12-1975

Analysis of the Sediment Filtering Action of Grassed Media

Digital Object Identifier: https://doi.org/10.13023/kwrri.rr.90

Billy J. Barfield
University of Kentucky

David T. Y. Kao
University of Kentucky

E. W. Tollner
University of Kentucky

Research Report No. 90

ANALYSIS OF THE SEDIMENT FILTERING ACTION OF GRASSED MEDIA

by

Billy J. Barfield
David T. Y. Kao
Principal Investigators

E. W. Tollner
Graduate Student Assistant

Project Number: A-049-KY
Agreement Numbers: 14-31-0001-4017 (FY 1974)
14-31-0001-5017 (FY 1975)
Period of Agreement: July, 1973 through June, 1975

University of Kentucky Water Resources Institute
Lexington, Kentucky 40506

The work on which this report is based was supported in part by funds provided by the Office of Water Research and Technology, United States Department of the Interior, as authorized under the Water Resources Research Act of 1964.

December, 1975

PREFACE

This treatise is one of three manuscripts submitted as a completion report for a research project entitled "Sediment Filtration Capacity of Grassed Areas." The long range objective of the project is to develop procedures for designing sediment filters which use grassed media. The research reported in this account involves the use of a rigid simulated media to eliminate the spatial variability inherrent in real grass, and hence to help elucidate the pertinent variables affecting the mechanics of flow and sediment movement in a grass type media. We do not feel that this is a serious limitation, because the optimum filtration action occurs in non-submerged grass channels where the blades are approximately rigid. The progress in understanding the filtering action has prompted research in which actual grass media is used.

ABSTRACT

The movement of sediment in non-submerged flow through a rigid grass media was studied experimentally by simulating the media with cylindrical nails. Models of sediment movement were developed from probablistic reasoning and from the use of existing parameters describing total bed material in open channel flow. In the probability analysis, the percent sediment trapped was found to be a power function of the number of potential fall paths, N_f, a particle could make from the surface to the bed while traveling through the filter media. The percent trapped was also found to be an inverse power function of the Reynolds number Re_T. The characteristic length used in the Reynolds number was a hydraulic radius calculated assuming rectangular open channel flow with a width equal to the spacing between elements and a depth equal to the depth of flow. This is defined as the spacing hydraulic radius, Rs. The percent trapped was finally related exponentially to a combined power function of N_f and Re_T.

Total bed material transport functions of Graf and Einstein were modified and evaluated as predictors of suspended and bed load. Bed shear was assumed to be equal to $\gamma R_s S$ where γ is the weight density of water and S is channel slope. Both Graf's and Einstein's parameters were found to be good predictors of suspended and bed load.

Based on the results of the study, procedures are proposed for analyzing the trapping capability of sediment by grass filters.

Descriptors: Sediment Transport*, Erosion Control*, Suspended Load, Bed Load, Turbulence, Grassed Waterways*, Sediment Yield, Trap Efficiency*

Identifiers: Grass Filters, Turbulent Hydraulics

ACKNOWLEDGMENTS

Appreciation is expressed to Dr. C. T. Haan for his meaningful contribution to the project while one of the principal investigators was on sabbatical leave. Thanks is also extended to the Kentucky Water Resources Research Institute for its support of the project. The investigators and graduate assistant also extend special thanks to Mr. O. J. Yeoman, for his tireless efforts which were put into the project.

Appreciation is also extended to the Kentucky Institute of Mines and Minerals Research and to the Kentucky Agricultural Experiment Station for partial support of the project.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

Reason for the Study

Erosion from construction sites is the cause of fifty percent of the sediment pollution in this country (Robinson, 1971). One of the sediment control procedures recommended by The U.S. Environmental Protection Agency is the use of grass filters in the drainage ways from disturbed areas. The grass slows down the flow and thereby decreases the sediment carrying capacity. This causes the grassed media to serve as a filter for sediment.

In order to determine the width, length, and slope of the grassed waterway serving as a filter, it is necessary to define the filtering action of the media as a function of sediment parameters, flow rate, and morphological parameters describing the grass media. The objectives of this research was to define the important parameters and propose the functional relationships.

Previous Research

Ree (1949) presented data showing that the velocity profile over a submerged grassway was nearly uniform over the lower 2/3 of the depth of the grass in comparison with that of the remainder of the profile. Hence, it would appear that the turbulent shear was less within that portion of the grass than in the remainder of the channel. Fenzl and Davis (1962) reported that the hydraulic resistance was primarily a function of the flow depth, velocity, stem diameter and stem density in partially submerged flow when using both simulated and actual vegetation (alfalfa and Bermuda grass). His regression analysis revealed that deflection did not significantly contribute to the overall resistance with these grasses. The point was made that in a denser grass the deflection probably would be significant. Kouwen (1970) presented data showing that for submerged flow with low slopes the von Karman's turbulence coefficient tended to be lower than the commonly accepted value of 0.4 in most open channels (Graf, 1971). This would appear to predict that sediment would tend to settle from a shallow flow through a grassed area when it would remain in suspension over a conventional bottom.

The above-mentioned reports did not involve sediment. Wilson (1967) in an empirical study on Bermuda grass found that maximum percentages of sand, silt and clay were trapped at about 300, 1500 and 12,200 cm (10, 50 and 400 ft.). Criteria for selecting grasses for use in filters were given. A relationship between the physical parameters was not presented in Wilson's report.

CHAPTER II

PROBABILITY ANALYSIS OF SUSPENDED LOAD

Description of the Suspended Sediment Transport Process

Suspended sediment is that material which moves randomly in the flow, maintained in suspension by the turbulence of the flow. In an alluvial bed channel this material will intermittently fall to the bed only to be picked up at some later time and injected into the flow due to turbulent lift and drag forces. The number of particles falling to the bottom per unit time increases with the fall velocity of the particles and the concentration of particles in the flow. The number leaving depends on bed shear and lift force as well as the rate of fluctuation of these forces.

Under steady state conditions the suspended concentration of sediment is such that the number of particles hitting the surface equals the number leaving. If the concentration of sediment in the flow is larger than the steady state value, the number of particles hitting the surface exceeds those leaving and deposition occurs. Inversely, when the suspended concentration is less than the steady state value, erosion occurs.

If the stream bed were an ideal absorber, i.e. held in place all those particles hitting it, eventually all of the particles in suspension would be removed. The distance required for removal would depend on particle size as well as turbulence of the flow.

As sediment laden water flows through a grassed area, the same mechanism of suspended sediment transport that applies to an alluvial channel should also apply. The structure of the turbulence, however, will be different due to the presence of the grass blades retarding the flow.

Approach to the Problem

As the sediment water mixture initially flows through a grass filter, the roughness of the bed makes it approximate an ideal absorber. In this case, the probability of trapping can be analyzed by the probability of a particle reaching the bed as discussed in this chapter. After flow has occurred for some time, the bed around the grass blades becomes essentially an alluvial bed and no longer acts as an ideal absorber. This case is discussed in subsequent chapters.

The hydraulics of sediment-laden shallow flow through a grassed channel is very difficult to describe theoretically. In many cases there is a constant rate of sediment deposition, resulting in a continual change of the hydraulic variables. One must also consider the reaction of the flexible vegetation to flow. Another problem is the lack of available information on sediment movement in flows of this type. These problems are all compounded by the fact that the type or amount of vegetation is constantly changing from month to month. These problems require that the analysis be essentially empirical or dimensional. We decided to use dimensional analysis with physical reasoning to aid in selecting terms.

Model Development

The physical parameters considered to be important in the development of a sediment trapping model were flow rate and depth, particle size (fall velocity), particle concentration, spacing of the media and the channel length. Simulated, rigid media was used to eliminate the variability due to biological effects and the effect of waving vegetation. It was felt that this would clarify the effects of the other physical variables. A sediment particle was assumed to be effectively trapped if it remained stationary or moved as bedload. It is felt that the depressions among the stools and clumps of vegetation would serve as bedload traps in an actual grass situation. The effect of deposition as it affected the section volume available for trapping was neglected. A probabilistic approach based on turbulent diffusion was used in developing a model to describe the phenomena. A definition sketch of the physical situation is given in Figure 1.

The fraction of sediment trapped, as well as the probability of being trapped, is given by the difference of incoming and outgoing sediment concentrations, $S_i - S_o$ divided by the incoming concentration, S_i. Since a particle is more likely to be trapped if it moves to the bed a large number of times, it was assumed that the probability of trapping is related to some power function of the potential number of times, N_f, that a particle could fall from the surface to the bottom as it traveled through the test section. N_f is referred to in this report as the particle fall number. A typical path of motion is given in Figure 2. It is

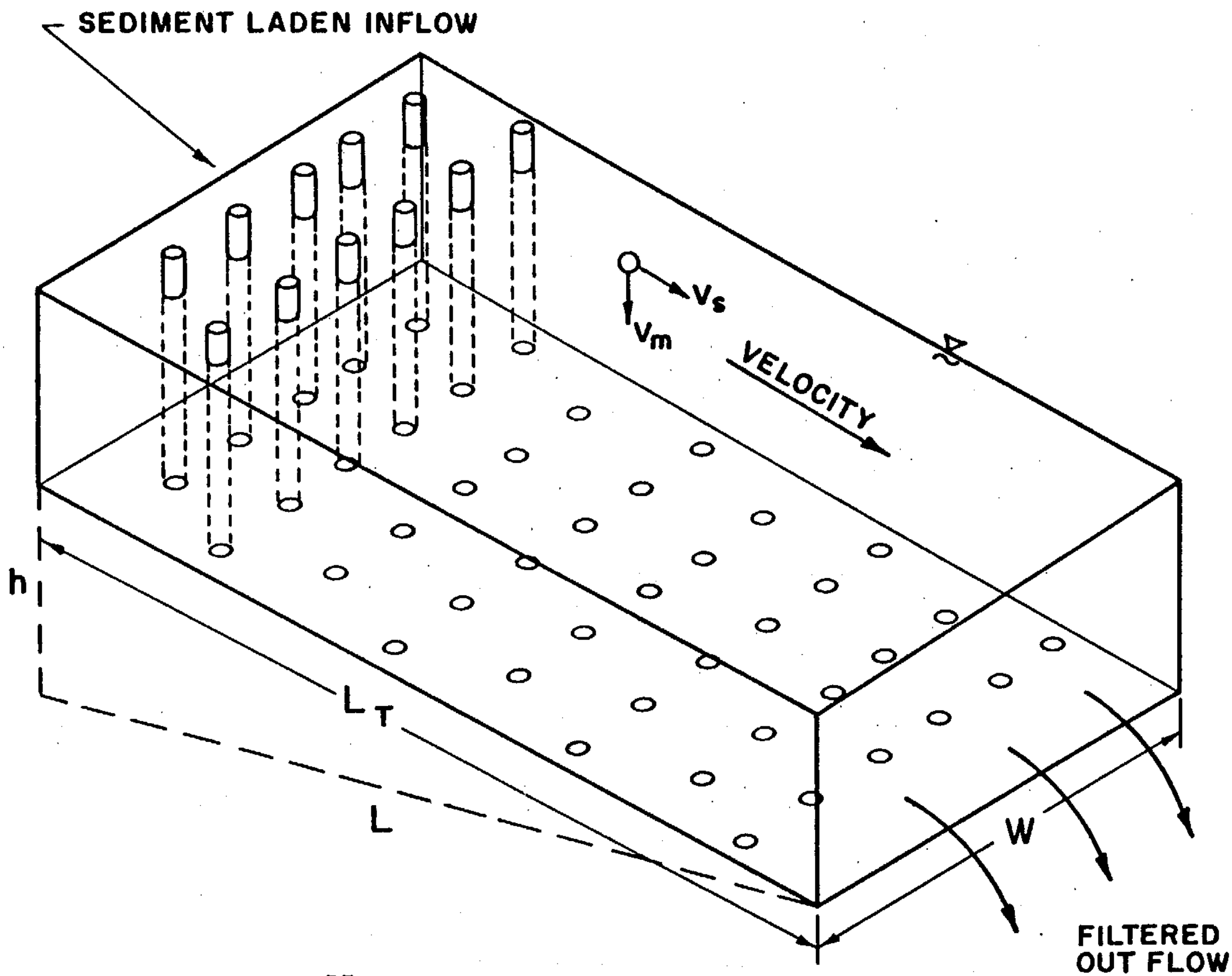


FIGURE 1: Definition sketch.

