PRELIMINARY
SUBJECT TO REVISION

SEDIMENT DISCHARGE IN IRRIGATION CANALS[a]

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SYNOPSIS

Generally, sand-bed canals operate in the lower flow regime with a bed roughness of ripples, ripples superposed on dunes or dunes. Within this regime the resistance to flow is large, average velocities are small, bed material discharge is small, and banks are relatively stable. Knowledge of the regimes of flow and forms of bed roughness can be used with permissive velocities, the tractive force theory, regime concepts or modified regime concepts to determine the geometry of sand-bed canals. Similarly, knowledge of the mechanics of flow can be utilized with bed material discharge concepts to estimate the bed-material discharge of canals. The sediment carrying characteristics of the canal determine the quality and quantity of the sediment that can be allowed to enter the canal from the river and this affects the design of the diversion and sediment exclusion and ejection structures. As a part of the problem the characteristics of the bed material in a river or canal vary with distance. In canals and rivers a sorting process takes place that causes a reduction in the size of the bed material with distance downstream which causes a change in channel geometry. In summary, the design of functional sand bed channels should utilize knowledge of the mechanics of flow including relations for determining channel geometry, bed material discharge, and certain concepts from fluvial morphology.

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INTRODUCTION

The success or failure of a sand-bed canal is dependent on several factors but predominately upon its ability to transport the required quantity of water and sediment with minimum scour and deposition. In order to design such a channel it is necessary to consider the mechanics of flow of water and sediment in alluvial channels, fluvial morphology and specific design concepts.

THE MECHANICS OF FLOW IN SAND-BED CHANNELS

In a sand-bed channel the interaction of the fluid and the bed at their interface generates different roughness elements depending on many inter-related variables such as the median fall diameter of the bed material, depth of flow, average velocity, and the characteristics of the water-sediment liquid. A useful parameter that is a good indicator of the form of bed roughness for a particular bed material is the stream power $\tau_o V$, where $\tau_o = \gamma DS$ approximates the tractive force on the bed for wide channels, and V is the average velocity of flow.

The major forms of bed roughness that develop on the bed of sand channels in order of occurrence with increasing stream power are: ripples, ripples superposed on the backs of dunes, dunes, a transition range of stream power within which the form roughness changes from dunes to plane or flat bed, plane bed, standing waves and antidunes.

The bed roughnesses are subdivided into a lower regime and an upper regime of flow that are joined by a transition region. The classification of a bed form by regime is based upon the concentration of bed material, the mode of transport, the water-surface bed-phase relation and the resistance to flow. The regimes of flow, bed forms and associated flow phenomena are summarized in Fig. 1.[3] In Fig. 1 the bed material concentration is computed on a dry weight basis. Movement of sediment by discrete steps means that the bed load travels up the back of the ripples or dunes and slides and rolls down their avalanche faces where it is stored temporarily until uncovered by subsequent downstream movement of the roughness elements. Continuous movement implies continuous motion of the bed material at the sand-water interface but individual particles may still move intermittently. Out of phase means that the bed configurations and the undulations of the water surface over them are out of phase as for tranquil flow over a sill or broad-crested weir.[4] The total resistance to flow results from the combined effect of grain roughness and form roughness. When the bed roughness is ripples and/or dunes the resistance to flow results from both form roughness and grain roughness and resis tance to flow is relatively large. When the bed is plane, and for mildly active

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[3] Simons, D. B., Richardson, E. V. and Nordin, C. F., 1964, Sedimentary structures generated by flow in alluvial channels. Presented at the 38th Annual Meeting, Society of Economic Paleontologists and Minerologists, Tronto, Canada, May 18.

[4] Rouse, H., 1946, Elementary mechanics of fluids, John Wiley and Sons, Inc.

standing waves and antidunes the resistance to flow is small and is largely caused by a rolling grain roughness which is less than the static grain roughness.

The bed roughness and resistance to flow for a canal or river is usually more complex than implied by the preceding discussion. When depth of flow, channel slope and velocity vary with position in the channel, bed configurations differ from one area to another, and one type of roughness will blend into the other. This is particularly true of rivers because of greater variations in the cross section and slope of channel and the correspondingly large variations in the stream power $\tau_o V$.

Other bed forms of significance which occur in sand-bed canals and rivers are the large middle, point and alternate bars. In canals both point bars and alternate bars are common. The point bars form along the inside or convex banks of curves of all sand bed channels which transport bed material. When these bars are removed by dredging or other methods they are soon re-deposited by the flow. The rate at which these bars develop indicate that an efficient sediment ejector can be designed by locating a structure under that portion of the bed where the point bar forms for periodic flushing of the point bar to the river or for continuous flushing to the river of the bed material carried to the point bar area by the flow.[5]

The alternate bars are those sand bars that form adjacent to the bank on one side of the straight channel and then on the other in a staggered pattern. These bars may be as wide as half the main channel and have lengths equal to two or more channel widths. In properly designed canals flowing at or near

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[5]Karaki, S. S., and Haynie, R. M., 1962, Model investigation of the silt excluder system for the Trimmu-Sidhnai Link, Colorado State University Report CER62SSK58.

design discharge the bars may cover large areas of the bed and will have ripples and dunes superposed on them but the bars are small in amplitude, perhaps smaller than the average amplitude of the dunes, so that they are difficult to detect. But as discharge is decreased, increasing the width-depth ratio of the channel these alternate bars increase in amplitude until their surfaces may be exposed at the water surface by their growth and changes in the geometry of the cross-section. These bars temporarily store some of the bed material, particularly the finer fractions and cause the flow to meander around them, deflecting the flow into the bank first on one side of the channel and then on the other causing greater bank instability and bank irregularities and perhaps meandering. The growth of these bars during low flow and the flushing downstream of these bars at high flow is part of the hydraulic sorting mechanism which causes the median diameter of the sand bed of a channel to decrease with distance downstream, a problem that will be discussed later.

PREDICTION OF BED CONFIGURATION

Resistance to flow, channel stability, and bed material discharge are related to form or forms of bed roughness. One of the most useful relations for predicting the form of bed roughness is given in Fig. 2, which relates stream power, median fall diameter of bed material and form of bed roughness. The relation is based upon flume, canal and river data.[6,3] All three types of data verify the relation within useful limits. Note that ripples do not usually occur when $d > 0.65$ mm and that the range of stream power $\tau_o V$ within

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[6] Simons, D.B., Richardson, E.V., 1963, A study of the variables affecting flow characteristics and sediment transport in alluvial channels. Presented at the Federal Inter-Agency Sedimentation Conference, Jackson, Miss. Jan. 28 - Feb. 1.

[3] Ibid.

which dunes develop decreases as the fall diameter of the bed material decreases. In fact with fine sand $d < 0.2$ mm, it is difficult to establish flow conditions that will cause dunes because of the narrow range of flow conditions and stream power which favor dune development.

The fall diameter and the fall velocity of bed material vary with temperature and concentration of fine sediment. This is illustrated by Figs. 3 and 4.[3,7] Figure 3 shows the variation of viscosity of water and fine sediment with temperature and Fig. 4 shows the variation of fall velocity of bed material with concentration of bentonite at constant temperatures for sands I, II_2 and III_3 which have median fall diameters of 0.19, 0.27 and 0.47 mm respectively at 24°C. Using Fig. 4 consider the 0.27 mm bed material, sand II_2. It has a fall velocity of 4.0 cm per sec in clear water but will have a fall velocity of only 0.9 cm per sec with a wash load concentration of 100,000 ppm bentonite. It can be concluded from Figs. 2, 3, and 4 that changes in temperature and/or concentration of wash load can change the fall velocity and hence the fall diameter of the bed material sufficiently to change the form of bed roughness, the resistance to flow, and in some cases the regime of flow. Also, the presence of fine sediment is necessary for berms to form in canals. The development of berms of fine material significantly increases the bank stability, reduces the seepage of water through the banks and in many instances may reduce the seepage through the bed.

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[3] Ibid.

[7] Simons, D. B., Richardson, E. V., and Haushild, W. H., 1963, Studies of flow in alluvial channels, some effects of fine sediment on flow phenomena. U.S. Geological Survey, WSP 1498G.

FORM OF BED ROUGHNESS IN STABLE SAND-BED CANALS

To assure that sand-bed canals will have a reasonable degree of stability it is, in general, essential to design them to operate in the lower flow regime where the most usual bed configurations are ripples superposed on dunes or dunes. In this regime the dimensionless Chezy coefficient $C/\sqrt{g}$ ranges from as small as 7.75 to 13.90 and Manning's n ranges from about 0.02 to 0.035 for ripples and dunes. The average velocity in stable sand bed canals is relatively small ranging from about 0.45 to 1.0 mps or 1.5 to 3.28 fps. When the velocities are smaller than 0.45 mps (1.5 fps) the canal may operate satisfactorily excluding problems of possible aquatic growth but can only carry a small bed-material discharge. When canals are designed to flow at velocities in excess of 0.92 mps (3 fps) one should refer to Fig. 2 to verify that the flow will be in the lower regime. With velocities in excess of 0.92 mps there is always the danger of a sufficiently large stream power to cause upper regime flow with a plane bed. This may be serious because with the change in form of bed roughness and regime of flow there will be a relatively large reduction in resistance to flow, a large increase in the average velocity, a large increase in the bed material discharge capability and the resultant higher velocity may erode the banks. However, there may be exceptions to the foregoing. It should be emphasized that the average velocity and the stream power at which flow changes from the lower to the upper regime is small when the median fall diameter of the bed material is small. Similarly the Froude number at which the shift in regime occurs becomes smaller as the bed material becomes smaller. To illustrate, a shift from lower to upper regime can occur at a Froude number as small as 0.21 - 0.30 when $d \leqq 0.20$ mm. If the average velocity in a channel flowing in the upper regime is relatively small and the banks are sufficiently resistant to erosion it is possible to have a stable channel in the upper regime but this situation is more the exception than the rule.

