,.0186,.0371
0330 DATA .0742,.1485,.297,.594
0340 REM  ************ SEDIMENT SIZE ABBREVIATIONS  ***************
0350 DATA VFS,FS,MS,CS,VCS,VFG,FG,MG,CG,VCG,SC,LC
0360 FOR X=1 TO 12
0370 READ J(X)
0380 NEXT X
0390 FOR X=1 TO 12
0400 READ E$(X)
0410 NEXT X
0420 REM ********  READ IN CURVE DATA  ******************
0430 REM K=1,2,3,4,5, IS S2=0.3,0.5,0.7,0.9,1.0
0440 REM I=1,6 IS C8(CS) AND REYNOLD NUMBER
0450 REM J=1,2,...,10  ARE LOG OF VALUES
0460 FOR K=1 TO 5
0470 FOR I=1 TO 6 STEP 5
0480 FOR J=1 TO 10
0490 READ E(K+I,J)
0500 NEXT J
0510 NEXT I
0520 NEXT K
0530 DATA .556,1.204,1.813,2.602,2.903,3.114,3.301,3.602,3.954,4.477
0540 DATA -.464,.065,.536,1.114,1.321,1.459,1.575,1.752,1.942,2.22
0550 DATA .532,.929,1.398,1.778,2.255,2.813,3.342,4.255,5,5.477
```

```
0560 DATA -.482,-.133,.251,.551,.908,1.308,1.651,2.191,2.594,2.837
0570 DATA .505,1.114,1.58,1.954,2.663,3.114,3.699,4.114,4.602,5.699
0580 DATA -.496,.052,.436,.728,1.244,1.561,1.95,2.203,2.464,3.031
0590 DATA .477,1,1.623,2.699,3.146,3.929,4.301,4.875,5.301,5.778
0600 DATA -.51,-.021,.494,1.322,1.637,2.14,2.376,2.703,2.931,3.179
0610 DATA .447,1.114,1.763,2.301,2.845,3.532,4.114,4.532,5.114,6
0620 DATA -.525,.099,.623,1.053,1.455,1.929,2.301,2.556,2.887,3.349
0630 REM  ***********   PROBLEM DATA   ****************************
0640 REM  ********  DATA  PROBLEM 1  *******************************
0650 DATA  80,3.08,8.2,.5,195,.71,1,3,4150,1,.0001515,2.65,.7
0660 DATA  .23,.04,.02
0670 REM  **********  DATA  PROBLEM 2  *****************************
0680 DATA 80,2.65,10.1,.5,232,.71,1,3,910,1,.0001114,2.65,.7
0690 DATA .22,.05,.02
0700 REM  ************* DATA  PROBLEM 3  ***************************
0710 DATA  65,3.12,8.3,.5,200,.65,1,4,524,1,.0001612,2.65,.7
0720 DATA .15,.09,.07,.04
0730 REM  ***************  DATA  PROBLEM 4  ************************
0740 DATA  65,3.43,8.6,.5,157,.73,1,4,1560,1,.0001754,2.65,0.7
0750 DATA .11,.07,.04,.05
0760 REM  ***************  DATA PROBLEM 5  *************************
0770 DATA 81.5,2.89,9.97,.5,232,.98,1,2,4180,1,.0000892,2.65,0.7
0780 DATA .01,.01
0790 REM  ***************  DATA PROBLEM 6  *************************
0800 DATA 74,1.98,5.5,.5,71.5,.97,1,2,142,1,0.0001077,2.65,.7
0810 DATA .02,.01
0820 REM  ***************  DATA PROBLEM 7  *************************
0830 DATA 74,2.33,5.7,.5,132,.73,1,3,251,1,0.0001179,2.65,.7
0840 DATA .22,.04,.01
0850 REM  ***************  DATA PROBLEM 8  *************************