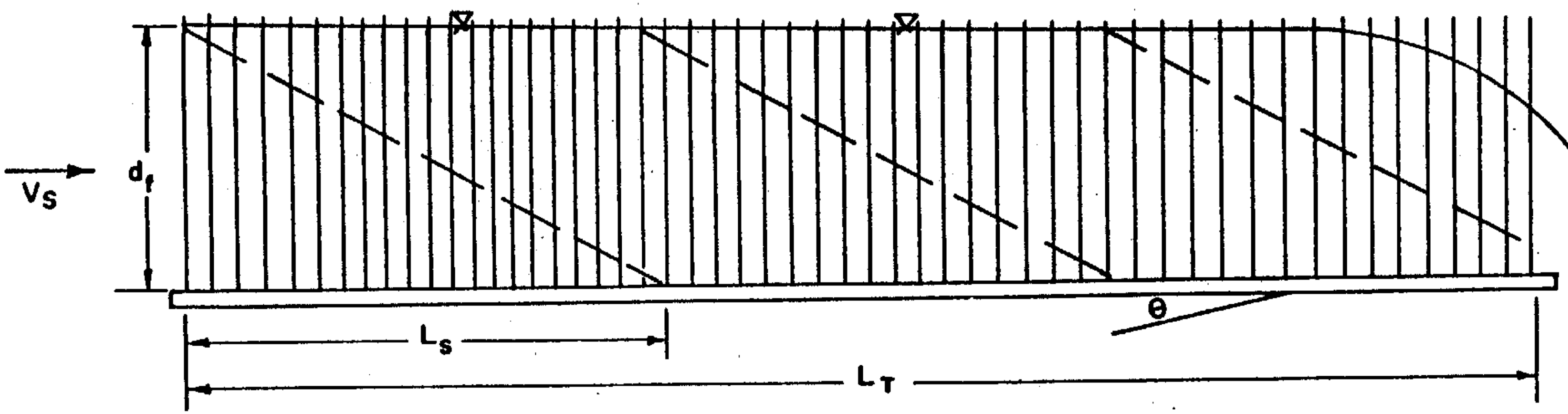


FIGURE 2: Illustration of potential fall paths.

further assumed that the trapping probability is inversely related to a power function of some turbulence index (T) since the number of particles in suspension increases with increasing turbulence. These assumptions can be summed up as follows:

$$\text{Function Trapped} = \frac{S_i - S_o}{S_i} \quad , \tag{1a}$$

$$P[\text{trapping}]=\phi_1 \ (N_f) \tag{1b}$$

and

$$P[\text{trapping}]=\phi_2\left(\frac{1}{T}\right) \tag{1c}$$

or

$$\frac{S_i - S_o}{S_i} = \phi_3 \left[N_f, \frac{1}{T}\right] \tag{1d}$$

The number of times a particle will fall, N_f, is given by:

$$N_f = \frac{L_T V_m}{V_s d_f} \tag{2}$$

where L is the section length, V_m is the settling velocity, V_s is the flow velocity and d_f is the flow depth.

The RMS turbulent Reynolds number Re_T, was taken as an indicator of the level of turbulence. Re_T is given by,

$$Re_T = \frac{\sqrt{\bar{u}'^2} \ L_c}{\nu} \tag{3}$$

where $\sqrt{\bar{u}'^2}$ is the RMS turbulent velocity, L_c is a characteristic length, and ν is the kinematic visosity. Based on research by

Tollner (1974), a reasonably good predictor of the RMS turbulent velocity in a simulated rigid media is given by,

$$\sqrt{\overline{u'^2}} = 23.5\ V_s \left(\frac{V_s L_c}{\nu}\right)^{-0.68} \tag{4}$$

A plot of equation (4) along with the data from Tollner is given in Figure 3. The best representation for the characteristic length, L_c, was found to be the spacing hydraulic radius, R_s, where R_s is defined as

$$R_s = \frac{S_s\ d_f}{2d_f + S_s} \tag{5}$$

where S_s is the spacing defined in Figure 4. Combining equations (1) to (5) yields,

$$\frac{S_i - S_o}{S_i} = \phi_3 \left[(L_T\ V_m/V_s d_f)\quad , \quad \frac{1}{23.52\ {\frac{V_s\ R_s}{\nu}}^{0.32}} \right] \tag{6}$$

Experimental investigations were conducted to determine the form of ϕ_3 which best approximated equality of the fraction trapped and the parameters on the right of equation (6).

Experimental Procedures

Artificial rigid grass media of three different spacings were built by inserting 8d finish nails into the bottom of three 210 cm x 13.5 cm x 10 cm plexiglass flumes with the arrangement shown in Figure 4. A schematic of the experimental equipment is given in Figure 5.

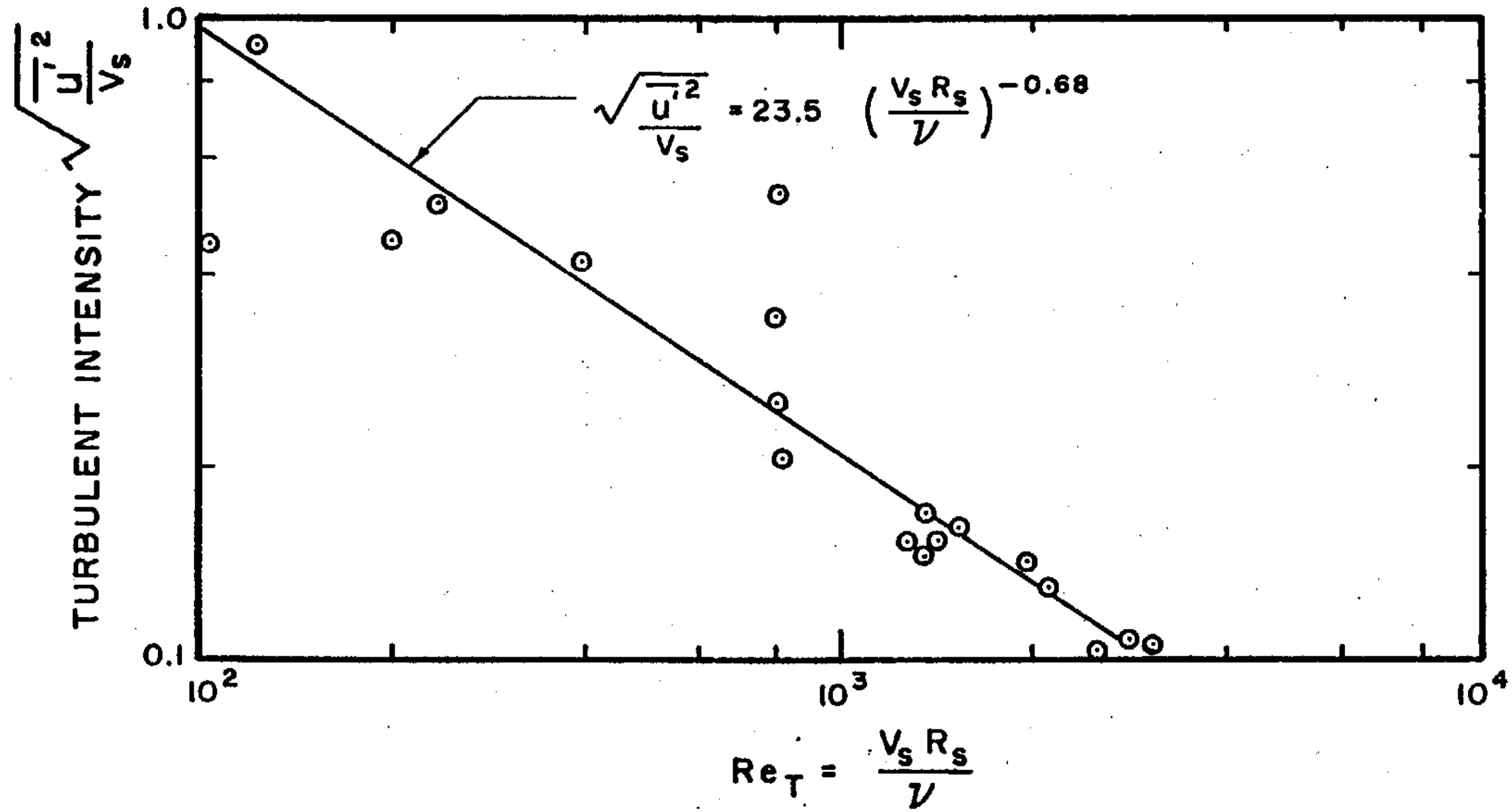


FIGURE 3: Turbulent intensity as a function of turbulent Reynold's number.

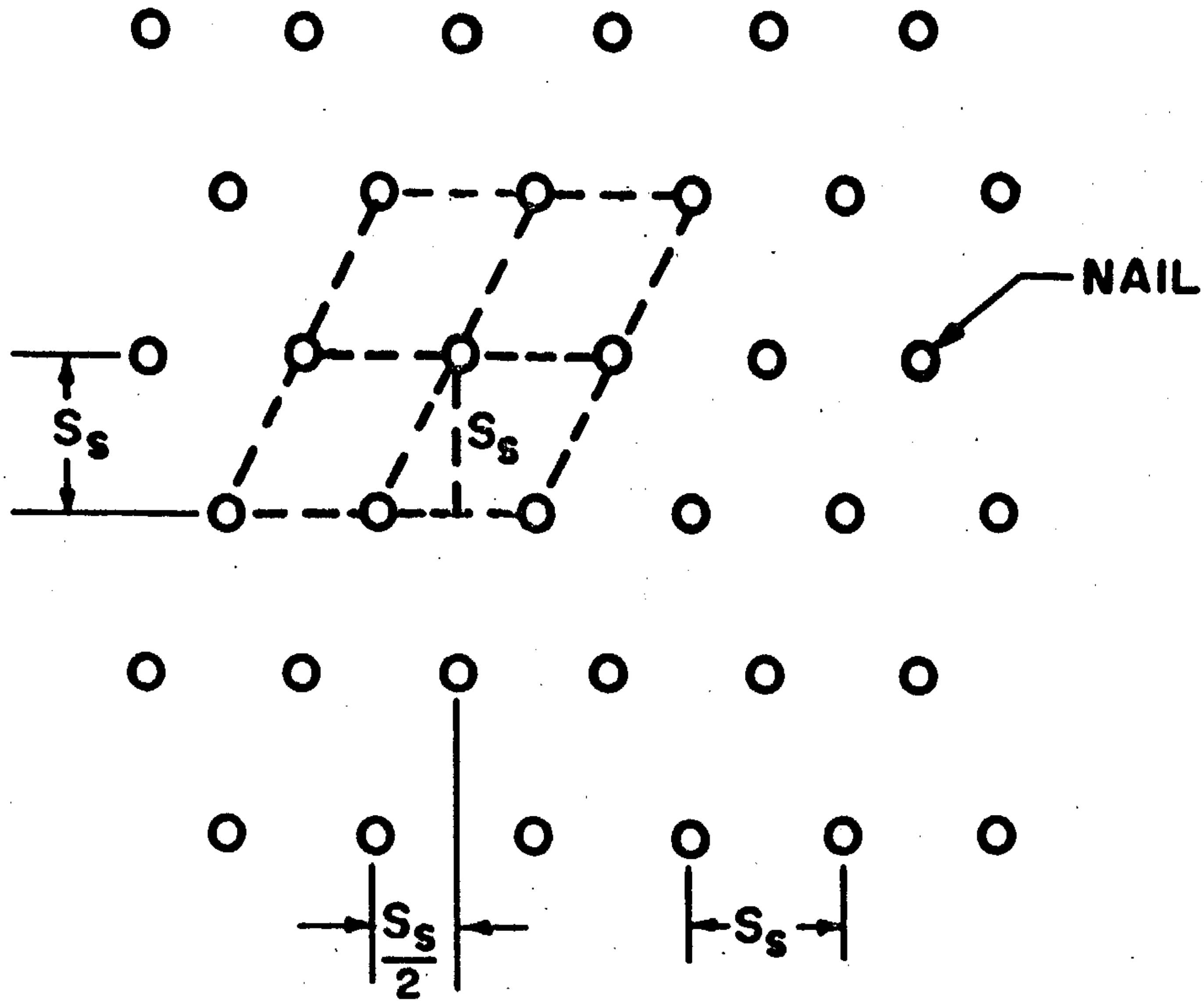


FIGURE 4: Nail arrangement.