THE GEOMETRY OF STABLE CHANNELS

Some of the most common methods of determining the geometry of stable, sand-bed canals include:

1. Permissible velocities
2. Tractive force
3. Regime concepts
4. Modified regime concepts

An excellent summary of permissible velocities for various design conditions was presented by Lane.[8] The development and application of the tractive force method was presented in the same reference. Most of the regime concepts were summarized in an ASCE task committee report on resistance to flow in open channels.[9] More recently modified regime concepts have been presented by Simons and Albertson[10] and Henderson[11]. Still more recently two reports

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[8] Lane, E. W., 1955, Design of stable channels, Trans. of ASCE, Vol. 120.

[9] ASCE Task Committee, 1963, Friction factors in open channels, Journal of the Hyd. Division, Proceedings of ASCE, HY2.

[10] Simons, D. B. and Alberston, M. L., 1963. Uniform water conveyance channels in alluvial material, Trans. of ASCE, Vol. 128, Part 1.

[11] Henderson, F. M., 1963. Stability of alluvial channels, Trans. of ASCE, Vol. 128, Part 3.

on resistance to flow have been completed which advance the concept of working with equivalent plane bed or smooth boundary channels.[6,12]

A summary of the most common equations used to design stable channels in alluvium is presented in Table 1.

[6] Ibid.

[12] Simons, D. B. and Richardson, E. V., 1964. Resistance to flow in alluvial channels, U.S. Geological Survey Professional Paper. In press.

TABLE 1. EQUATIONS TO ESTIMATE CHANNEL GEOMETRY

	Engineer	Date	Equations	References
1.	Chezy	1769	$V = \left(\frac{C}{\sqrt{g}}\right) \sqrt{gRS}$	Fluid Mechanics Texts
2.	Manning	1889	$V = (1.486/n)\ R^{2/3}\ S^{1/2}$	Fluid Mechanics Texts
3.	Kennedy	1895	$V = K_c\ D\ Km$	1. Lacey, Gerald, 1958. Flow in alluvial channels with sandy mobile beds. Institute of Civil Engineers, London.
			K_c ranges from 0.39-0.84	
			Km ranges from 0.52-0.73	
4.	Lindley	1919	$V = 0.95\ D^{0.57}$	
			$V = 0.57\ B^{0.36}$	(1)
			$B = 3.8\ D^{1.61}$	
5.	Khannaq	1920	$V = 0.0216RS$	(1)
6.	Beleida	1921	$V = 0.02808RS$	(1)
7.	Malakal	1921	$V = 0.046RS$	(1)
8.	Lacey	1929-58	$V = 1.17\ f^{1/2}\ R^{1/2}$	
			$f = 0.73\ V^2/R$	
			$P = 2.67\ Q^{1/2}$	
			$V = \text{Constant}\ R^{0.619}\ S^{0.357}$	(1)
			$V = 16\ R^{2/3}\ S^{1/3}$	
			$A = 1.26\ Q^{5/6}/f^{1/3}$	
			$R = 0.47\ Q^{1/3}/f^{1/3}$	

TABLE 1. EQUATIONS TO ESTIMATE CHANNEL GEOMETRY (cont'd)

Engineer	Date	Equations	References
9. Bose	1936	$V = 1.12\ R^{1/2}$ $S = 2.09 \times 10^3\ d^{0.86}/Q^{.21}$ $A = PR$ $P = 2.8\ Q^{1/2}$ $R = 0.47\ Q^{1/3}$	"Friction factors in open channels" p. no. 3464, Jour. of Hyd. dn. Proc. ASCE, Vol. 89, No. HY2, March 1963.
10. Malhotra	1939-40	$V = 18.18\ R^{0.632}\ S^{0.343}$	(1)
11. Blench	1939-60	$V = \sqrt[6]{F_b F_s Q}$ $B = \sqrt{F_b\ Q/F_s}$ $D = \sqrt[3]{F_s Q/F_b^2}$ $S = F_b^{5/6}\ F_s^{1/12}/(1 + \frac{C}{233})\ KQ^{1/6}$ Bed factor $F_b = V^2/D$ Side factor $F_s = V^3/B$ $K = 3.63\ g/\nu^{1/4}$	Comrie, J., 1961, Civil Engineering Reference Book, Second Edition, Butterworth and Co., Ltd., 88 Kingsway, London.
12. Leliavsky	1955	$V = TR^{0.85}\ S^{0.72}$ $T = \left[147 + 3.92\ (z - 10)^{0.383}\right]$	Leliavsky, S., 1955, An introduction to fluvial hydraulics, Constable and Co., Ltd.

TABLE 1. EQUATIONS TO ESTIMATE CHANNEL GEOMETRY (cont'd)

Engineer	Date	Equations	References
13. Ning Chien	1955	$V^2/R = C\,(q_t/q)^{1/2}$ $(R^{1/2}S)^{2/3} = C\,(q_t/q)^{1/6}$ q_t = Sediment load per unit width q = Discharge per unit width	Ning Chien, 1955, A concept of Lacey's Regime Theory, Am. Soc. of Civil Engineers, Sep. No. 620.
14. Inglis-Lacey	1958	$W_s \; \alpha \; Q^{1/2} I^{1/4}/g^{1/4} m^{1/4}$ $A \; \alpha \; Q^{5/6} I^{-1/12}$ $S \; \alpha \; Q^{-1/6} I^{5/12} g^{1/12} m^{5/12}$ $V \; \alpha \; g^{1/2} D\, S/Em^{1/2}$ $V^3/W_s \; \alpha \; g^{3/2} m^{1/2}$ $V^2/gD \; \alpha \; I^{1/2}$ Inglis No. $I = XV_s/(\nu g)^{1/3}$ $E = P/W_s = D/R$	(1)
15. Liu and Hwang	1959	$V = C_a R_b^{\,x} S^y$	Liu, H. K. and Hwang, S. Y., 1959, A discharge formula for flow in straight alluvial channels, ASCE Trans. Paper No. 3276.

TABLE 1. EQUATIONS TO ESTIMATE CHANNEL GEOMETRY (cont'd)

Engineer	Date	Equations	References
16. Kansoh	1960	$V = 0.56\ D^{0.64}$, fps $V = 0.36\ D^{0.64}$, meters/sec $B = 2.383\ Q^{0.50}$ $D = 0.531\ Q^{0.361}$ for sand beds and cohesive banks $D = 0.305\ Q^{0.361}$ for coarse non-cohesive materials.	2. Discussion on "Uniform water conveyance channels in alluvial material", Simons, D.B. and Albertson, M.L., Paper no. 3399, Trans. ASCE, Vol. 128, 1963, Part 1.
17. Ghaleb	1960	$V = 284\ D^{.727}$, metric units	(2)
18. Jareki	1960	V_b = competent bottom velocity $V_b = 0.645\ d^{4/9}$, fine materials $V_b = 0.518\ d^{1/2}$, coarse material	"Design of stable channels with tractive forces and competent bottom velocity" Sedimentation section, Hydrology Branch, Dn. of Proj. Invest., Bureau of Reclamation, Denver, Colo. March 1960.
19. Sethna	1962	$V = \frac{66.5}{m^{0.1}}\sqrt{RS}$, bed material moving $V = \frac{2525}{m^{0.2}}\ RS$, bed material not moving $S = 0.52\ f^{0.6}/Q^{0.2}$ $f = \frac{G/L}{8.95 m^{0.2}}$ G/L = grams/liter of silt charge	"Uniform flow of water in alluvial channels" Sethna, T.R., Paper No. 6524, Proc. Intsn. Civ. Engrs., vol. 21, Jan. 1962.

TABLE 1. EQUATIONS TO ESTIMATE CHANNEL GEOMETRY (cont'd)

Engineer	Date	Equations	References
20. Ahmad and Rehman	1963	$S = K_2 f^{5/3} / Q^{1/6}$ $K_2 = 0.45 \times 10^{-3}$ to 0.7×10^{-3} $S = K_3 f^{5/3} / q^{1/3}$ $K_3 = 0.35 - 0.42$ $f = K_4 \sqrt{d}$ $K_4 = 1.1 - 3.0$ $K_{4ave} = 1.9$ $b = K_1 Q^{1/2}$ $K_1 = 2.67 - 3.90$ as $Q/Q_o = 1$ to 0.4 Q_o = design discharge	"Appraisal and analysis of new data from alluvial canals of West Pakistan in relation to regime concepts and formulae," Ahmad, M., and Rehman, A., West Pakistan Engineering Congress, Oct. 1963.
21. Simons and Albertson	1963	Regime type relations modified to include the type of bank material and bed material concentration.	Simons, D.B., and Albertson, M.L., 1963, Uniform water conveyance channels in alluvial material, Trans. ASCE, Vol. 128, Part 1.