0860 DATA 85,2.80,9.8,.5,227,.95,1,2,2660,1,0.0001129,2.65,.7
0870 DATA .04,.01
0880 REM  ***************  DATA PROBLEM 9  *************************
0890 DATA 84,2.29,6.05,.5,129,.91,1,3,1120,1,0.0000961,2.65,.7
0900 DATA .06,.02,.01
0910 REM  ***************  DATA PROBLEM 10  ************************
0920 DATA 79,2.81,11.6,.5,260,.89,1,3,882,1,0.0000869,2.65,.7
0930 DATA .09,.01,.01
0940 REM  ***************  DATA PROBLEM 11  ************************
0950 DATA 80,2.34,5.8,.5,129,.93,1,3,968,1,0.0001204,2.65,.7
0960 DATA .05,.01,.01
0970 REM  ***************  DATA PROBLEM 12  ************************
0980 DATA 86,2.92,12.0,.5,256,.96,1,2,2440,1,0.0001,2.65,.7
0990 DATA .03,.01
1000 REM  ***************  DATA PROBLEM 13  ************************
1010 DATA 86,2.10,5.3,.5,70.5,.98,1,2,3330,1,0.0000884,2.65,.7
1020 DATA .01,.01
1030 REM  ***************  DATA PROBLEM 14  ************************
1040 DATA  82.4,3.01,11.8,.5,268,.97,1,1,3650,1,0.0000884,2.65,.7
```

```
1050 DATA .03
1060 REM  ***************  DATA PROBLEM 15  *************************
1070 DATA 63,4.24,9.8,.5,308,.63,1,3,1290,1,0.0002188,2.65,.7
1080 DATA .04,.07,.26
1090 REM  ***************  DATA PROBLEM 16  *************************
1100 DATA 72,3.31,8.45,.5,207,.78,1,4,1923,1,0.0001587,2.65,.7
1110 DATA .14,.04,.03,.01
1120 REM  ***************  DATA PROBLEM 17  *************************
1130 DATA 72,2.74,6.5,.5,202,.62,1,3,467,1,0.0001315,2.65,.7
1140 DATA .09,.08,.19
1150 REM  ***************  DATA PROBLEM 18  *************************
1160 DATA 77,3.17,8.5,.5,193,.75,1,4,1790,1,0.0002793,2.65,.7
1170 DATA .11,.06,.04,.04
1180 REM  ***************  DATA PROBLEM 19  *************************
1190 DATA 64,3.93,10.6,.5,313,.37,1,3,1350,1,0.0002,2.65,.7
1200 DATA .20,.32,.11
1210 REM  ***************  DATA PROBLEM 20  ************************
1220 DATA 67,3.02,8.2,.5,196,.85,1,4,2310,1,0.0001492,2.65,.7
1230 DATA .06,.04,.03,.02
1240 REM  ***************  DATA PROBLEM 21  ************************
1250 DATA 68,3.09,8.7,.5,183,.38,1,4,680,1,0.000333,2.65,.7
1260 DATA .30,.15,.09,.08
1270 REM  ***************  DATA PROBLEM 22  ************************
1280 DATA 75,3.10,8.2,.5,190,.87,1,4,1090,1,0.0001814,2.65,.7
1290 DATA .05,.04,.03,.01
1300 REM  ***************  DATA PROBLEM 23  ************************
1310 DATA 67,3.10,8.3,.5,190,.85,1,3,2660,1,0.0001814,2.65,.7
1320 DATA .10,.04,.01