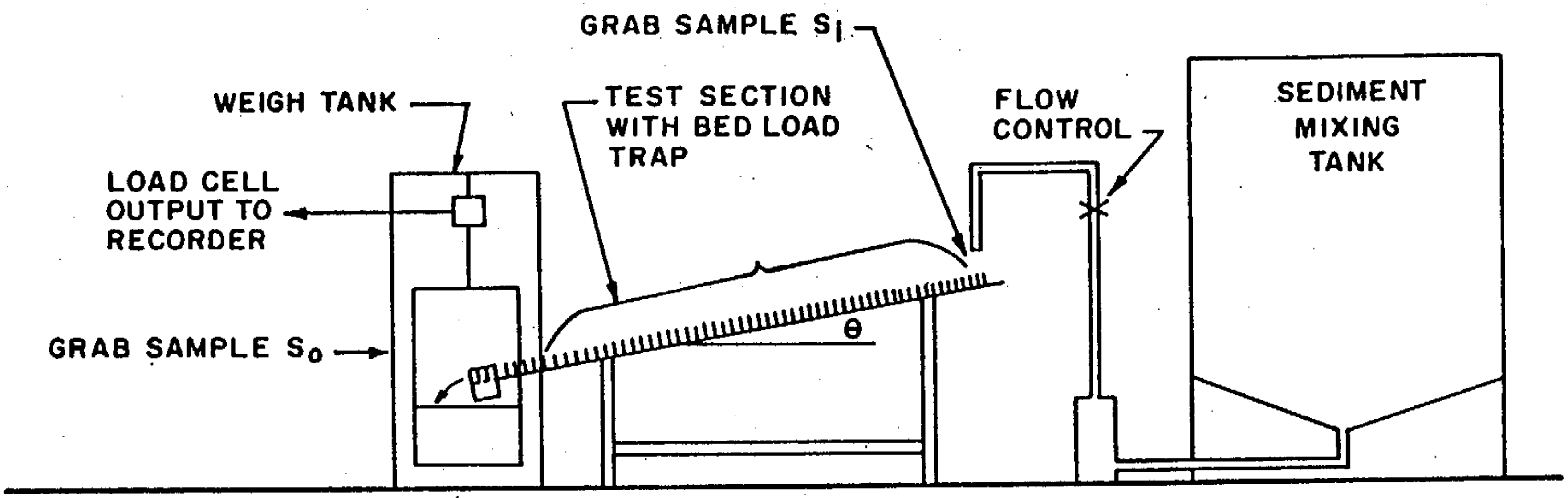


FIGURE 5: Schematic of experimental apparatus.

As mentioned earlier, it is possible to consider the bed of the grassed media as an ideal absorber. However, after sediment has been deposited the bed will become alluvial. In order to develop a conservate relationship, which could be used for both cases, we felt that it would be desirable to use experimental data from an alluvial bed between the nails rather than an absorbing bed. Any predictions of trapping efficiency made with the model would be conservative since any absorption in a real filter should yield a higher trapping efficiency than predicted.

The length of test section was varied by moving the flume inlet. A bedload trap was located at the discharge end of the section. The bedload trap was composed of a section with an open bottom covered by standard window screen. The section was as wide as the flume and 12.70 cm long. From visual observation, the trap appeared to work well.

Sediment mixtures of varying concentrations were prepared in the mixing tank and run through the test sections while varying slope, spacing, particle size, flow rate and section length. A thin layer of sediment particles of the size being filtered was bonded to the channel bottom to maintain a uniform grain roughness for each test. The experimental procedures are discussed in more detail by Tollner (1974). The independent variables in equation (6) and their ranges are as given in Table 1. The dependent variable is the outflow sediment concentration. An experimental design of 68 runs was used with emphasis on obtaining an approximately uniform distribution of fraction trapped. The ranges of the hydraulic variables is shown in Table 2.

TABLE 1. EXPERIMENTAL VARIABLES

Variable	Levels	Range
Slope	5	0.0091 - 0.242
Spacing of blades	3	0.945 - 1.583 cm
Particle size	3	0.027 - .47 mm
Flow rate	5	90 - 1500 cm^3/sec
Section length	3	100 - 210 cm
Input sed. conc.	3	0.03 - .10 $\frac{gm\ sed}{gm\ H_2O}$

TABLE 2. HYDRAULIC VARIABLES

Variable	Range
Particle No., N_f	0.07 - 50.0
Turbulent Reynolds No., Re_T	100 - 300
Froude No., N_{Fr}	0.6 - 2.0
Flow Depth	0.45 - 5.2 cm
Velocity	15.0 - 60 cm/sec

Glass beads[1/] of the type used in pavement marking were used to simulate sediment particles. They were kept in suspension in a mixing tank by a reciprocating agitator. Grab samples of the inflow were taken near the beginning and end of each run in pre-weighed pint jars. Outflow grab samples were taken in similar containers near the beginning, middle and end of each trial. The

1/ Manufactured by Potters Industries Inc., P.O. Box 14, Carlstadt, N.J., 07072.

sediment concentrations were determined gravimetrically. Flow depth was obtained by taking a minimum of two depth measurements with micrometers situated in stilling wells along the channel. Uniform flow was established to within 0.05 cm with a slotted tailgate being used for depth control when necessary. The weight of solids and water flow from the flume was recorded continuously with the load cell-recorder combinations shown in Figure 5. Six replications of several tests each provided data showing that flow rate and depth measurement could be expected to have a three percent variation.

A summary of the experimental data is contained in the appendix.

Flow Velocity and Settling Velocity Calculation

The flow velocity was calculated from

$$V_s = \frac{Q_s}{A_W} \tag{7}$$

where A_W is the width times depth minus the projected area of one row of nails. Q_s, the average total mass flow rate, is given by;

$$Q_s = \frac{(1 + S_i)\ (Q_W) + (1 + S_o)\ (Q_W)}{1} = \frac{(2 + S_i + S_o)\ Q_W}{2} \tag{8}$$

where S_i and S_o are input and output sediment concentrations $\frac{\text{gms sed}}{\text{gm } H_2O}$ and Q_W is the pure water flow rate $cm^3/$ sec given by

$$Q_W = Q_{sw}\ (1 - S_{os}) \tag{9}$$

S_{os} is the output concentration $\frac{\text{gms sed}}{\text{gm } (H_2O + \text{Sed})}$ and Q_{sw} is the rate of change of weight per unit time in the weight tank.

It was observed that if the mean flow velocity V_s, the spacing hydraulic radius R_s, and channel slope S, were substituted into Manning's formula to determine the roughness coefficient n, a constant value of n = 0.007 was obtained with a standard deviation of 0.0008 over all test conditions. Hence, for the test channels it was assumed that the velocity could be predicted by,

$$V_s = \frac{1}{0.007} R_s^{2/3} S^{1/2} \tag{10}$$

The grain roughness on the channel appeared to have a negligible effect on the roughness coefficient. It should be pointed out here that only the nail configuration shown in Figure 4 was used. Manning's n would vary with the shape and arrangement of the filter media.

It has been documented by several investigators that the mean settling velocity is affected by the particle concentration. The following relationships were derived from data presented by Nordin and Dempster (1963):

$$V_m = 7.31 \exp [-10.5(S_i - S_o)/2] \quad (\text{diam} = 0.47 \text{ mm}) \tag{11a}$$

$$= 0.347 \exp [-30.0(S_i - S_o)/2] \quad (\text{diam} = 0.067 \text{ mm}) \tag{11b}$$

$$= 0.067 \exp [-39.5(S_i - S_o)/2] \quad (\text{diam} = 0.020 \text{ mm}) \tag{11c}$$

These were used because of the importance of the concentration variable. It might be noted that the first term of each equation represents the single particle fall velocity. The evaluation of the single particle fall velocity was discussed by Tollner (1974).

Experimental Observations

Several qualitative observations were made as the test runs were executed. For the tests involving the larger beads on the flatter slopes the sediment formed a distinct profile which moved down the channel as the test progressed. At some point after a test was started the mixture would flow over the previously deposited sediment (which had submerged the nails) where the tractive force was sufficient to prevent further deposition until the flow reached the leading edge of the sediment profile. At this point the nails would then slow the flow to a point at which settling occurred. With the larger sediment on steeper slopes, the high trapped fraction was mostly due to the high rate of bedload transport.

The test on the smallest beads generally produced the lower trapped fractions (lower bedload rates). Some deposition was noted on the flatter slopes. The depth of deposited material appeared to decrease uniformally with distance from the inlet, thereby increasing the slope. The medium-sized beads generally produced results lying between those for the largest and smallest particle size.

A summary of the data is included in the appendix.

Discussion of Model Assumptions

The calculated particle number, N_f, had a range of 0.07 - 50.0. Based on a logarithmic regression the percent trapped could be expressed by

$$\% \text{ Trap} = 44.1 N_f^{0.29} \qquad (12)$$

A plot of equation (12) along with the data is given in Figure 6. The correlation coefficient, r, was found to be equal to 0.88, with nearly all of the variation occurring in the range of 0.04 < % Trap < 0.8.

A similar analysis was carried out with the turbulent Reynold's Number, which varied from 100 - 300. The following relationships were obtained:

$$\% \text{ Trap} = 4.1 \times 10^2 \; (Re_T)^{-0.28} \qquad (d = 0.47 \text{ mm}) \qquad (13a)$$

$r = 0.72$

$$\% \text{ Trap} = 1.1 \times 10^6 \; (Re_T)^{-1.98} \qquad (d = 0.067 \text{ mm}) \qquad (13b)$$

$r = 0.64$

$$\% \text{ Trap} = 6.0 \times 10^5 \; (Re_T)^{-2.07} \qquad (d = 0.022 \text{ mm}) \qquad (13c)$$

$r = .49$

A plot of equation (13) along with the data is shown in Figure 7.

This anslysis was performed for each particle size because flow conditions were varied with particle size in order to obtain an approximately uniform distribution of percent of sediment trapped.

Equations (12) and (13) verify the assumptions that the fraction of sediment trapped is directly proportional to the particle number and inversely proportional to the turbulent Reynolds Number.