TABLE 1. EQUATIONS TO ESTIMATE CHANNEL GEOMETRY (cont'd)

Engineer	Date	Equations	References
22. Anding	1964	Applicable to Mississippi River cross-sections $V = K_v \sqrt{f R}$ $V = K_r R^{2/3} S^{1/3}$ $S = f^{5/3}/1750 Q^{1/6}$ $f = 8\sqrt{d}$ $P = 2.67 Q^{1/2}$ K_v and K_r = varying empirical constants. d = grain size in inches	Written communication on "Potamology studies - Mississippi River - Hydraulic Analysis of Channel Characteristics - etc." Anding, M.G., U.S. Army Engr. Dist., Vicksburg, Mississippi.

CHANNEL DESIGN RELATIONS THAT INCLUDE A SEDIMENT TERM AS A VARIABLE

Several equations, particularly recent ones, proposed for designing stable channels contain a bed-material discharge term. This is one possible way of considering bed material discharge. For example, Inglis[13] included a sediment concentration term in each of his qualitative regime equations, see Table 1. Blench[14] included a sediment concentration term in one of his slope equations which in functional form states that

$$S = f(F_b, F_s, Q, S, C, \nu) \qquad (1)$$

Carl R. Miller and other U. S. Bureau of Reclamation personnel developed a velocity relationship which in functional form assumes that for a sand-bed canal

$$V = f(Q, C_s, S, \omega) \qquad (2)$$

Subsequent experimentation with Eq. 2 yielded

$$V = 3.64 Q^{0.24} C_s^{0.16} S^{0.18} \omega^{0.47} \qquad (3)$$

The writers tested this relation by comparing the computed average velocity in mps with the measured average velocity for the field data collected from large canals in West Pakistan by Tipton and Kalmbach, Inc., Denver, Colorado, Harza International and others[15].

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[13] Lacey, G., 1958, Flow in alluvial channels with sandy mobile beds, The Institution of Civil Engineers, London.

[14] Blench, T., 1964, River engineering, Dept. of Civil Engineering, University of Alberta, Edmonton.

[15] West Pakistan Water and Power Development Authority and Participating Agencies, 1963, Canal and headworks data observation programme - 1962 data tabulation, Released by Harza Engineering Co., International.

Figure 5 shows a plot of computed versus measured average velocities for the West Pakistan Canals. Considering full supply conditions the computed velocity is within about 25 percent of measured for most of the canals. For about 90 percent of the canal observations the concentration of suspended bed material greater than 0.062 mm in diameter, ranged from 25 to 850 ppm in the West Pakistan canals. Considering extremes two canals carried approximately 1200 ppm of suspended bed material. Referring to Eq. 3 a 10 percent variation in the concentration of suspended bed material will cause only a 1.6 percent change in estimated average velocity. Hence, the equation is insensitive to variations in the concentration of bed material.

Utilizing the West Pakistan canal data, other canal data and flume data Harza Engineering[16] developed a relation which states that

$$\left(\frac{q}{\omega}\right)^{1/2} S = f(C) \tag{4}$$

The foregoing relation is similar to one published by Mushtaq Ahmad and A. Rehman[17] that is based upon a large amount of data from flumes, canals and rivers. They stated that

$$C = \phi\left(\frac{q^{2/3} S}{\sqrt{\omega}}\right)$$

and that

$$\frac{q^{2/3} S}{\omega^{1/2}} = 1 + 5C^{2/3} \tag{5}$$

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[16] Harza Engineering, Written communication on canal design.

[17] Ahmad Mushtaq and Rehman, A., 1962, Appraisal and analysis of new data from alluvial canals of West Pakistan in relation to regime concepts and formulae, Proc. of West Pakistan Engineering Congress, Lahore, Vol. 46, Paper 351.

where S is the slope per thousand feet and C is the concentration of bed material, see Fig. 6.

Such relations provide a useful estimate of the approximate bed material discharge sand bed channels can carry. However, Eq. 5 is based upon flow conditions ranging from negligible bed material transport to the very large bed material transport rates associated with upper regime flow and unstable channels. Consequently, when Eq. 5 is used for design the results obtained should be checked to verify that the desired regime of flow and form of bed roughness will occur, see Fig. 2.

BED MATERIAL DISCHARGE IN ALLUVIAL CHANNELS

Probably the most usual, and in general the best procedure for designing sand-bed canals capable of carrying a particular discharge of bed material involves first the determination of the geometry of the canal and its discharge capacity. This can be done using a number of approaches as previously indicated by the numerous design relations that have resulted from analytical studies and experimental studies of the problem in both the laboratory and the field, see Table 1. Using the preliminary design data various bed material discharge concepts can be used to estimate the bed material discharge in the tentative channel and if necessary the design can be revised to satisfy or more nearly satisfy the imposed requirements.

Some of the most useful bed material discharge concepts include: Einstein's bed-load function[18]; modifications of the Einstein function[19,20,21,22] and other methods.[23,24,25,26]

With few exceptions the bed material discharge relations are based upon limited theoretical concepts and analysis of experimental data collected from flumes, canals, and rivers. Most flume data have been collected at depths less than 0.5 ft and similarly most of the canal and river data are for relatively shallow flow. Typical shallow sand-bed streams for which excellent data have been collected by the U. S. Geological Survey and others include the Niobrara River, the Middle Loup River, and the Rio Grande.

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[18] Einstein, H.A., 1950, The bed-load function for sediment transportation in open channel flows, Tech. Bul. No. 1026, U. S. Dept. of Agriculture.

[19] Colby, B. R., and Hembree, C.H., 1955, Computations of total sediment discharge, Niobrara River near Cody, Nebraska, U. S. Geological Survey WSP 1357.

[20] Hubbell, D. W., and Matejka, D. Q., 1959, Investigations of sediment transportation Middle Loup River at Dunning, Nebraska, U. S. Geological Survey WSP 1476.

[21] Mao, S.W. and Rice, L., 1963, Sediment-transport capability in erodible channels, Journal of the Hydraulics Division, ASCE, Vol. 89, No. HY4, Part 1.

[22] Bishop, A.A., Simons, D.B., and Richardson, E.V., 1964, Total bed material transport, ASCE Journal of Hydraulics Division. In press.

[23] Laursen, E.M., 1958, The total sediment load of streams, Journal of the Hydraulics Division, ASCE, Vol. 84, No. HY1, Proc. Paper 1530, Feb.

[24] Chang, F. M., 1962, An investigation of total sediment discharge in alluvial channels, Ph. D. dissertation, Colorado State University, Fort Collins, Colorado.

[25] Colby, B.R., 1964, Discharge of sands and mean-velocity relationships in sand-bed streams, U. S. Geological Survey Prof. Paper 462-A

[26] Nordin, C. F., Jr., 1964, Study of channel erosion and sedimentation transport, Journal of the Hydraulics Division, ASCE, HY4, July.

These rivers differ from stable canals in that they may shift to upper regime flow at flood stage which is the exception for stable canals unless the bed material is quite fine and the banks are relatively resistant to scour.

Application of most methods of estimating bed material discharge indicate discharges or bed material concentrations which show considerable scatter in the lower flow regime within which most stable canals operate, give better results in the transition and upper flow regime and may yield questionable values and should be applied with caution when average depth of flow is larger than about 4 ft.

A study of the suspended bed material discharge data collected from deep canals and rivers verify that these channels carry more suspended bed material and total bed material discharge than most concepts and theories indicate. Most of the large canals with depths ranging from 5 to 10 ft that have been and are being studied in West Pakistan carry an average concentration of suspended bed material, $d > 0.062$ mm, ranging from about 100-500 ppm when conveying the design discharge. However, concentrations ranging from 25 to 1200 ppm have been observed in some canals. Most of the current methods used to estimate the average concentration of bed material coarser than 0.062 mm indicate values ranging from about 25 to 50 ppm.

Based upon experience the modified Einstein method should give a good estimate of the true bed material discharge but is only useful when the measured suspended bed material is known. In Table 2 the total bed material

TABLE 2

COMPARISON OF THE TOTAL BED MATERIAL DISCHARGE
COMPUTED BY MODIFIED EINSTEIN AND EINSTEIN METHODS
WEST PAKISTAN CANALS

CANAL	Bed Material Discharge in Tons, per day	
	Modified Einstein	Einstein
Upper Gogera, 42[1]	20,400	1,500
Upper Gogera, 106	6,140	1,630
Panjnad, 68	3,290	415
Panjnad, 137	3,164	510
Panjnad, 137	3,670	500
Abassia, 9	66	33
Rangpur, 11	910	120
Lower Jhelum, 160	2,720	415
Lower Chenab, 147	7,610	1,200
Lower Chenab, 147	9,270	1,100
Upper Chenab, 100	32,640	4,130

[1]Distance from headworks in thousands of feet.

discharge computed by the Einstein method[18] and the total bed material discharge computed by the modified Einstein procedure[19, 20] are presented for some of the large West Pakistan canals. These results emphasize the need for added research on bed material discharge relations and in particular emphasize the inadequacy of existing design concepts when depth of flow is large.