1330 REM  ***************  DATA PROBLEM 24  ************************
1340 DATA 72,3.15,8.5,.5,193,.80,1,3,2330,1,0.0002,2.65,.7
1350 DATA .06,.13,.01
1360 REM  ***************  DATA PROBLEM 25  ************************
1370 DATA 64,4.84,6.9,.5,356,.52,1,4,1100,1,0.0001243,2.65,.7
1380 DATA .32,.09,.04,.03
1390 REM  ************************************************************
1400 FOR Z=1 TO R
1410 PRINT
1420 PRINT
1430 PRINT
1440 PRINT USING 1450,Z
1450 :  PROBLEM NUMBER ###
1460 READ T,V,D,A,B,A1,S,H,C,@,S1,G5,S2
1470 C4=0
1475 REM:  V1 IS AVERAGE VELOCITY OF MEASURED ZONE
1480 N=.1198+.00048*T
1490 V1=(((1+N)*V)/((D-A)*D**N))*((D**(N+1)/(N+1))-(A**(N+1)/(N+1)))
1495 REM: TOTAL SEDIMENT TRANSPORTED IN MEASURED ZONE IS G
1500 G=(D-A)*V1*.002695*C
1510 Q1=V1*(D-A)*B                  REM: MEASURED FLOW (CFS)
```

```
1520 Q2=V*D*B                      REM: TOTAL FLOW (GIVEN INFORMATION)
1525 REM:  TOTAL TONS/DAY OF SILTS AND CLAYS
1530 G1=G*A1*(Q2/Q1)*B
1540 R1=D/11.24                    REM: LOWER ZONE UPPER LIMIT
1550 R2=D/2.5                      REM: MIDDLE ZONE UPPER LIMIT
1560 C1=260.67-.667*T              REM: C1=CZ
1570 IF @.LT.2 THEN 1640            REM:  PRINTS ALL VARIABLES
1580   PRINT "AVERAGE VELOCITY=";V
1590   PRINT "TOTAL DEPTH=";D
1600   PRINT "UNMEASURED DEPTH=";A
1610   PRINT "STREAM WIDTH=";B
1620   PRINT "TEMPERATURE=";T
1630   PRINT "SEDIMENT CONCENTRATION=";C
1640 S9=S
1650 GOSUB 3960               REM:  SUBROUTINE TO CALC FALL VEL
1660 FOR X=S TO H
1670 W(X)=W(X)/30.48          REM:  CONVERTS TO FT/SEC FROM CM/SEC
1680 Z(X)=(W(X)*V)/(C1*D*S1)  REM: ZI VALUES
1690 Z(X+20)=Z(X)             REM: RETAINS INITIAL Z(I) VALUE
1700 IF @.LT.2 THEN 1730
1710 PRINT USING 1720,X,W(X),Z(X)
1720 : SEDIMENT SIZE= ##  FALL VELOCITY= ##.##  Z= ##.####
1730 NEXT X
1740 FOR X=S TO H
1750 READ P(X)        REM: READS IN PERCENTAGES FOR SIZES IN SAMPLE
1760 IF @.LT.2 THEN 1790
1770 PRINT USING 1780,X,P(X)
1780 :  SEDIMENT SIZE= ##     % SEDIMENT IN SAMPLE= ##.##
1790 NEXT X
1800 FOR X=S TO H
1810 Y(X)=G*P(X)             REM: MEASURED TONS/DAY OF EACH SEDIMENT SIZE
1820 F(X+20)=.5*Z(X)
1830 F(X+40)=.244*Z(X)
1840 F(X+60)=-.756*Z(X)           REM: F VALUES ARE Z & NV EXPONENTS
1850 F(X+80)=1+N-(.756*Z(X))
1860 F(X+100)=1+N-Z(X)
1870 F(X+120)=1+N-(1.5*Z(X))
1880 F(X+140)=N-(.756*Z(X))
1890 IF @.LT.2 THEN 1960
1900 PRINT USING 1910,X,Y(X),F(X+20)
1910 : SEDIMENT SIZE= ##  TONS/DAY= ######  F1= ##.####