Final Model

Linear regression analysis with various transformations was used to determine if the fraction trapped could be related to some combination of the independent variables. The independent variables used were the turbulent Reyonlds number, Re_T, and the particle fall

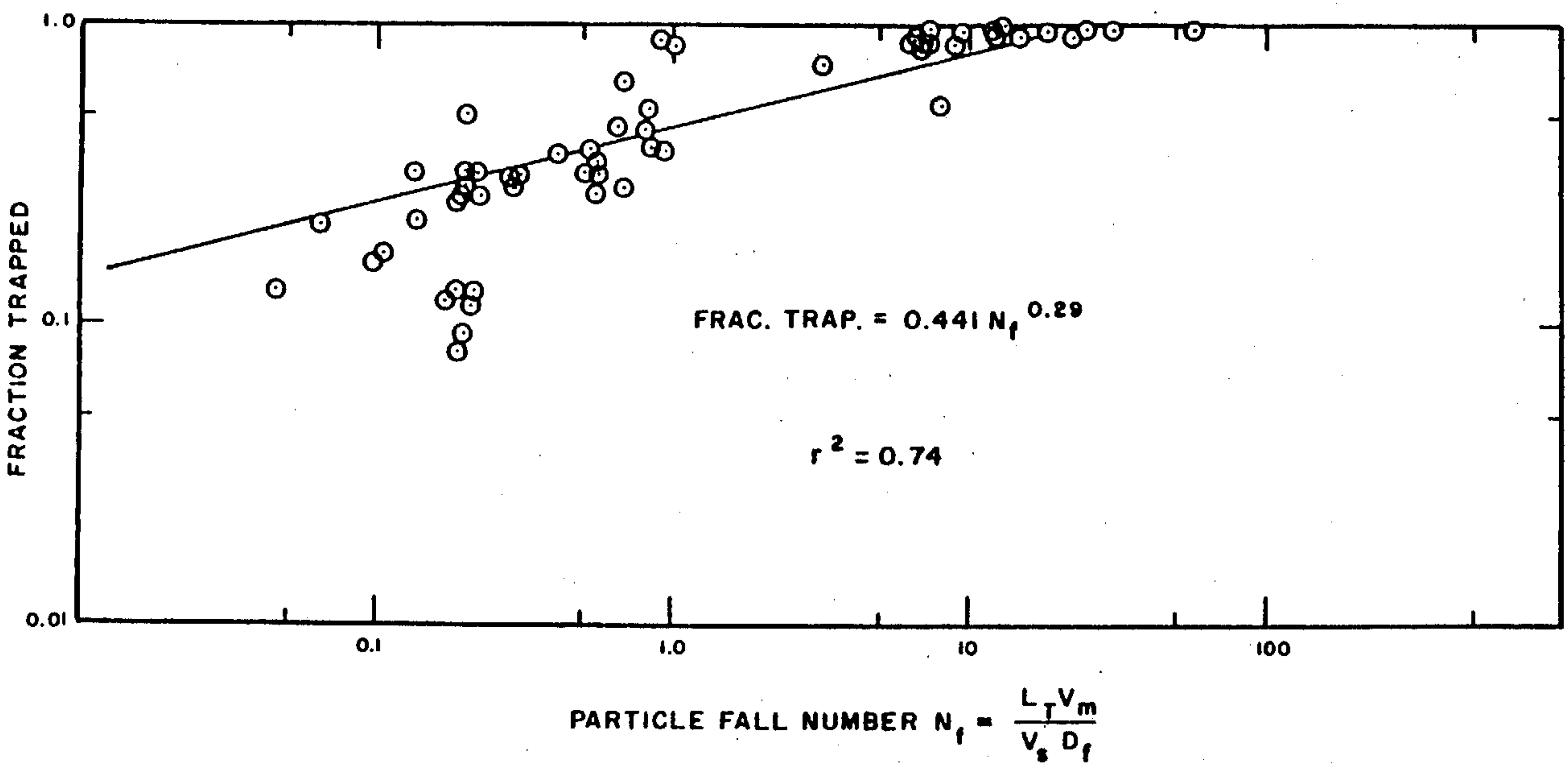
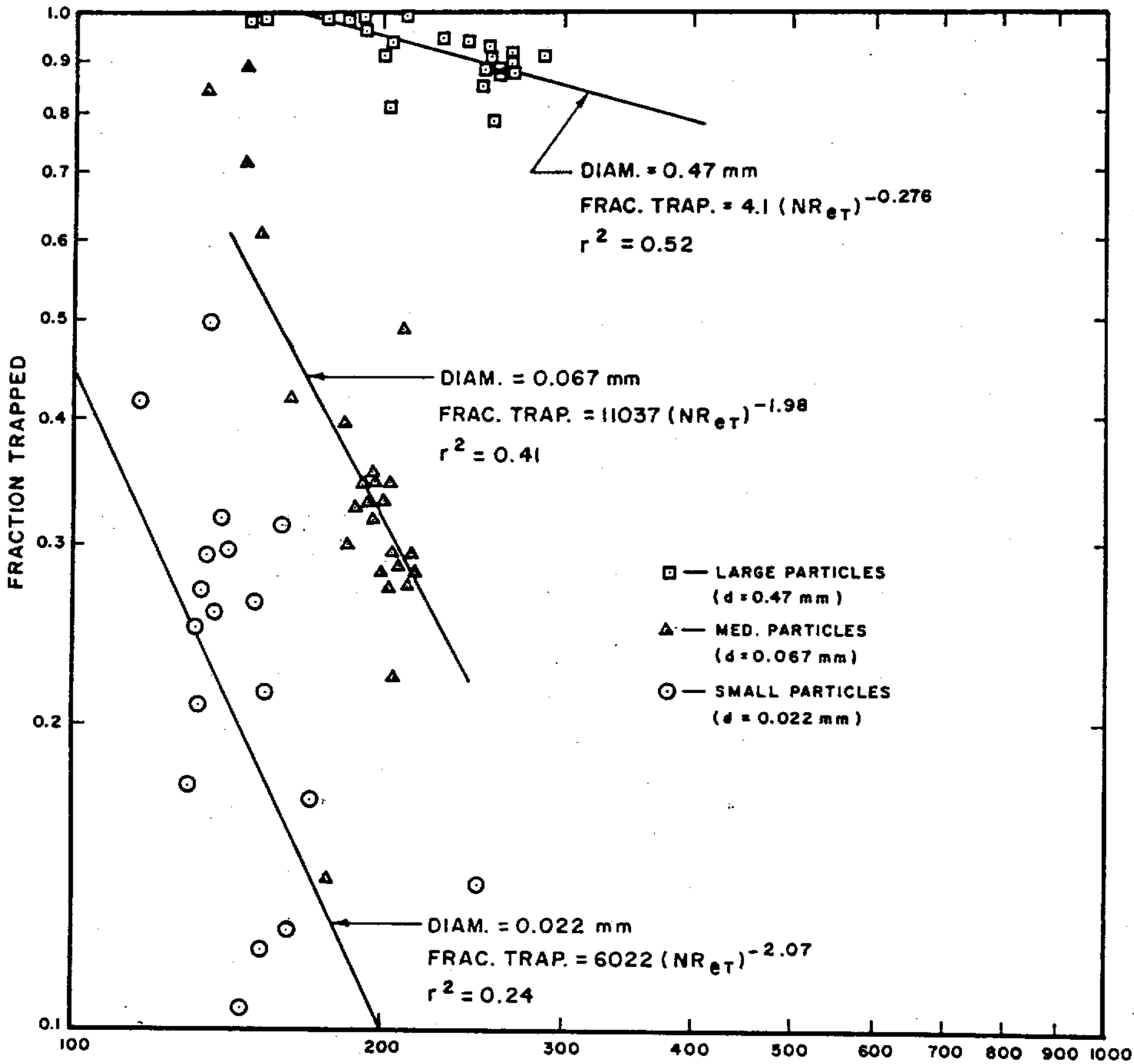


FIGURE 6: Fraction trapped versus particle fall number.



$$NR_{eT} = 23.52 \left[\frac{V_s R_s}{\nu} \right]^{0.32}$$

FIGURE 7: Fraction sediment trapped versus turbulent Reynold's number.

number N_f. A model constraint was that $(S_i - S_o)/S_i$ must be bounded between zero and one. The relationship yielding the maximum correlation coefficient r, was selected to define the functional form of equation (6).

Using an inverse transformation suggested by Davis (1962), the following functional form was found to effectively describe the data while being bounded by zero and one.

$$\frac{S_i - S_o}{S_i} = \text{Exp } \{-A \frac{(Re_T)^B}{(N_f)c}\} \tag{14}$$

The values of the coefficients A, B, and C were determined from the experimental data by taking log transforms and performing linear regression. The correlation coefficient was 0.87. All coefficients were found to be significantly different from zero by the student's t test. Substituting the coefficients A, B, and C determined from regression, equation (14) becomes

$$\frac{S_i - S_o}{S_i} = \text{Exp } \{-1.05 \times 10^3 \left(\frac{V_s R_s}{\nu}\right)^{0.82} \left(\frac{V_m L_T}{V_s d_f}\right)^{-0.92}\} \tag{15}$$

A plot of equation (15) along with the experimental data is given in Figure 8. V_s, R_s, and V_m can be calculated by applying equations (5), (10), and (11) respectively.

Several attempts to obtain improved r values were made. r was increased by dividing the flow depth by the Cosine of the slope angle in equation (2). A form of the Froude number for larger slopes

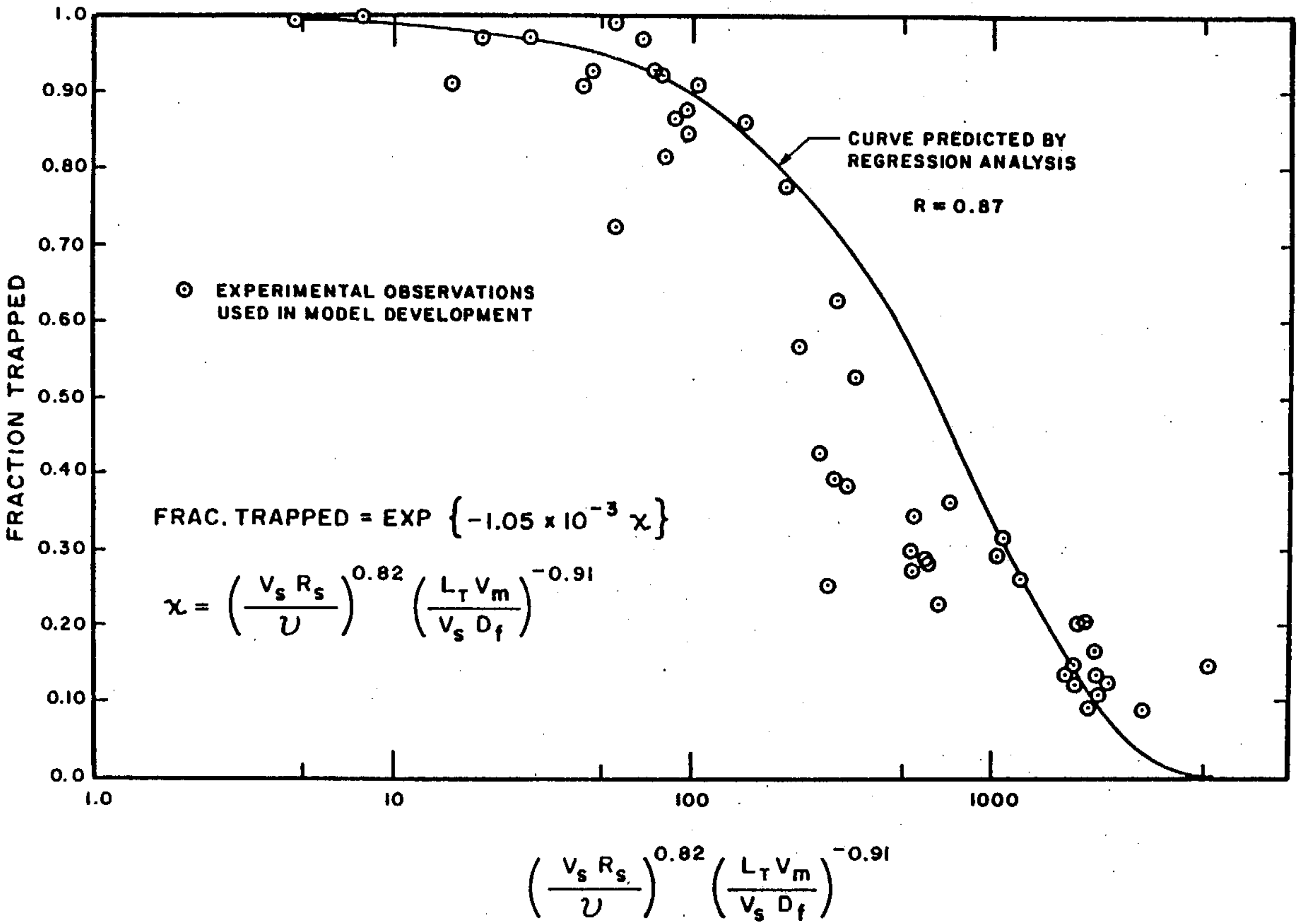


FIGURE 8: Trapping function.

was also included in the turbulence index term of equation (6). A slight improvement in r was observed, however, it was considered insignificant. The addition of the Froude Number was rejected because the resulting model was much more complicated.