The most direct and useful method of determining the bed material discharge in large, deep channels is to use relations based upon existing theories and data collected from similar systems. The method presented by Bishop, Simons and Richardson[22] works quite well for canals with $Q < 2,000$ cfs. This method is based upon large flume data[27] and canal and river data that have resulted from studies conducted in the United States by the U.S. Geological Survey and the U.S. Bureau of Reclamation. This method employs the first nine steps proposed by Einstein[18], the shear intensity-transport relations developed for sands ranging in size from 0.19 to 0.93 mm, see Fig. 7, and Eq. 6.

$$Q_T = 52700\, \phi_T\, W d^{3/2} \tag{6}$$

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[18] Ibid

[19] Ibid

[20] Ibid

[22] Ibid

[27] Simons, D. B., and Richardson, E. V., 1961, Studies of flow in alluvial channels, basic data from flume experiments, U.S. Geological Survey Colorado State University Report CER61EVR31.

The accuracy that can be expected from this method when working within the range of conditions upon which it is based is indicated in Fig. 8. The total bed material discharge of the rivers included in this study was computed by the modified Einstein procedure.

Recently a study by Mao and Rice[21] outlined a method of estimating the bed material discharge capacity of canals and rivers by applying the Einstein procedure and the philosophy that canals have a maximum bed material transport capacity in excess of that given by the usual application of the Einstein function. This assumption was made to justify the relatively large bed material discharge observed in the large canals of West Pakistan.

Working with flume data, rivers which range in discharge from a fraction of a cms up to and including the Mississippi River, Bruce Colby[25] has developed useful relations between average velocity, the fall diameter of the bed material, depth of flow, the temperature of the water, the concentration of sediment finer than 0.062 mm referred to as fine sediment or wash load and the bed material discharge. The principal results of this study are presented in Figs. 9 and 10. Colby's application of these figures to a practical river problem is illustrated in the following example:

Given:	Mean velocity	6.5 fps
	Depth	4.8 ft
	Median size of bed sediment	0.43 mm
	Water temperature	75^{0}F

Concentration of fine sediment, mostly bentonite - 33,000 ppm

Find: Bed material discharge per foot of width in tons per day.

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[21] Ibid

[22] Ibid

[25] Ibid

Summary of the computations: From Fig. 10 the discharges of sands are about 92 and 150 tons per day per foot of width for depths of 1.0 and 10 feet, respectively. Hence, about 130 tons per day per foot of width can be interpolated for the depth of 4.8 feet. The adjustment coefficients from Fig. 9 for 75^{0}F and a depth of 4.8 feet is 0.86 for a median diameter of 0.20 or 0.30 mm. Also, the adjustment coefficient for 33,000 ppm of fine sediment, mostly bentonite, is 1.92 for a median diameter of 0.20 to 0.30 mm, and the total adjustment coefficient is 1.92 x 0.86 or 1.65. According to the right-hand graph of Fig. 10, the effect of a change in viscosity or apparent viscosity is only 78 percent as large for the median diameter of 0.43 mm as for a median diameter of 0.20 or 0.30 mm. Therefore, 78 percent of (1.65 - 1.00) or 0.51 is added to 1.00 to obtain the estimated adjustment coefficient for the median diameter of 0.43 mm. The 130 tons per day which could well be rounded to 200 tons per day per foot because the discharge of sands ordinarily should not be determined to more than two significant figures.

The Colby method[25] was checked using flume data, canal data including that recently collected from large canals in West Pakistan and some river data. This resulted in Fig. 11[28] that relates bed material discharge per ft of width, average velocity and fall diameter of bed material. The results generally agree with the results proposed by Colby and can be used to estimate bed material discharge in canals.

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[25] Ibid

[28] Haynie, R. M., 1964, Design of stable channels in alluvial materials, Ph.D. dissertation, Colorado State University.

A further study of the preceding bed material discharge relations and the proposed method of estimating bed roughness, Fig. 2, suggested a possibility of combining the bed roughness and sediment discharge relations on a single graph for design purposes. This was done as illustrated by Figs. 12 and 13. Figure 12 relates the stream power $\tau_o V$, the median fall diameter of the bed material d and the third and fourth variables are bed roughness and the bed material discharge per unit of width. To use this relation: determine the channel geometry W, D and S and the average velocity for the proposed channel, estimate the median diameter of the bed material considering the characteristics of the parent stream, study diversion conditions at the headworks to the canal, including the effects of exclusion and/or ejection structures on the characteristics of the bed material allowed to enter the canal, the characteristics of the natural material in which the canal will be excavated and possible effects of temperature and concentration of wash load on the median fall diameter of the bed material. Compute the tentative stream power. Enter Fig. 12 with stream power and the estimated median fall diameter of the bed material. Read directly from Fig. 12 the anticipated bed roughness and the probable bed material discharge capacity of the canal. Revise the design as required to assure the desired form of bed roughness and the most desirable bed material discharge capacity that can be obtained. Similarly, Fig. 13 relates the average stream velocity, the median fall diameter of the bed material, the form of bed roughness and the unit bed material discharge. Both Figs. 12 and 13 can be used the same way.

The velocity-discharge curves are based upon Colby's[25] relations and the prediction of bed roughness is based upon velocity, depth of flow, and median fall diameter of bed material. Figure 13 may be superior to Fig. 12 for predicting the bed material discharge but may not be as reliable as Fig. 13 for predicting form of bed roughness. Consequently a cross check by using both figures is recommended.

VARIATION OF CHANNEL GEOMETRY AND SIZE OF BED MATERIAL IN CANALS AND RIVERS

Other problems pertinent to design of stable canals that should be considered are:

1. The incompatability of the bed material of the river and that which the canal can carry.
2. The change of bed material characteristics with distance in rivers and canals, and the effects of these changes on channel geometry and bed material discharge.
3. The application of equations that have been developed for steady uniform or steady non-uniform flow to unsteady non-uniform flow problems.

The usual condition that prevails when water and sediment are diverted from a river to a canal is that the river is relatively steep, the canal is relatively flat and the larger size fractions of bed material of the river are too coarse to be handled even in small quantities by the canal. Consequently, for

[25] Ibid.

successful canal operation both the quality and the quantity of sediment entering the canal must be controlled. The coarser fraction of the river bed material must be kept from the canal so that the quantity and quality of the finer bed material allowed to enter the canal are consistant with the transport capability of the canal.

If size fractions of the bed material from the river, too coarse for the canal to handle without a change in canal geometry, enter the canal there will be rapid aggradation in the head reach causing a reduction of channel cross-section and discharge capacity. Ultimately, sufficient aggradation and steepening of the head reach may occur to change the flow conditions from lower regime to upper regime, Fig. 2. With this change there may be high velocity flow and bank instability. The width-depth ratio will be excessive for the new flow conditions, large alternate bars may develop, the relatively high velocity flow may cut a new channel with quite different dimensions into or partly into the bed of the main channel and into the banks of the original channel wherever the flow comes in contact with the original banks.

Channel changes in both rivers and canals were treated qualitatively by Lane.[29] He proposed the relation

$$Q_s d \approx QS \qquad (7)$$

This qualitative relation states that the behavior of a channel depends upon the discharge of bed material Q_s, the median diameter of the bed material d, the water discharge Q and the channel slope S. In order to emphasize the

[29] Lane, E. W., 1955, The importance of fluvial geomorphology in hydraulic engineering, ASCE Proc., vol. 81, No. 745.

full meaning and the significance of this relation Fig. 14 was developed by W. H. Borland and others of the U. S. Bureau of Reclamation. This figure illustrates that any change in one or more of the variables of Eq. 7 will require compensating changes in one or more of the other variables in order to restore equilibrium or balance. This concept should be considered when designing canals. The usefulness of Lane's Eq. 7 is enhanced if the size of the bed material is assumed to be the median fall diameter of the bed material adjusted for the effects of temperature change and concentration of fine sediment, see Figs. 3 and 4.

If a canal operates so there is no significant imbalance in Eq. 7 and so that the velocity is small enough to assure channel stability the channel is well designed. On the other hand, if bed material is coarser than the canal can carry at the design slope, bed material discharge and water discharge capacity the canal will start to adjust to the imposed conditions. Referring to Fig. 14 the canal would have to steepen (aggrade) to accommodate the coarse sediment. This may reduce the channel cross section and change the resistance to flow so that the canal will not accommodate the design discharge. With a reduction in water discharge a still further increase in channel slope is required to transport the coarse sediment leading to further complications.

Figures 15 and 16 show the decrease in size of bed material with distance that occurs in alluvial rivers and canals. This change in the size of bed material with distance has been attributed to abrasion and chemical weathering, to hydraulic sorting and more commonly to the combined effect of these actions. There is a corresponding reduction of slope of channel with distance downstream as shown in Fig. 17. Unfortunately, no general quantitative numerical relation between size of bed material and channel slope has been developed. Nevertheless, it is a well known fact that for a given discharge steep slopes are associated with coarse bed material and flat slopes are associated with fine bed material.