1920 PRINT USING 1930,F(X+40),F(X+60),F(X+80),F(X+100)
1930 :    F2= ##.####   F3= ##.####  F4= ##.####  F5=##.####
1940 PRINT USING 1950,F(X+120),F(X+140)
1950 :    F6= ##.####   F7= ##.####
1960 NEXT X
1970 REM    T1,T2,T3 ARE PARTS OF EQUATIONS TO CALC M(X)
1980 FOR X= S TO H
1990 T(X)=(R1**F(X+40)*R2**F(X+20)*(D**F(X+120)-R2**F(X+120)))/F(X+120)
```

```
2000 T(X+20)=(R1**F(X+40)*(R2**F(X+100)-R1**F(X+100)))/F(X+100)
2010 T(X+40)=(R1**F(X+80)-(2*J(X))**F(X+80))/F(X+80)
2020 NEXT X
2030 IF A.LT.R2 THEN 2060
2040    GOSUB 2840                    REM: MEASURED TO UPPER ZONE
2050   GOTO 2100
2060 IF A.LT.R1 THEN 2090
2070    GOSUB 2740                    REM: MEASURED TO MIDDLE ZONE
2080  GOTO 2100
2090    GOSUB 2640                    REM: MEASURED IN LOWER ZONE
2100 F=0
2110 FOR X=S TO H
2120   L(X)=(M(X)*D**(F(X+140)))/(43.2*P(X)*(1+N)*V)     REM: CLI
2130   L(X+20)=L(X)*(2*J(X)/D)**(F(X+60))                REM: CI
2140 IF @.LT.2 THEN 2170
2150   PRINT USING 2160,X,L(X),L(X+20)
2160 :   SEDIMENT SIZE= ##    C= ######.###    CL= ########.##
2170 F=100-L(X+20)                 REM:  TESTS TO SEE IF CL IS WITHIN 0.5
2180  IF F.GT.-0.50 THEN 2280    REM:      OF 100 PCF
2190  IF C4=20 THEN 2280
2195 REM:  SETS 1ST SIZE THAT EXCEEDS 100 PCF TO S SO LOOP
2197 REM:       ONLY REPEATS SIZES THAT EXCEED LIMIT
2200    C5=C5+1
2210   IF C5.GT.1 THEN 2230
2220 S=X
2230   F(X+60)=LOG(100/L(X))/LOG(2*J(X)/D)
2240  Z(X)=-F(X+60)/.756           REM: CALCULATES NEW Z FOR CI=100
2250  IF @.LT.2 THEN 2280
2260   PRINT USING 2270,X,C4,Z(X)
2270 :   SEDIMENT SIZE= ##    COUNTER C4= ##      NEW Z= ##.####
2280 NEXT X
2290 C5=0
2300 C4=C4+1
2305 REM:  RETURNS TO RECALCULATE Z,M,F's,C & CL FOR SIZES
2307 REM:         EXCEEDING 100 PCF
2310  IF F.LT.-0.5 & C4<20 THEN 1800
2320 S=S9
2330 FOR X=1 TO 5
2340 PRINT
2350 NEXT X
2360 PRINT USING 2370
2370 :  SIZE   ORIGINAL Z(I)  FINAL Z(I)   ORIGINAL M(I)   FINAL M(I)
2380 PRINT
2390 FOR X=S TO H
2400 PRINT USING 2410,E$(X),Z(X+20),Z(X),M(X+20),M(X)
2410 : ###         ##.####         ##.####         ####.##        ####.##
2420 NEXT X
2430 FOR X=1 TO 10
2440 PRINT
```

```
2450 NEXT X
2460 IF A.LT.R2 THEN 2490     REM: CALCULATING UNMEASURED SEDIMENT
2470   GOSUB 3110             REM: UPPER ZONE A
2480  GOTO 2530
2490 IF A.LT.R1 THEN 2520
2500  GOSUB 3020              REM: MIDDLE ZONE A
2510  GOTO 2530
2520   GOSUB 2940                   REM: LOWER ZONE A
2530 G2=0