The power model of the form suggested by equation (15) was by far the best form of the functional relationship. Additive and multiplicative forms gave r values of less than 0.1. Other variations on equation (15) which were considered included a variable kinematic viscosity with concentration as suggested by Happel and Brenner (1965) which reduced the r value by 4%. The use of equations relating the fall velocity to sediment concentration was found to be a definite improvement (5% increase in r) over using a non-adjusted fall velocity. The method of computing the flow velocity, V_s, was found to be superior to a method which did not correct for the presence of the nails and also to a method which involved the average cross-sectional area of the channel as compared to the cross-sectional area within a row of nails.

Einstein (1968) observed that an exponential distribution best described the depth of deposition of sediment particles with length over a gravel bed. This would indicate that the decrease in concentration was also some exponential function in keeping with these results.

Discussion of the Trapping Model

The model as presented in equation (15) is bounded between zero and one and the component terms behave as one would expect.

As the variables of spacing, flow depth, or slope angle increase, the trapping percentage goes down. As length and settling velocity increase the trapped percentage increases which is as one would expect.

It can be seen in Figure 8 that a reasonably good relationship does exist between the fraction trapped and the independent variables for the data collected over the range shown in Table 1. It would be highly desirable to have more data that contained longer lengths and finer clay sized particles since clay is frequently a major component of urban runoff.

Data from Tollner (1974) were analyzed to see if the model adequately predicted the times when greater than 95% of the sediment would be trapped. The relationship appeared adequate for all 54 cases. Check data were also collected in the range of $0 \leq \frac{S_i - S_o}{S_i} \leq 90\%$ using the equipment described in this paper. Since the model would probably be used in practive to predict the necessary combinations of dependent variable to have trapping of 95%+, it is felt that the accuracy has been adequately demonstrated for other than clay particles.

More research is required to adequately apply the results of this model to an actual design situation. The model needs to be modified to account for the effects of deposition. This would be very important in most practical situations where longer times would probably be involved. How to best represent a nonhomogeneous soil and, the effect of a given flexible, biologically active vegetation, and the effects of frequent inundations is currently under consideration. The mode of sediment transport is also under consideration in an actual grass situation.

Summary and Conclusions on Probabilistic Model

A model of the trapping of suspended sediment by a rigid grass media was developed. The fraction trapped was found to be dependent upon media spacing, flow depth and velocity, sediment concentration and particle size, and the section length.

The exponential model shown in equation (15), along with equations (5), (10), and (11) substituted in, was found to provide an adequate relationship between the fraction trapped and the dependent physical variables for short durations. Each term behaves as one would expect, and the range of the exponential is properly bounded.

CHAPTER III

SUSPENDED LOAD ANALYSIS USING TOTAL BED MATERIAL FUNCTIONS

Total Bed Material Functions

Total bed material functions (TBMF) describe the bed and suspended load sediment transport capacity of an open channel with alluvial boundaries. Graf (1971, chapter 9) has an excellent summary of these functions, all of which are steady state. The majority of the TBMF define some dimensionless transport parameter as function of a dimensionless shear intensity. This shear intensity involves a computation of the shear on the bed. In order to use the functions for a grass filter it is necessary to find a method of partitioning drag between the filter elements and the bed. In this report bed shear was calculated as discussed subsequently and then used in the TBMF. An evaluation was then made of how well the TBMF would predict suspended load and bed load. Suspended load is discussed in this chapter and bed load in a subsequent chapter.

Partitioning of Drag Between Media Elements and Bed

In normal open channel flow, the component of the fluid weight parallel to the bed is resisted entirely by frictional drag on the bed. In flow through a grassed media, the weight component is resisted by drag on the grass blades as well as drag on the bed. As mentioned earlier, partitioning of the drag is necessary in order to use the TBMF for sediment transport in grass filters.

Two approaches were used to partition drag in this study. One approach was that of Li and Shen (1973). In this approach, a drag coefficient[1/], C_D, is used along with the mean velocity to calculate the drag or an individual filter element. By knowing the number of elements per unit area, m, and the total drag on an element, τ, the drag on the bed can be calculated from

$$\tau_B^L = \tau - \tau_g \tag{16}$$

where

$$\tau = \gamma RS \tag{17}$$

and

$$\tau_g = mC_D \frac{\rho V_s^2}{2} \tag{18}$$

The other approach to partitioning the drag was based on the assumption that the flow could be represented by a series of channels with a hydraulic radius equal to the spacing hydraulic radius. Under this assumption, the bed shear becomes

$$\tau_B^R = \gamma R_s S \tag{19}$$

where τ_B^R is the bed shear calculated by the spacing hydraulic radius method.

1/ Taken from Figure 9, Li and Shen (1973). The flow conditions used closely approximate those of the test in this report.

No data are available on drag measurements to directly test the procedures. The only evaluation possible was to use the procedures in the TBMF and see how well the functional relationships worked. A direct comparison between the two methods was possible, however, using the hydraulic data collected in the trapping studies described in Chapter II. This data is summarized in the appendix. The comparison is shown in Figure 9. Obviously, the two methods do not agree well, particularly at high shears.

<u>Evaluation of the Parameters of Graf and Einstein as Predictors of Suspended Load</u>

<u>Graf's Method</u>. Graf et al (1968) proposed a shear intensity and a transport function for TBMF in a closed conduit. Graf's shear intensity parameter ψ_G, is

$$\psi_G = \frac{(\gamma_s - \gamma)\ d}{\tau_B} \tag{20}$$

where γ_s is the weight density of the sediment, d is the average diameter of the sediment particle, and other terms as previously defined. The transport parameter proposed by Graf and modified for suspended load is

$$\Phi_S^G = \frac{S_o\ V_s\ R_s}{\sqrt{(\gamma_s/\gamma - 1)\,gd^3}} \tag{21}$$

where g is the accelaration of gravity and other terms as previously defined.

A plot of these parameters based on the experimental data summarized in the Appendix is shown in Figures 10 and 11 for bed shear calculated from equations (16) and (19) respectively. There

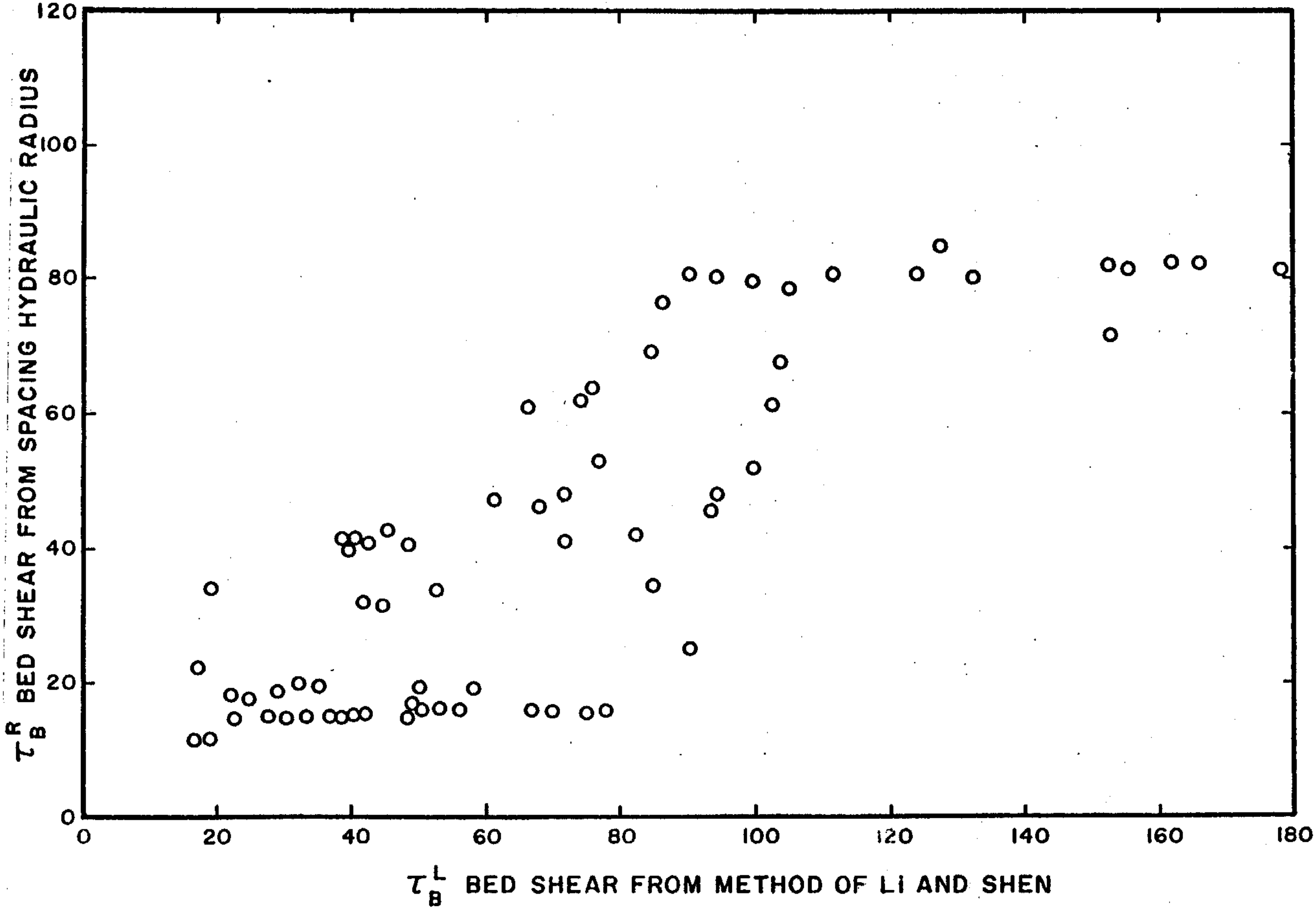


FIGURE 9: Comparison of bed shear calculations from method of Li and Shen (1973) and using spacing hydraulic radius.