Figure 16 for the Marala Ravi Canal, West Pakistan, emphasizes both of the problems under discussion. Note that the canal has steepened dramatically from the accumulation of the coarse fractions of bed material entering from the river in the head reach of the canal. Also note that there is a systematic reduction in size of bed material with distance downstream of the diversion. Two curves are required to illustrate this reduction in size of bed material, one for the head reach in which the coarser fractions are accumulating and in which rate of change of size of bed material with distance is large, and another below the headreach which is more typical of the size reduction with distance experienced in natural channels but which must also be related to hydraulic sorting and limited aggradation.

The problem of bed material in the river that is too coarse for the canal to accommodate can only be solved by adequate design of the head works and exclusion and/or ejection structures to limit the sediment in quality and quantity to that which the canal can carry. By applying the basic concepts of fluvial geomorphology, studying existing canals and rivers, and using appropriate bed material transport theories, the size and quantity of bed material that the canal can accommodate near the headworks without undergoing detrimental changes can be estimated. However, this problem is far from simple and is further complicated for the canal by the reduction of size of bed material with distance which implies a continued change in channel geometry, particularly slope, and the ability to transport bed material with distance.

Recently a study was made of the change in size of bed material with distance in canals and rivers.[30] This study emphasized that hydraulic sorting accounts for most of the change in size of bed material with distance in canals. The study further indicated that the reduction in size of bed material with distance is exponential and can be approximated by

$$d_x = d_o e^{-\alpha x} \tag{8}$$

One would expect that α should vary with size of bed material, channel slope and discharge but no quantitative relation of this type has been developed. Similarly, studies by Rafay and others[29] showed that slope of channel also decreases exponentially with distance such that

$$S_x = S_o e^{-\theta x} \tag{9}$$

The variable θ should vary with size of bed material, discharge and consequently be related to α in Eq. 8 but no quantitative relations between α and θ or between θ and size of bed material, channel geometry and discharge have been developed.

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[30] Rafay, T., 1964, Analysis of change in size of bed material along alluvial channels, M. S. Thesis, Colorado State University, Fort Collins, Colorado.

[29] Ibid.

Despite the short comings of Eqs. 8 and 9 they point out that canals should be designed to accommodate change in size of bed material, change in bed-material transport capability and the change in channel geometry with distance. Lacey[13] recognized that a canal develops a slope which reduces with distance downstream of the headworks. To compensate for this reduction he suggested an overall reduction in design slope based upon head reach conditions of about 10 percent.

Actually in design one can establish, by referring to similar canals, an approximate value of α . Then an appropriate canal design equation involving slope and size of bed material can be selected. For simplicity consider the Bose or Institute equation from Table I.

$$S \times 10^{3} = \frac{2.09\, d^{0.84}}{Q^{.21}} \tag{10}$$

If the equation is rewritten as

$$S_x \times 10^{3} = 2.09\, d_x^{\,0.84}/Q^{0.21} \tag{11}$$

and if Eq. 8 is rewritten as

$$d_x = d_o e^{-\alpha x} \tag{12}$$

and is combined with Eq. 10, a relation for channel slope which considers the effect of the change in size of bed material on slope results.

$$S_x \times 10^{3} = 2.09 \left[d_o e^{-\alpha x}\right]^{0.84} / \, Q^{0.21} \tag{13}$$

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[13] Ibid

Such a relation can be used to approximate the ultimate profile of a canal, see Figure 18. However, the bed material and other variables in such canals are subject to continual change which raises a valid question - is such a channel ever stable? The answer may be no but this does not preclude designing to optimize the performance of the channel.

SUMMARY

The design of a stable sand-bed channel requires consideration of the characteristics of the river that the canal diverts from, the diversion works, the use of suitable exclusion and/or ejection works as required to control excessive inflow of bed material, the type of material and the terrain through which the canal is to be constructed, and other factors.

The dimensions and slope of the canal can be determined by the application of various concepts such as permissible velocities, tractive force regime relations and modified regime relations. A modified regime procedure is recommended for the determination of width, depth, and related dimensions. The slope can be determined by various methods but the concept of using depth adjustment ΔD or hydraulic radius adjustment ΔR relations and a resistance diagram that involves $c/\sqrt{g}$, $Re = V_* D/\nu$ and $\frac{\Delta D}{D}$ or $\frac{\Delta R}{R}$ has considerable merit. The design, regardless of procedure used, should be checked to determine the bed configuration the channel will have. Plane bed, upper regime flow which involves relatively large average velocity should be avoided except in special cases. Such a design usually requires bank treatment to assure channel stability. The tractive force concept can be used to design

a protective armor for the banks and even the bed consisting of gravel, rock, crushed rock etc. when high velocities are unavoidable or when such a design is justified.

An integral part of the design is the determination of the quality and quantity of the bed material the canal can carry. Several suitable methods exist for estimating the bed material discharge in shallow flumes, canals and rivers but very few work well for deep canals and rivers. In general, for canal design the use of relations involving velocity or stream power, bed-material discharge and fall diameter of bed are recommended.

Finally, the design should consider the reduction in size of bed material in alluvial channels caused by hydraulic sorting and selective transport on channel slope, the channels ability to transport bed material, channel geometry and channel stability. These factors affect the design of the diversion structure, sediment control structures and other overall design problems.

NOMENCLATURE

Symbol	Definition	Dimensions	Units
C	Concentration of sediment	ppm	0
C_s	Concentration of suspended sediment	ppm	0
$C/\sqrt{g}$	Chezy coefficient of discharge in dimensionless form	0	---
D	Average depth of flow	L	m
d	Median diameter bed material	L	mm
d_o	Median diameter of bed material at the reference station	L	mm
d_x	Median diameter of bed material at a distance x downstream of the reference station	L	mm
F_b	Bed factor	---	---
F_s	Side factor	---	---
Q	Discharge of water-sediment mixture	L^3/T	cms
Q_s	Bed material discharge	F/T	gm/sec
Q_t	Total bed material discharge	F/T	gm/sec
q	Discharge of water-sediment mixture per unit width	$L^3/T/L$	cms/m
R	Hydraulic radius of flow	L	m
R_e	Reynold's number	0	---
S	Slope of energy gradient	0	---
S_o	Slope of channel at the reference station	0	---
S_x	Slope of channel at distance x downstream of the reference station	0	---
V	Average velocity	L/T	m/sec
V_*	Shear velocity	L/T	m/sec
W	Width of channel	L	m
x	Some distance downstream of the reference station	L	m

Symbol	Definition	Dimensions	Units
α	Exponential constant in the equation for the reduction in size of bed material	0	---
γ	Specific weight of water	F/L^3	gm/cm^3
ΔD	Adjustment to the average depth of flow	L	m
ΔR	Adjustment to the hydraulic radius of flow	L	m
θ	Exponential constant in the equation for the reduction in the slope of channel	0	---
ν	Kinematic viscosity	L^2/T	m^2/sec
τ_o	Tractive or shear force developed on the bed γDS	F/L^2	kg/m^2
ϕ_t	Intensity of transport for bed material discharge	---	---
ω	Fall velocity of sediment particles	L/T	m/sec

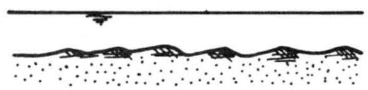
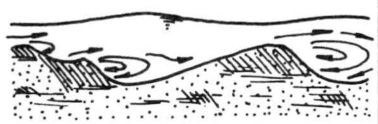
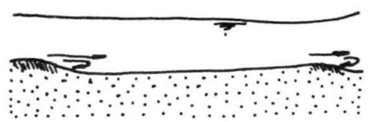
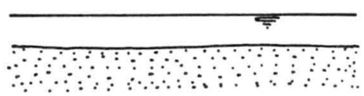
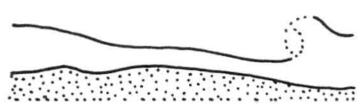
FLOW REGIME	BED FORM	BED MATERIAL CONCEN-TRATION	MODE OF TRANSPORT	WATER SURFACE BED PHASE RELATION	RESISTANCE TO FLOW
LOWER	 Ripples	0 - 200 ppm	Discrete Steps 	Out of Phase	Form roughness predominates–spacing and amplitude of roughness elements vary with the fall diameter of bed – material, $C/\sqrt{g}$ varies from 7.75 to 13.90
	 Dunes	100-1200ppm			
TRAN-SITION	 Washed out Dunes	1,000 - 1200 ppm			Variable
UPPER	 Plane	1,800 - 2000 ppm	Continuous 	In Phase	Grain roughness predominates – for Plane bed $C/\sqrt{g}$ varies from 14.0 to 21.0
	 Antidunes	1,800 - 6,000 ppm	Continuous 		
	 Breaking Antidunes	1800 —	Discontinuous 		