2540 FOR X=S TO H
2550  U(X)=M(X)*(2*J(X))**(F(X+80))          REM: CALCULATES BED LOAD
2560 O(X)=(U(X)+Y(X)+K(X))              REM:  TOTAL LOAD PER SIZE/FT
2565 REM:  G2 IS THE TOTAL LOAD TONS/DAY NOT INCL SILT & CLAY
2570   G2=O(X)+G2
2580 IF @.LT.2 THEN 2610
2590  PRINT USING 2600,X,U(X),O(X)
2600 :   SEDIMENT SIZE= ##  BED LOAD= #####.##  TOTAL LOAD= #####.##
2610 NEXT X
2605 REM: G3 IS TOTAL LOAD TONS/DAY INCLUDING SILTS & CLAYS
2620 G3=G2*B+G1
2630 GOTO 3200
2640 REM**SUBROUTINE TO CALCULATE M(X) WHEN A IS IN LOWER ZONE *****
2650 FOR X=S TO H
2660   M(X)=Y(X)/(((R1**F(X+80)-A**F(X+80))/F(X+80))+T(X+20)+T(X))
2670 IF @.LT.2 THEN 2700
2680   PRINT USING 2690,X,M(X)
2690 :  SEDIMENT SIZE = ##    LOWER ZONE M= ####.####
2700   IF C4.GT.0 THEN 2720
2710 M(X+20)=M(X)   REM:  RETAINS ORIGINAL M(X)
2720 NEXT X
2730 RETURN
2740 REM ** SUBROUTINE TO CALCULATE M(X) WHEN A IS IN MIDDLE ZONE**
2750 FOR X=S TO H
2760 M(X)=Y(X)/((R1**F(X+40)*(R2**F(X+100)-A**F(X+100))/F(X+100))+T(X))
2770   IF @.LT.2 THEN 2800
2780   PRINT USING 2790,X,M(X)
2790 :   SEDIMENT SIZE= ##   MIDDLE ZONE M= ###.####
2800   IF C4.GT.0 THEN 2820
2810   M(X+20)=M(X)        REM:  RETAINS ORIGINAL M(X)
2820 NEXT X
2830 RETURN
2840 REM ** SUBROUTINE TO CALCULATE M(X) WHEN A IS IN UPPER ZONE***
2850 FOR X=S TO H
2860  M(X)=(R1**F(X+40)*R2**F(X+20)*(D**F(X+120)-A**F(X+120))/F(X+120))
2865  M(X)+Y(X)/M(X)
2870  IF @.LT.2 THEN 2900
2880 PRINT USING 2890,X,M(X)
2890 :   SEDIMENT SIZE= ##    UPPER ZONE M= ###.####
2900 IF C4.GT.0 THEN 2920
```

```
2910 M(X+20)=M(X)      REM: RETAINS ORIGINAL M(X)
2920 NEXT X
2930 RETURN
2940 REM ** SUBROUTINE CALCULATES UNMEASURED LOAD ***************
2945 REM **    WHEN A IS IN LOWER ZONE **************************
2950  FOR X=S TO H                          REM: K(X)=UNMEASURED LOAD
2960   K(X)=M(X)*((A**(F(X+80))-(2*J(X))**(F(X+80)))/F(X+80))
2970  IF @.LT.2 THEN 3000
2980  PRINT USING 2990,X,K(X)
2990 :  SEDIMENT SIZE= ##   LOWER ZONE UNMEASURED LOAD = #####.##
3000 NEXT X
3010 RETURN
3020 REM ** SUBROUTINE CALCULATES UNMEASURED LOAD **********
3025 REM **    WHEN A IS IN MIDDLE ZONE  ******************
3030 FOR X=S TO H
3040 K(X)=(R1**F(X+40)*(A**F(X+100)-R1**F(X+100))/F(X+100))
3045 K(X)=K(X)+(M(X)*T(X+40))
3050 K(X)=K(X)*M(X)        REM:  K(X) IS UNMEASURED LOAD
3060  IF @.LT.2 THEN 3090
3070  PRINT USING 3080,X,K(X)
3080 :  SEDIMENT SIZE= ##  MIDDLE ZONE UNMEASURED LOAD = #####.##
3090 NEXT X