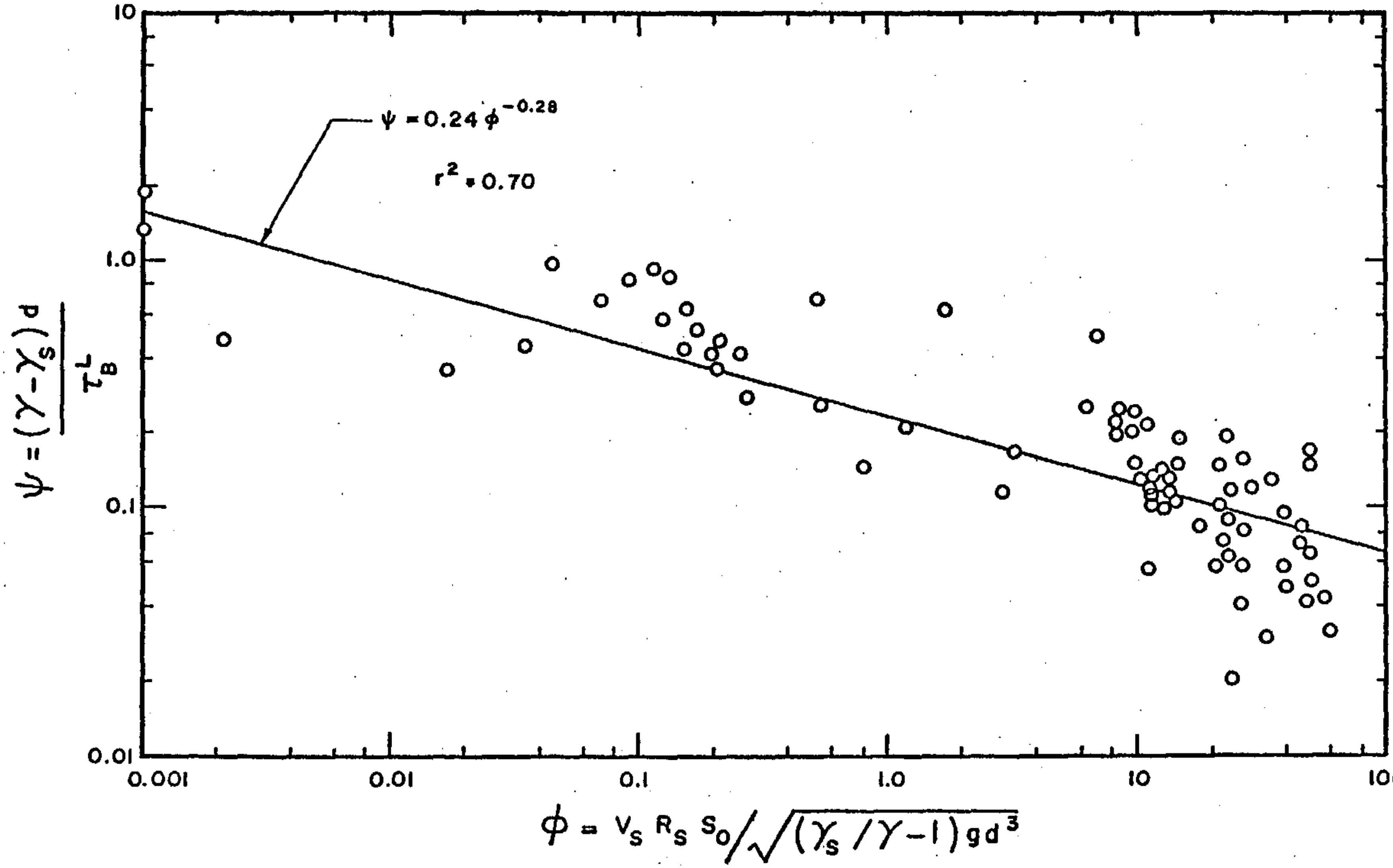


FIGURE 10: Graf's total bed material function as modified for suspended load using bed shear calculated from Li and Shen (Equation 16).

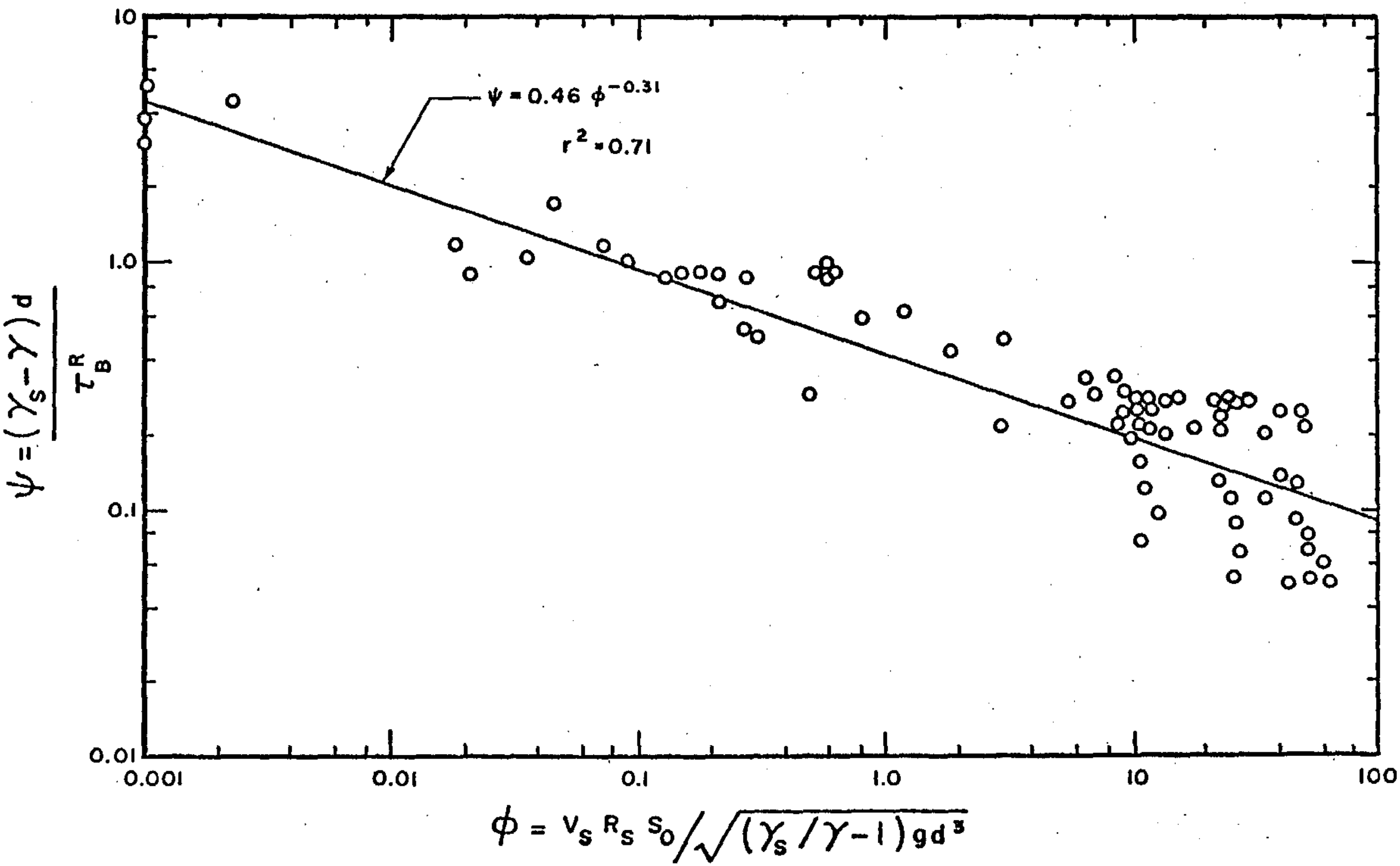


FIGURE 11: Graf's total bed material function as modified for suspended load using bed shear calculated from spacing hydraulic radius (Equation 19).

appears to be little difference in the correlation between the two parameters when either equation (16) or (19) is used to calculate the bed shear. Since equation (19) is much the simpler of the two, it is the recommended procedure. The functional relationship using equation (19) for bed shear is

$$\psi_G = 0.46 \; (\phi_S^G)^{-0.31} \tag{22}$$

with an r value of 0.84.

Einstein's Method

Bed Load parameters proposed by Einstein (1942) were also evaluated as predictors of suspended load. The shear intensity parameter is the same as that of Graf, or

$$\psi_E = \psi_G = \frac{(\gamma_s - \gamma) d}{\tau_B} \tag{23}$$

Einstein's transport parameter as modified for suspended load is

$$\phi_S^E = \frac{S_o Q \gamma_s}{\gamma W} \Bigg/ \sqrt{\frac{(\gamma_s - \gamma)}{\gamma} \; g d_f^3} \tag{24}$$

A plot of ϕ_s^E versus ψ_E is shown in Figure 12 using bed shear as calculated from hydraulic radius in equation (19). The functional relationship is

$$\psi = 0.73 \; (\phi_S^E)^{-0.49} \tag{25}$$

with a correlation coefficient of 0.80. This is slightly below that of equation (21) for the Graf et al parameters.

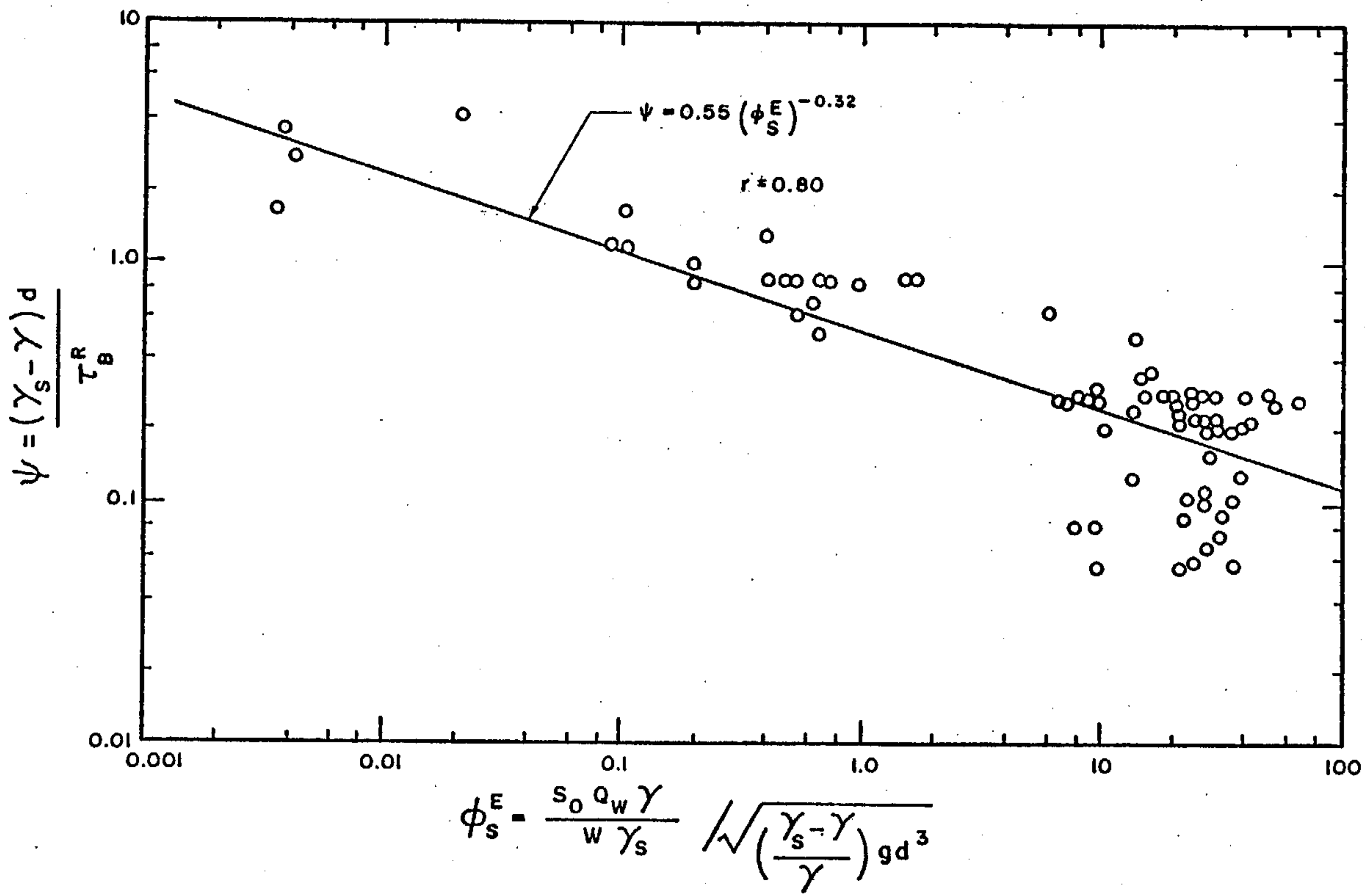


FIGURE 12: Einstein's bed load function as modified for suspended load in a rigid grass media.

A latter procedure proposed by Einstein (1950) for TBMF was not evaluated since it was not possible to determine some of the input parameters.

Summary and Conclusions on Total Bed Material Functions as Predictors of Suspended Load in Rigid Grass Media.

The total bed material functions parameters of Einstein (1942) and Graf et al (1968) utilizing shear intensity as an independent parameter were evaluated as predictors of steady state suspended sediment transport grass filters. Shear on the channel bottom was predicted both by a method proposed by Li and Shen (1973) and by a method using the spacing hydraulic radius. Both the Graf et al parameters and the Einstein parameter were good predictors of suspended sediment transport. The Graf et al parameters were slightly superior to those of Einstein. The correlation coefficient between the Graf et al parameters was approximately the same for both methods of predicting bottom shear. Since the method based on the hydraulic radius is the much simpler relationship, it is the recommended one.