FIG. I THE CHARACTERISTICS OF FLOW IN SAND – BED CHANNELS

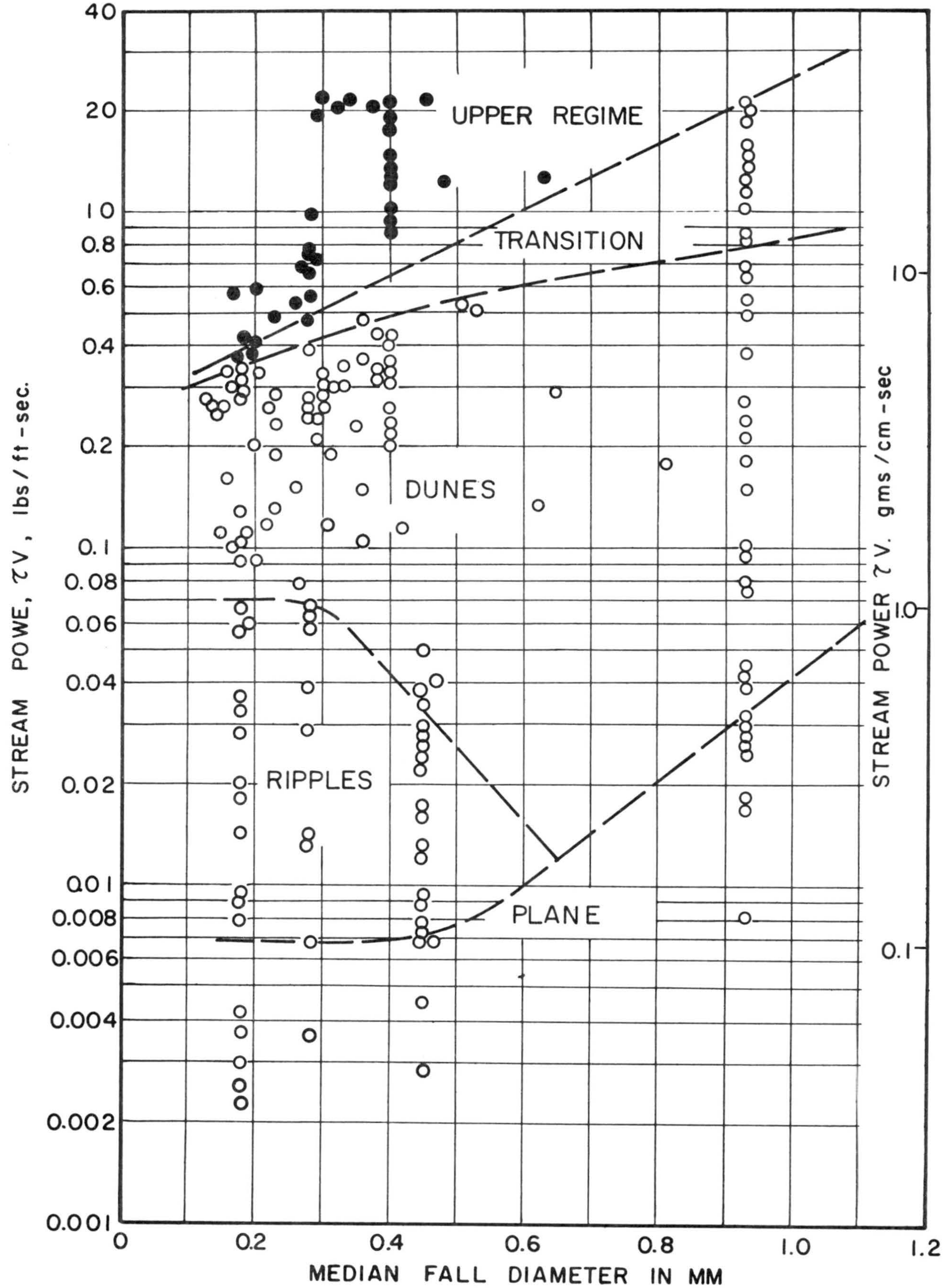


FIG. 2 RELATION OF STREAM POWER & MEDIAN FALL DIAMETER TO FORM OF BED ROUGHNESS

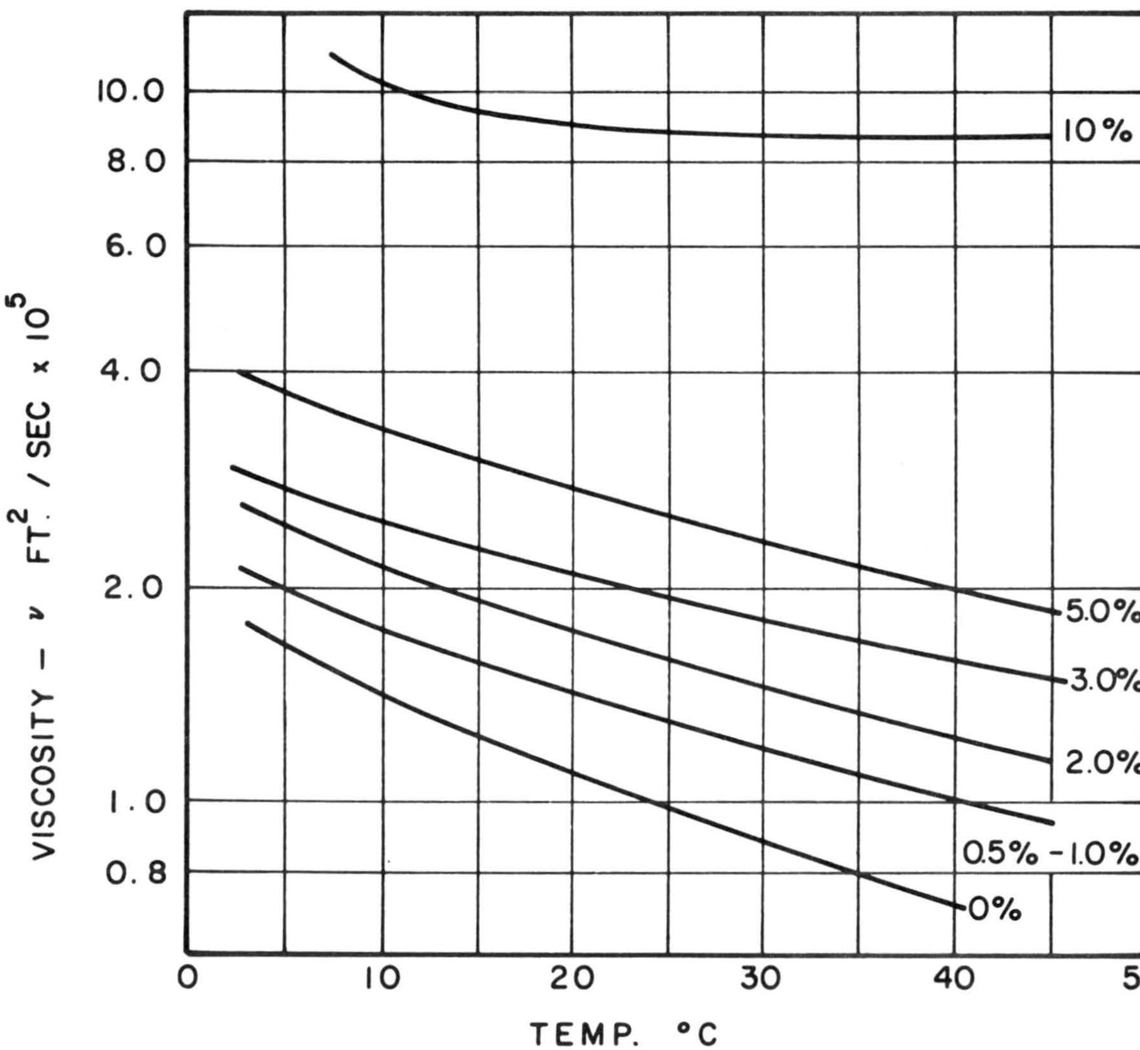


FIG. 3 APPARENT KINEMATIC VISCOSITY OF WATER-BENTONITE DISPERSIONS AFTER SIMONS, RICHARDSON AND NORDIN

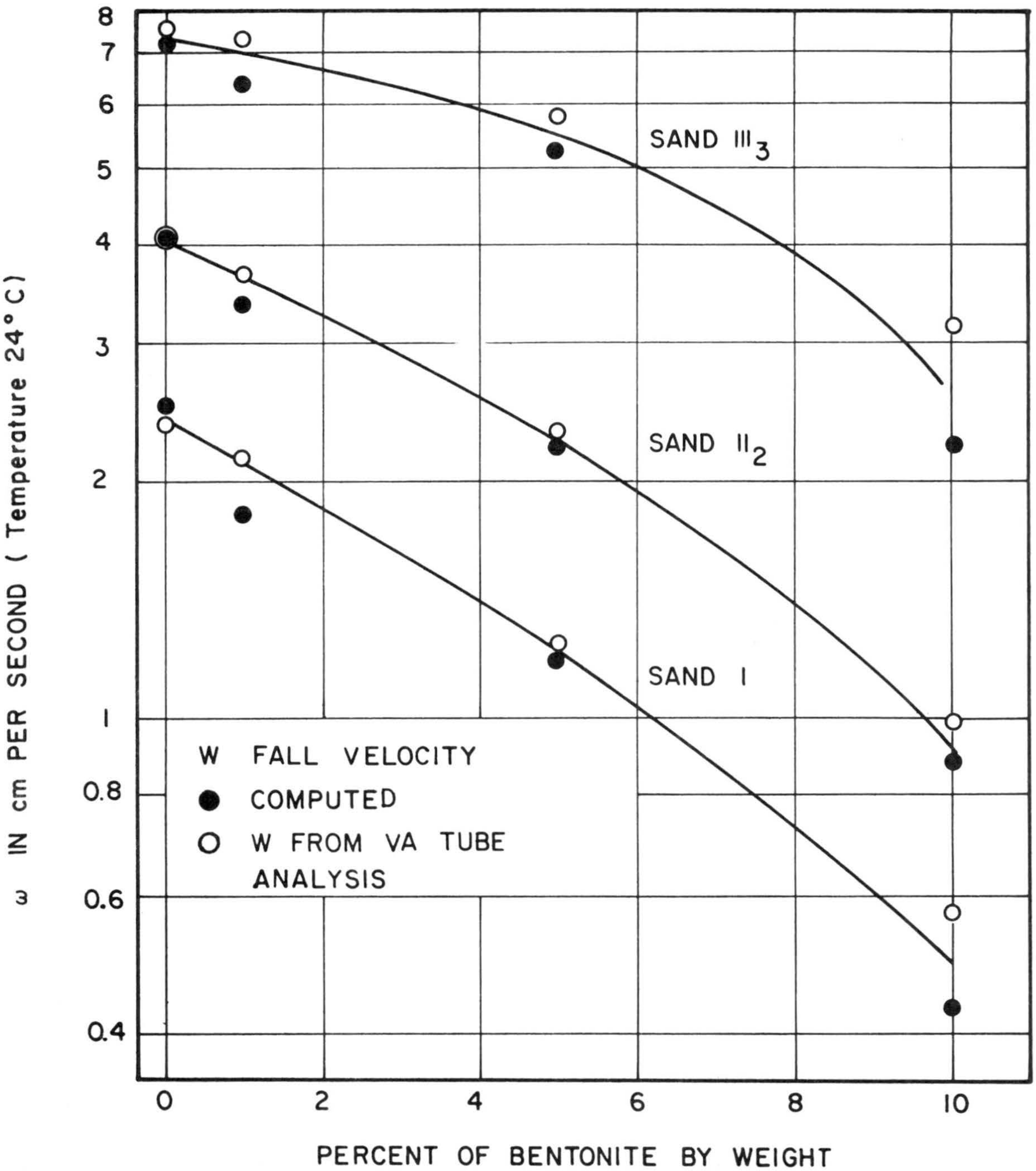