3100 RETURN
3110 REM  SUBROUTINE TO CALCULATE UNMEASURED LOAD   ********
3115 REM   *****    WHEN A IS IN UPPER ZONE   **************
3120 FOR X=S TO H
3130 K(X)=R1**(F(X+40))*R2**(F(X+20))*(A**(F(X+120))-R2**(F(X+120)))
3135 K(X)=K(X)/F(X+120)
3140  K(X)=M(X)*(K(X)+T(X+20)+T(X+40)) REM:  K(X) IS UNMEASURED LOAD
3145 IF @.LT.2 THEN 3180
3150  PRINT USING 3170,X,K(X)
3160 :  SEDIMENT SIZE= ##   UPPER ZONE UNMEASURED LOAD= #####.##
3170 NEXT X
3180 RETURN
3190 PRINT USING 3210
3200 :  SIZE  MEASURED LOAD    UNMEASURED LOAD    BED LOAD  TOTAL LOAD
3210 PRINT USING 3230
3220 :       (TONS/DAY)          (TONS/DAY)    (TONS/DAY)  (TONS/DAY)
3230 PRINT
3240 IF G1.LT.1 THEN 3280
3250 PRINT USING 3270,G1
3260 :  SILTS AND CLAYS                                     ######.##
3270 FOR X=S TO H
3290 PRINT USING 3300,E$(X),Y(X)*B,K(X)*B,U(X)*B,O(X)*B
3300 :  ###     #####.##           ####.##         ####.##  ######.##
3310 NEXT X
3320 FOR X=1 TO 6
3330 PRINT
3340 NEXT X
```

```
3350 PRINT "TOTAL SUSPENDED AND BED LOAD (TONS/DAY) =";G2*B
3360 PRINT "TOTAL SEDIMENT LOAD (TONS/DAY)=";G3
3370 GOTO 4540
3380 REM ************* CALCULATE KINEMATIC VISCOSITY ***************
3390 C5=(T-32)*(5/9) REM:  CALCULATED TEMPERATURE CENTIGRADE
3400 C6=C5-20
3410   IF C5.GT.20 THEN 3440
3415 REM:  N1 IS THE KINEMATIC VISCOSITY
3420 N1=10**(1301/(998.333+8.1855*C6+.00585*C6*C6)-3.30233)
3430 GOTO 3460
3440 C7=20-C5
3450 N1=.01002*(10**((1.3272*C7-.001053*C6*C6)/(C5+105)))
3460 N1=N1/10000              REM:  KINEMATIC VISCOSITY IN SQ M/SEC
3470 P=N1*10.7639
3480 P=P*100000
3490 RETURN
3500 REM ************* INTERPOLATE SHAPE FACTOR  ************
3510 IF M=2 THEN 3580
3520 IF S2.GE.0.3.AND.S2.LT.0.5 THEN S3=0.3
3530 IF S2.GE.0.5.AND.S2.LT.0.7 THEN S3=0.5
3540 IF S2.GE.0.7.AND.S2.LT.0.9 THEN S3=0.7
3550 IF S2.GE.0.9.AND.S2.LT.1.0 THEN S3=0.9
3560 IF S2.EQ.1 THEN S3=1
3570 RETURN
3580 IF S2.GT.0.3.AND.S2.LT..5 THEN S3=0.5
3590 IF S2.GT.0.5.AND.S2.LT.0.7 THEN S3=0.7
3600 IF S2.GT.0.7.AND.S2.LT.0.9 THEN S3=0.9
3610 IF S2.GT.0.9.AND.S2.LT.1.0 THEN S3=1.0
3620 RETURN
3630 REM  ***************  INTERPOLATE TO GET CD  *********************
3640 IF S3.GT.0.3 THEN 3690
3650 K=1
3670 A1=30000
3680 B1=.958
3690 GOTO 3870
3690 IF S3.GT.0.5 THEN 3740
3700 K=2
3710 A1=300000
3720 B1=1.216
3730 GOTO 3870
3740 IF S3.GT.0.7 THEN 3790
3750 K=3
3760 A1=500000
3770 B1=1.52
3780 GOTO 3870
3790 IF S3.GT.0.9 THEN 3840
3800 K=4
3810 A1=600000