CHAPTER IV

ANALYSIS OF BED LOAD

Method of Analysis

Bed load transport rate per unit width of stream, q_B, was measured for each of the tests summarized in the Appendix by dividing the total material trapped in the bed load trap by the total time of each test and the width of the channel. This data along with the hydraulic data for each test was used to evaluate the parameters of Graf et al (1968) and Einstein (1942) as predictors of bed load in a rigid grass media.

Analysis of Graf's Parameters

The shear intensity parameter is the same as that given by equation (20). The transport parameter as modified for bed load is

$$\phi_B^G = \frac{q_B \; W \; V_s \; R_s}{\gamma_s \; Q_W} \Bigg/ \sqrt{\frac{(\gamma_s - \gamma)}{\gamma} \, g d^3} \qquad (25)$$

where q_B is the bed load sediment transport rate per unit width of channel and other terms as previously defined.

Using the data summarized in the Appendix, a relationship between ϕ_B^G and ψ was determined by regression to be

$$\phi_B^G = 0.505 \; \psi^{-1.11} \qquad (26)$$

with an r value of 0.77. A plot of the experimental data along with equation (26) is shown in Figure 13.

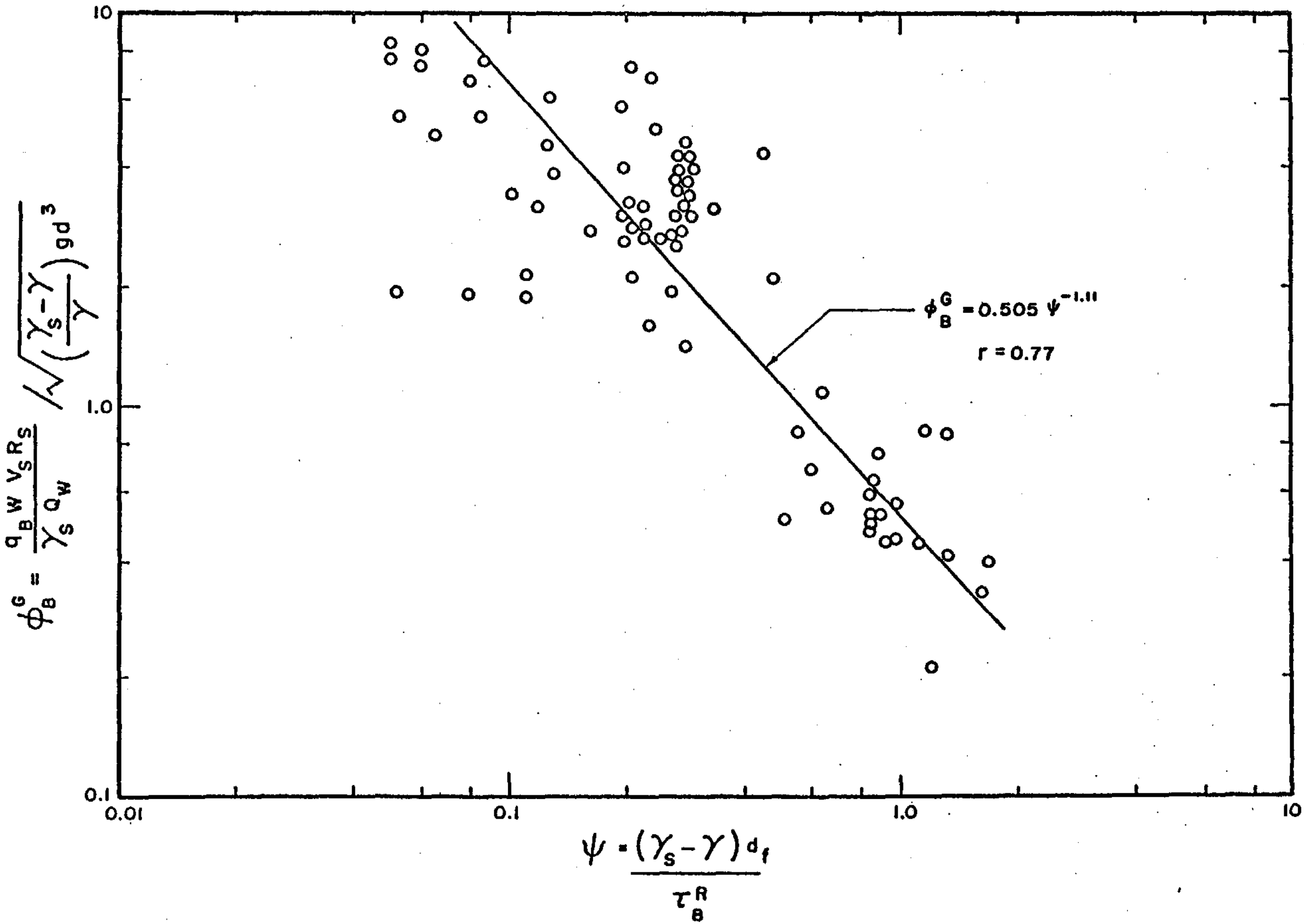


FIGURE 13: Graf's total bed material function as modified for bed load transport in a rigid grass media.

Analysis of Einstein's Parameters

As in the Graf et al parameters, Einstein's shear intensity parameter is the same as for suspended load given in equation (20). The transport parameter, ϕ_B^E for bed load is

$$\phi_B^E = \frac{q_B}{\gamma_s} \Bigg/ \sqrt{\frac{(\gamma_s - \gamma)}{\gamma} gd^3} \tag{27}$$

Using the data in The Appendix, the relationship between ψ and ϕ_B^E was determined by regression to be

$$\phi_B^E = 1.56\ \psi^{-1.355} \tag{28}$$

with an r value of 0.57. A plot of the experimental data along with equation (28) is shown in Figure 14.

Summary and Conclusion on Use of Bed Load Function for Predicting Bed Load in Rigid Grass Filters.

The total bed material function parameters of Graf et al and Einstein were evaluated as predictors of bed load transport in rigid grass filters when using the hydraulic radius technique equation (19) to predict shear on the bed. Both functions were reasonably good predictors of bed load. The parameters of Graf et al were clearly superior based on regression coefficients.

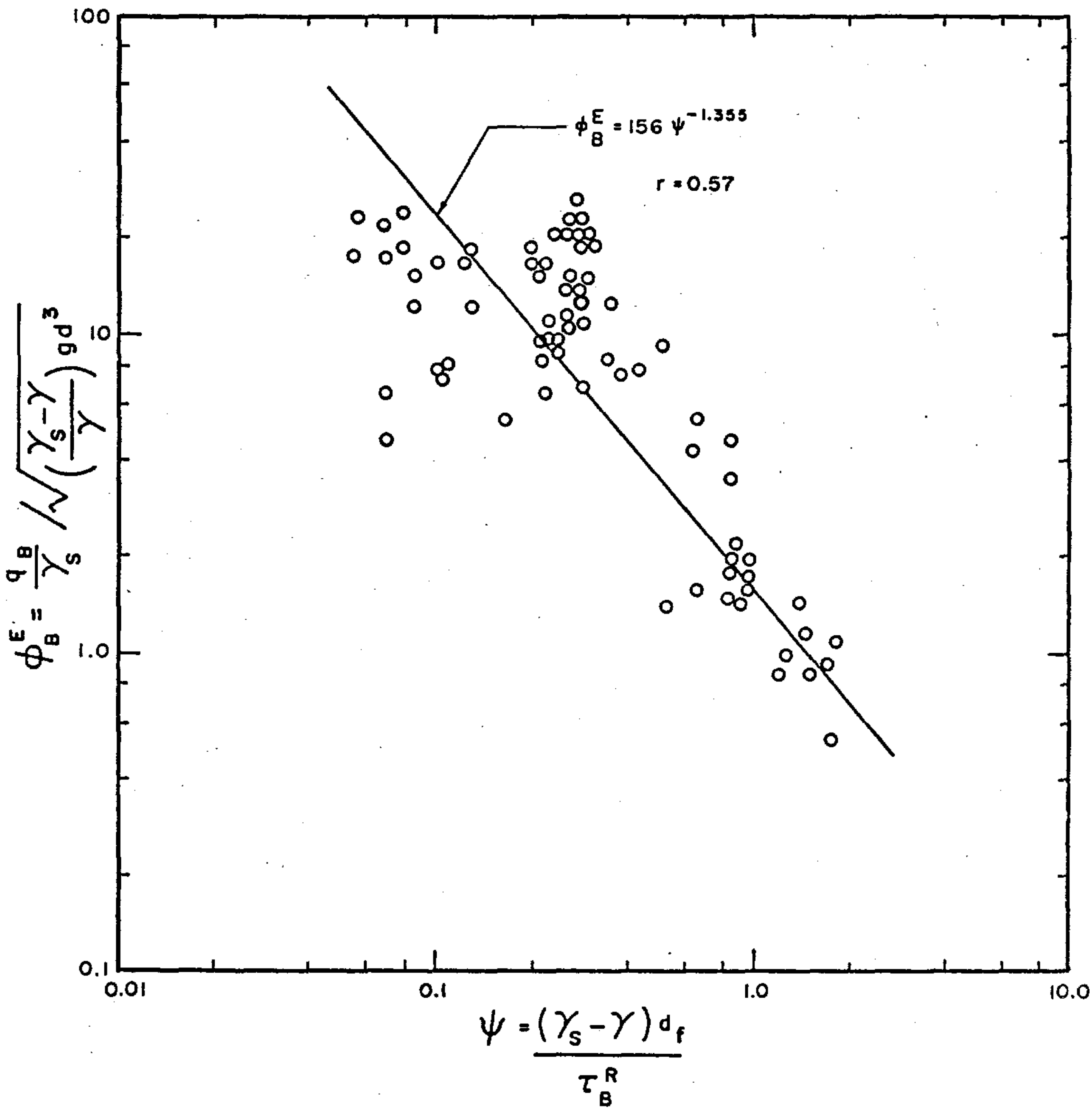


FIGURE 14: Einstein bed load function as modified for bed load transport in rigid grass media.

CHAPTER V

RECOMMENDATIONS AND CONCLUSIONS

The movement of sediment in non-submerged flow through a rigid grass media was studied experimentally by simulating the media with cylindrical nails. Analytical models of sediment movement were developed from probablistic reasoning and from the use of existing parameters describing total bed material transport in open channel flow. In both cases, functional relationships were developed between dimensionless parameters from experimental data.

Based on the results of the study reported herein, the procedures which follow are tentatively recommended for analyzing the trapping capability of sediment by grass filters in non-submerged flow when the flow rate and incoming sediment concentration are known:

1. Determine a characteristic spacing for the grass media.
2. Using the characteristic spacing and equations (5) and (10), calculate the flow depth d_f and flow velocity V_s.
3. Knowing the mean particle size, calculate the mean fall velocity.
4. During initial stages of flow, assume that the stools and bed roughness act as an effective bed load trap so that equation (15) can be used to predict the fraction trapped.
5. After sufficient deposition has occurred so that bed load transport has begun, the sediment transport capability of the grass filter can be analyzed from either equations (22) and (26) or equations (24) and (28). The fraction trapped would be the difference between incoming sediment load and the transport capability.

It should be pointed out that these procedures have only limited laboratory evaluation and no field evaluation. They should be used only as first order estimates. Further research is needed on the following questions to further enhance the results reported in this account:

1. How well can a given grass survive inundation?
2. What effect does the flexibility of real grass have on flow through the media?
3. At what point does the grass stop serving as an effective bed load trap?
4. How well does the assumption of a constant Manning's or in equation (10) represent a real grass?
5. How well does equation (19) predict bed shear?