FIGURE 4 VARIATION OF FALL VELOCITY WITH PERCENT OF BENTONITE IN WATER AFTER SIMONS, RICHARDSON & NORDIN

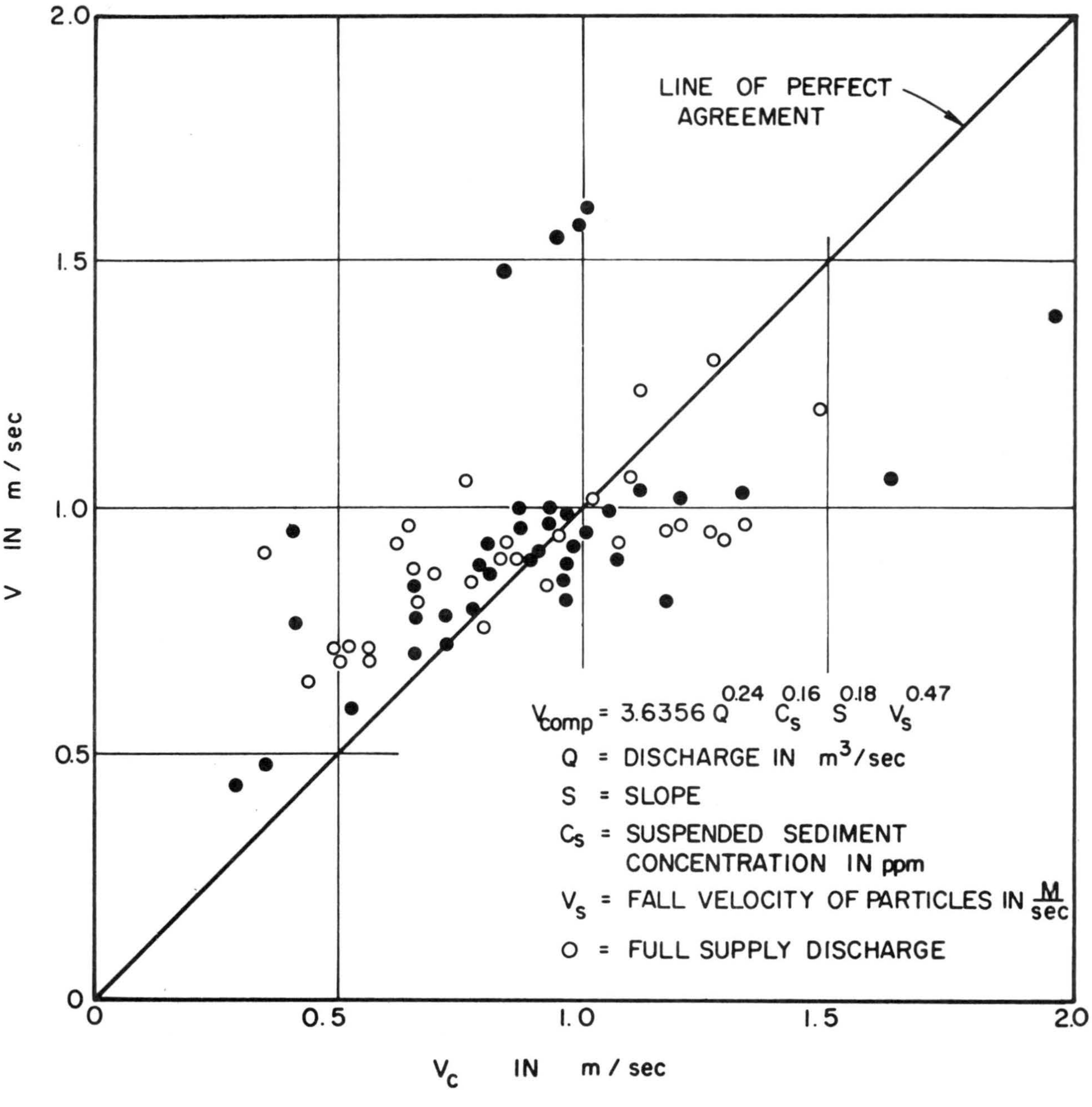


FIG. 5 A COMPARISON OF COMPUTED AND MEASURED AVERAGE VELOCITY FOR WEST PAKISTAN CANAL DATA

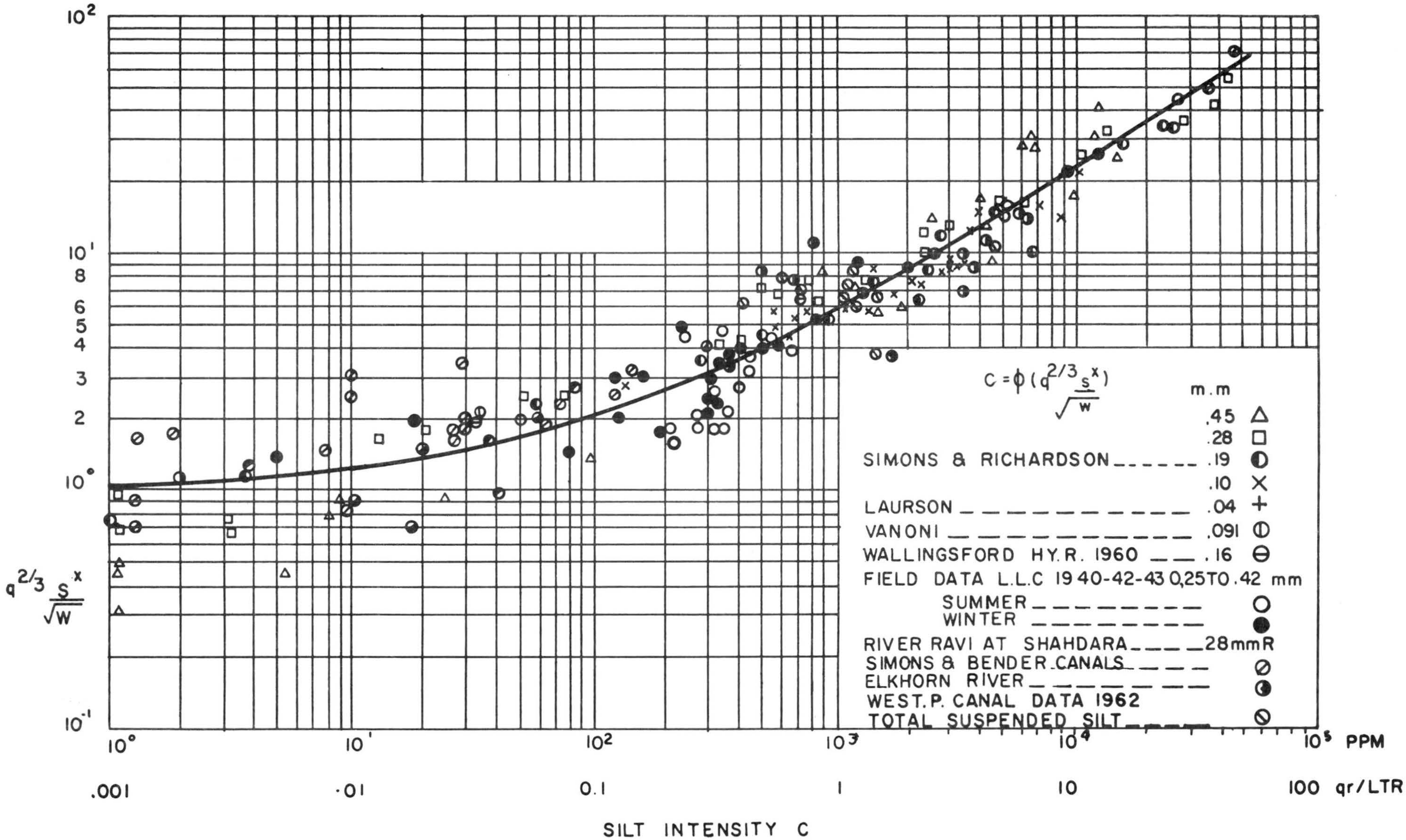


FIG. 6 RELATION OF $q^{2/3} \frac{s^x}{\sqrt{W}}$ TO SILT INTENSITY C AFTER AHMAD & REMIAN