3820 B1=1.949
```

```
3830 GOTO 3870
3840 K=5
3850 A1=1000000
3860 B1=2.235
3870 IF C8.GT.A1 THEN 3940
3880 FOR J=1 TO 10
3890 IF E(K+1,J).GT.FNA(C8) THEN 3910
3900 NEXT J
3910 Y=(FNA(C8)-E(K+1,J-1))*(E(K+I,J)-E(K+I,J-1))/(E(K+1,J)-E(K+1,J-1))
3920 Y=10**(E(K+I,J-1)+Y)
3930 GOTO 3950
3940 Y=B1*SQR(C8)
3950 RETURN
3960 REM  ***********  PROGRAM TO CALCULATE FALL VELOCITY  ***********
3970 G4=9.8054
3980 GOSUB 3380    REM:  SUBROUTINE TO CALC KINEMATIC VISCOSITY
3990 C9=3.141593
4000 FOR X=S TO H
4010 H(X)=J(X)*.3048     REM:  GEOMETRIC MEANS TO METRIC
4020 E=H(X)
4030 C8=((C9/6)*E**3*(G5-1)*G4)/N1**2
4040 DEF FNA(X)=.43429448*LOG(X)
4050 REM *****  USE REYNOLDS # TO GET FALL VELOCITIES*************
4060 M=1
4070 S4=0
4080 GOSUB 3500    REM:  SUBROUTINE TO INTERPOLATE SHAPE FACTOR
4090 GOTO 4140
4100 IF S2=S3 THEN 4200
4110 M=2
4120 S4=1
4130 GOSUB 3500    REM:  SUBROUTINE TO INTERPOLATE SHAPE FACTOR
4140 I=6
4150 GOSUB 3630    REM:  SUBROUTINE TO INTERPOLATE TO GET CD
4160 IF S4=1 THEN 4200
4170 R3=Y          REM:  REYNOLDS #
4180 S5=S3
4190 GOTO 4100
4200 R4=Y REM:   REYNOLDS NUMBER
4210 S6=S3
4220 IF R3=R4 THEN 4250
4230 R5=((FNA(R4)-FNA(R3))*(FNA(S2)-FNA(S5))/(FNA(S6)-FNA(S5)))
4232 R5=R5+FNA(R3)
4235 R5=10**R5            REM:    REYNOLDS NUMBER
4240 GOTO 4260
4250 R5=R3
4260 R6=(R5*N1)/E
4270 W(X)=R6
4280 W(X)=W(X)*100        REM:   FALL VELOCITY
4290 I(X)=R5              REM:   REYNOLDS NUMBER
```

```
4300 NEXT X
4310 REM
4320 REM  *********** TABLE OF RESULTS  ******************************
4330 REM
4340 PRINT
4350 PRINT
4360  PRINT
4370  PRINT
4380 PRINT USING 4390
4390 :  ----------------------------------------------------------
4400 PRINT USING 4410
4410 :  SIZE      SF    SP GRAV   TEMP C      REY NO         W
4420 PRINT USING 4430
4430 :  ----------------------------------------------------------
4440 PRINT
4450 FOR X=S TO H
4460 PRINT USING 4470,E$(X),S2,G5,C5,I(X),W(X)
4470 :  ###       ##.#   #.##      ##.#      ########       ###.##
4480 NEXT X
4490 PRINT USING 4500
4500 :  ----------------------------------------------------------
4510 PRINT
4520 PRINT
4530 RETURN
4540 NEXT Z
4550 END
```

APPENDIX D

Tables of Results

TABLE 2

Bed Material Loads
(tons/day)

Data Set	Ackers-White	Modified Toffaleti	Toffaleti	Modified Einstein
1	6205	17894	8906	25506
2	2783	5095	3366	6808
3	9467	4823	10973	4864
4	15407	7907	8495	7843
5	2721	1855	2965	10517
6	121	9	149	103
7	493	442	902	752