NOTATION

A, B, C,	Regression coefficients
A_W	Cross sectional flow area
d_f	Flow depth
L_c	Characteristic length
L_T	Section length
n	Manning's roughness
N_f	Number of times a particle will fall to the bottom
Q_s	Sediment flow rate
Q_{sw}	Total flow rate
Q_w	Water flow rate
γ	Correlation coefficient
Re_T	Turbulent Reynolds Number
R_s	Spacing hydraulic radius
S	Slope
S_i	Input sediment conc. $\frac{\text{gms sed}}{\text{gm } H_2O}$
S_o	Outflow sediment conc. $\frac{\text{gms sed}}{\text{gm } H_2O}$
S_{os}	Output sediment conc. $[\frac{\text{gms sed}}{\text{gm}(H_2O + \text{Sed})}]$
S_s	Section spacing
T	General turbulence index
u'^2	RMS turbulent velocity
V_m	Settling velocity
ν	Kinematic viscosity
γ, γ_s	Weight density of water and sediment respectively
W	Width of channel
V_s	Mean flow velocity

C_D	Drag coefficient on an individual filter element
m	Number of filter elements per unit area
τ	Total drag on bed and filter elements
τ_B^L, τ_B^R	Drag on the bed calculated by Li and Shen method and by spacing hydraulic radius method
τ_g	Drag on the filter elements
γ	Weight density of water
R	Hydraulic radius
d	Diameter of sediment particle
ψ_G, ψ_E	Shear intensity function of Graf and Einstein respectively
ϕ_s^G, ϕ_s^E	Transport function of Graf and Einstein respectively for suspended load
q_B	Bed load sediment transport per unit width of channel
ϕ_B^G, ϕ_B^E	Transport function of Graf and Einstein respectively for bed load

Bibliography

Brandt, G. H. (1972) An Economic Analysis and Sediment Control Measures for Watershed Undergoing Urbanization. Final Report prepared for the Dow Chemical Co., Midland, Michigan, 181 pp.

Butler, R. M., E. A. Myers, N. N. Walter and J. V. Husted. (1974) Nutrient Reduction in Wastewater by Grass Filtration. Paper No. 74-4024 presented June, 1974 at the ASAE meeting in Stillwater, Oklahoma.

Davis, D. S. (1962) Nomography and Empirical Equations. Reinhold Publishing Co. New York.

Einstein, H. A. (1942) Formula's for the Transportation of Bed Load. Trans. ASAE, 107:561-577.

Einstein, H. A. (1950) The Bed Load Function for Sediment Transport in Open Channel Flows. USDA-SCS Technical Bulletin No. 1026.

Einstein, H. A. (1968) Deposition of Suspended Particles in a Gravel Bed. Proc. ASCE 94(HY5):1197-1205.

Environmental Protection Agency. (1972) Guidelines for Erosion and Sediment Control Planning and Implementation. EPA-R2-72-015. U.S. Environmental Protection Agency, Washington, D. C., 228 pp.

Fenzl, R. N. and J. R. Davis. (1962) Hydraulics Resistance for Surface Flows in Vegetated Channels. Trans. ASAE 7(1): 46-53, 55.

Graf, W. H. (1971) Hydraulics of Sediment Transport. McGraw-Hill Inc., New York.

Graf, W. H. and E. Acaroglu. (1968) Sediment Transport in Conveyance Systems (Part I) Bull. Interm Assoc. Sci. Hydr. XIII^{e} annee, No. 2.

Happel, J. and H. Brenner. (1965) Low Reynolds Number Hydrodynamics. Prentice-Hall, Inc., New York.

Hudson, N. (1971) Soil Conservation. Cornell University Press, Ithaca, New York.

Kouwen, N. (1970) Flow Retardance in Vegetated Open Channels. Doctoral Thesis presented at the University of Waterloo, College of Engineering. Waterloo, Ontario.

Li, R. M. and H. Shen (1973) Effect of Tall Vegetation on Flow and Sediments. Proc. ASAE 99(HY5):793-814.

Nordin, C. F. and G. R. Dempster. (1963) Vertical Distribution of Velocity and Suspended Sediment; Middle Rio Grande and New Mexico River. U. S. G. S. Prof. Paper 462-B.

Ree, W. O. (1949) Hydraulic Characteristics of Vegetation for Vegetated Waterways. Agric. Engr. 30(4): 184-189.

Robinson, A. R. (1971) Sediment. Agric. Engr. 53(8):406-413.

Tollner, E. W. (1974) Modeling the Sediment Filtration Capacity of Simulated Rigid Vegetation. Unpublished Masters Thesis, Dept. of Agric. Engineering, University of Kentucky, Lexington, Kentucky.

Wilson, L. G. (1967) Sediment Removal from Flood Water. Trans. ASAE 10(1):35-37.

A P P E N D I X   A

DATA SUMMARY

TABLE A-1

DATA SUMMARY

Test	Velocity	Flow Depth	Nail Spacing	Slope	Length	Sed. Size	Fall Velocity	Input Conc.	Output Conc.	Bed Load	Profile*
		cm/sec	cm		cm	cm	cm/sec			gms/sec.cm	
1	39.01	2.21	1.583	0.143	210.0	0.045	7.31	.0601	0.0066	1.527	1
2	42.60	2.17		0.143	140.0			.0630	.0051	1.938	1
3	43.70	2.13		0.143	100.0			.0699	.0065	1.810	1
4	20.92	4.06		0.039				.0626	.0052	1.402	0
5	36.53	2.52		0.090				.0844	.00006	---	0
6	40.82	2.10		0.143				.0711	.0073	1.387	1
7	43.00	1.92		0.192				.0431	.0089	1.494	1
8	45.89	1.86	1.583	0.245	100.0			.0546	.0108	1.401	1
9	27.23	3.75	0.945	0.143	210.0			.0617	---	---	0
10	17.48	5.92	0.945	0.039	210.0			.0861	.0015	1.402	0
11	32.73	2.67	1.263	0.143	100.0			.0683	.0021	1.857	1
12	35.70	2.23	1.583					.0716	.0062	1.752	1
13	23.17	0.46						.0747	.00010	0.501	1
14	25.54	1.00						.0871	.0062	0.811	1
15	38.26	1.33						.0466	.0049	1.248	1
16	40.22	2.28						.0597	.0087	1.627	1
17	70.47	1.87						.0652	.0148	2.100	1
18	39.86	2.35						.0681	.0094	1.708	1
19	39.00	2.31						.0701	.0115	1.468	1
20	44.92	2.04	1.583	0.143	100.0			.1427	.0208	3.417	0
21	23.82	1.76	1.263	0.090	140.0			.1202	.0042	1.059	0
22	18.20	2.65	1.263	0.039	210.0			.0398	.0001	0.034	0
23	28.55	2.50	1.583	0.143	100.0			.177	.0336	4.555	0
24	17.07	1.81	0.945	0.039	210.0			.1623	.00007	---	0
25	12.70	5.93	0.945	0.039	210.0	0.045	7.31	.214	.0004	0.007	0

*1=no profile present

0=profile present

*1 - deposition did not alter the channel slope.
0 - deposition altered the channel slope.

TABLE A-1 (CONT'D)

Test	Velocity	Flow Depth	Spacing	Slope	Length	Sed. Size	Fall Velocity	Input Conc.	Output Conc.	Bed Load	Profile
26	60.03	1.38	1.583	.246	100	0.02	3.0	.0270	.0192	0.240	1
27	23.41	1.98	1.263	.070	140			.0295	.0139	0.277	1
28	27.38	1.71		.090	100			.0577	.0367	0.562	1
29	27.63	1.71		.090	140			.0575	.0374	0.472	1
30	27.40	1.71		.090	210			.0583	.0357	0.442	1
31	31.92	1.49		.143	140			.0553	.0393	0.382	1
32	26.88	1.79		.090				.0568	.0365	0.457	0
33	15.28	2.79		.039				.0578	.0215	0.480	0
34	35.54	1.32		.192				.0544	.0390	0.412	1
35	42.67	1.07		.246				.0516	.0398	0.390	1
36	31.75	1.26	1.263	.090				.0506	.0366	0.345	1
37	27.80	1.76	1.583	.090	140			.0571	.0380	0.465	1
38	27.26	2.50	1.263	.039	210			.0589	.0337	0.600	0
39	13.22	3.82	0.945	.090	210			.0666	.0075	0.240	0
40	27.97	1.77	0.945					.0602	.0405	0.480	1
41	27.23	1.05	1.263					.0577	.0352	0.382	1
42	21.83	0.42						.0599	.0166	0.292	1
43	27.94	2.99						.0594	.0418	0.645	1
44	31.80	4.14						.0590	.0408	0.825	1
45	20.14	4.37						.0623	.0420	0.495	1
46	29.68	3.11	1.263	.090	140			.0852	.0735	0.975	0
47	12.74	2.80	0.945	.039	210	0.02	3.0	.0914	.0123	0.277	0

TABLE A-1 (CONT'D)

Test	Velocity	Flow Depth	Spacing	Slope	Length	Sed. Size	Fall Velocity	Input Conc.	Output Conc.	Bed Load	Profile
48	45.90	2.13	1.583	.143	100	0.0027	0.067	.0285	.0246	.097	1
49	14.04	2.50	0.945	.039	210			.0283	.0196	.092	0
50	14.05	2.44	0.945		210			.0560	.0280	.160	0
51	17.63	3.18	1.263		140			.0360	.0300	.159	1
52	14.37	2.30	0.945		210			.0570	.0400	.265	0
53	13.57	2.51			210			.0530	.0390	.225	0
54	12.57	2.42			100			.0530	.0440	.229	0
55	13.10	2.57			140			.0520	.0410	.224	0
56	13.79	2.43		.039	210			.0530	.0400	.234	0
57	23.22	1.31		.143				.0540	.0490	.214	1
58	20.33	1.61		.090				.0480	.0430	.207	1
59	12.81	2.52		.039				.0470	.0340	.229	1
60	27.91	1.22		.192				.0480	.0440	.184	1
61	28.91	1.09	0.945	.246				.0480	.0420	.195	1
62	19.45	1.62	1.583	.039				.0590	.0520	.179	0
63	17.71	1.83	1.263					.0570	.0420	.190	0
64	13.22	2.53	0.945					.0490	.0330	.199	0
65	13.32	4.21						.0440	.0310	.213	0
66	11.51	1.04						.0470	.0260	.113	0
67	19.92	4.73		.090				.0560	.0440	.252	0
68	25.06	5.72	0.945	.090	210	0.0027	0.067	.0490	.0470	.276	1

TABLE A-1 (CONT'D)

Test	Velocity	Flow Depth	Spacing	Slope	Length	Sed. Size	Fall Velocity	Input Conc.	Output Conc.	Bed Load	Profile
69	12.5	2.31	0.945	0.039	210	0.0027	0.067	.1017	.0749	0.300	0
70	13.8	2.44		0.039	140			.1053	.0792	0.315	0
71	12.6	2.36		0.039	100			.1007	.0872	0.316	0
72	19.2	1.52		0.090	210			.1017	.0880	0.277	1
73	23.1	1.21		0.143				.1009	.0890	0.301	1
74	26.9	1.05		0.192				.0973	.0872	0.282	1
75	29.5	1.00	0.945	0.246				.0914	.0824	0.281	1
76	13.8	1.44	1.583	0.039				.0933	.0776	0.254	0
77	16.0	1.65	1.263					.1119	.0990	0.304	1
78	13.4	3.27	0.945					.0860	.0650	0.315	0
79	12.9	3.34			210			.0955	.0650	0.322	0
80	13.1	3.28			100			.0897	.0720	0.359	0
81	11.7	3.38		0.039	210			.0968	.0706	0.356	0
82	23.6	1.83		0.143				.0990	.0850	0.366	1
83	20.8	2.13		0.090				.0920	.0810	0.272	1
84	27.1	1.51		0.192				.0970	.0830	0.340	1
85	30.4	1.46		0.246				.0973	.0836	0.349	0
86	12.0	2.39		0.039				.0969	.0671	0.253	1
87	10.2	0.95		0.039				.0950	.0395	0.124	0
88	15.8	5.96	0.945	0.039	210	0.0027	0.067	.1040	.0870	0.395	1