8	3156	2453	3472	9851
9	392	758	771	1398
10	2960	2582	2332	4438
11	546	474	989	908
12	3845	2575	2748	8318
13	114	168	145	1349
14	3882	2930	2840	18387
15	43901	29447	65057	25890
16	5093	8323	4684	12184
17	1280	4388	1300	3047
18	4081	8330	4591	9194
19	32043	36047	35495	33739
20	1843	6432	2014	8182
21	3379	7504	3744	7718
22	2102	2843	1878	3900
23	1969	5850	1656	11138
24	3118	7375	3205	11149
25	18381	27053	24350	30987

TABLE 3

Bed Material Loads by Size Fractions
(tons/day)

	Very Fine Sand			Fine Sand		
Data Set	Esti-mate	Mod Toff	Toff	Esti-mate	Mod Toff	Toff
1	12669	13232	6904	2203	2870	1960
2	3350	3466	1419	761	938	1931
3	1097	1131	8761	658	780	2133
4	2142	2204	5903	1363	1597	2515
5	753	797	1415	753	1058	1522
6	6	6		3	3	136
7	261	284	587	47	87	290
8	1786	1863	1561	446	590	1890
9	326	364	500	109	244	233
10	1813	1883	238	201	267	2057
11	228	250	649	46	87	307
12	1796	1831	264	590	744	2446
13	70	72	122	70	97	24
14	2809	2930	881			1930
15	1780	1817	34036	3114	3467	29775
16	4200	4360	2549	1200	1492	1903
17	408	435	483	362	568	635
18	2760	2810	1714	1505	1626	2398
19	9488	9665	17950	15180	16644	16848
20	1813	1877	840	1209	1476	891
21	2706	2737	515	1352	1418	2426
22	709	732	635	567	671	922
23	3504	3601	635	1402	1612	665
24	1947	1996	1338	4218	4776	1566
25	11278	12817	7715	3172	6923	12101

Mod Toff = Modified Toffaleti
Toff = Toffaleti

TABLE 4

Bed Material Loads by Size Fractions
(tons/day)

	Medium Sand			Coarse Sand		
Data Set	Estimate	Mod Toff	Toff	Estimate	Mod Toff	Toff
1	1101	1790	42			
2	304	689	16			
3	511	1640	76	292	1271	3
4	779	1626	75	973	2480	3
5						
6						
7	12	71	25			
8						
9	54	149	39			
10	201	267	37			
11	46	138	33			
12						
13						
14						
15	11568	24162	1246			
16	900	1766	225	300	706	7
17	860	3384	174			
18	1003	1487	475	1003	2406	7
19	5218	9738	696			
20	907	1719	275	604	1360	8
21	811	990	770	721	2360	24
22	426	1013	299	142	426	22
23	142	637	337			
24	324	602	296			
25	1410	3722	4168	1057	3590	365

Mod Toff = Modified Toffaleti
Toff = Toffaleti

TABLE 5

Total Loads
(tons/day)

Data Set	Modified Toffaleti	Modified Einstein
1	57000	64613
2	15907	17620
3	9577	9618
4	22121	22056
5	75650	84314
6	298	392
7	1308	1618
8	44874	52271
9	5667	6307
10	20511	22366
11	4721	5156
12	59202	64954
13	7779	8250
14	93755	109212
15	57478	53920
16	31728	35587
17	7195	5854
18	27145	28009
19	53600	51291
20	32116	33866
21	10930	11144
22	15187	16243
23	35639	40926
24	33333	37108
25	45381	49314