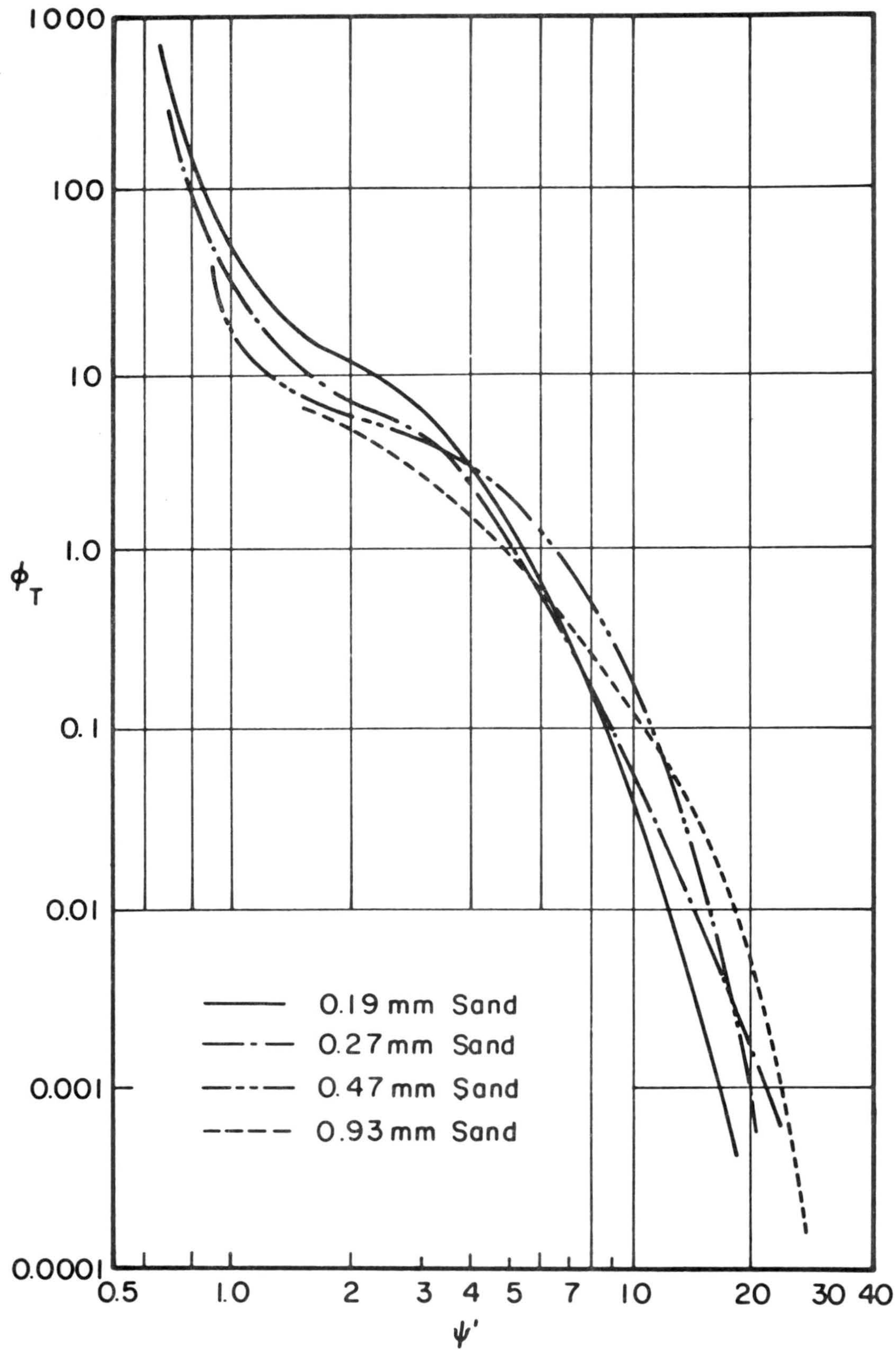


FIG. 7 COMPOSITE $\phi_T - \psi'$ CURVES FOR VARIOUS SAND FROM FLUME DATA AFTER BISHOP, SIMONS & RICHARDSON

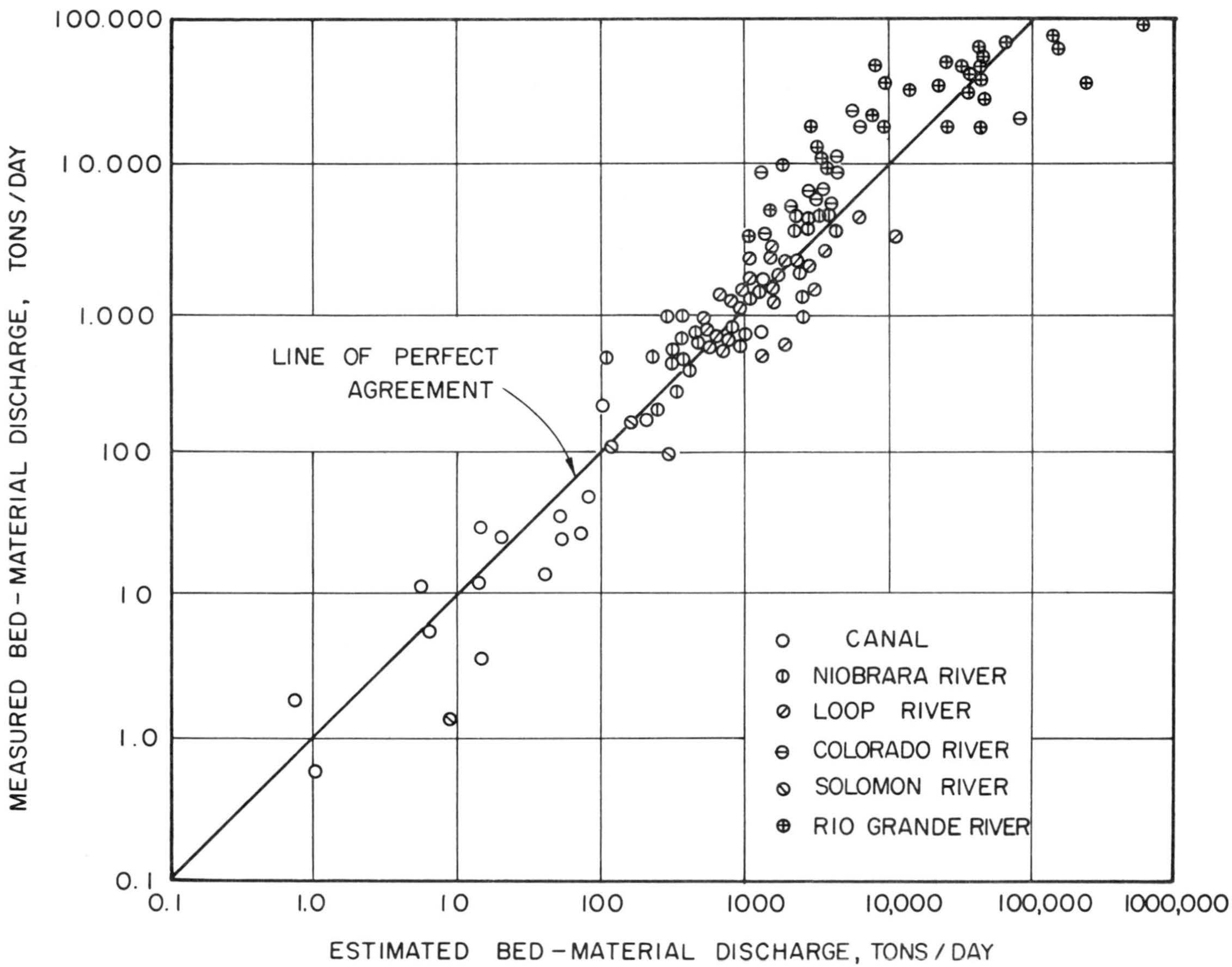


FIG. 8 MEASURED BED - MATERIAL DISCHARGE COMPARED TO BED - MATERIAL DISCHARGE ESTIMATED FROM LABORATORY CURVES AFTER BISHOP, SIMONS AND RICHARDSON

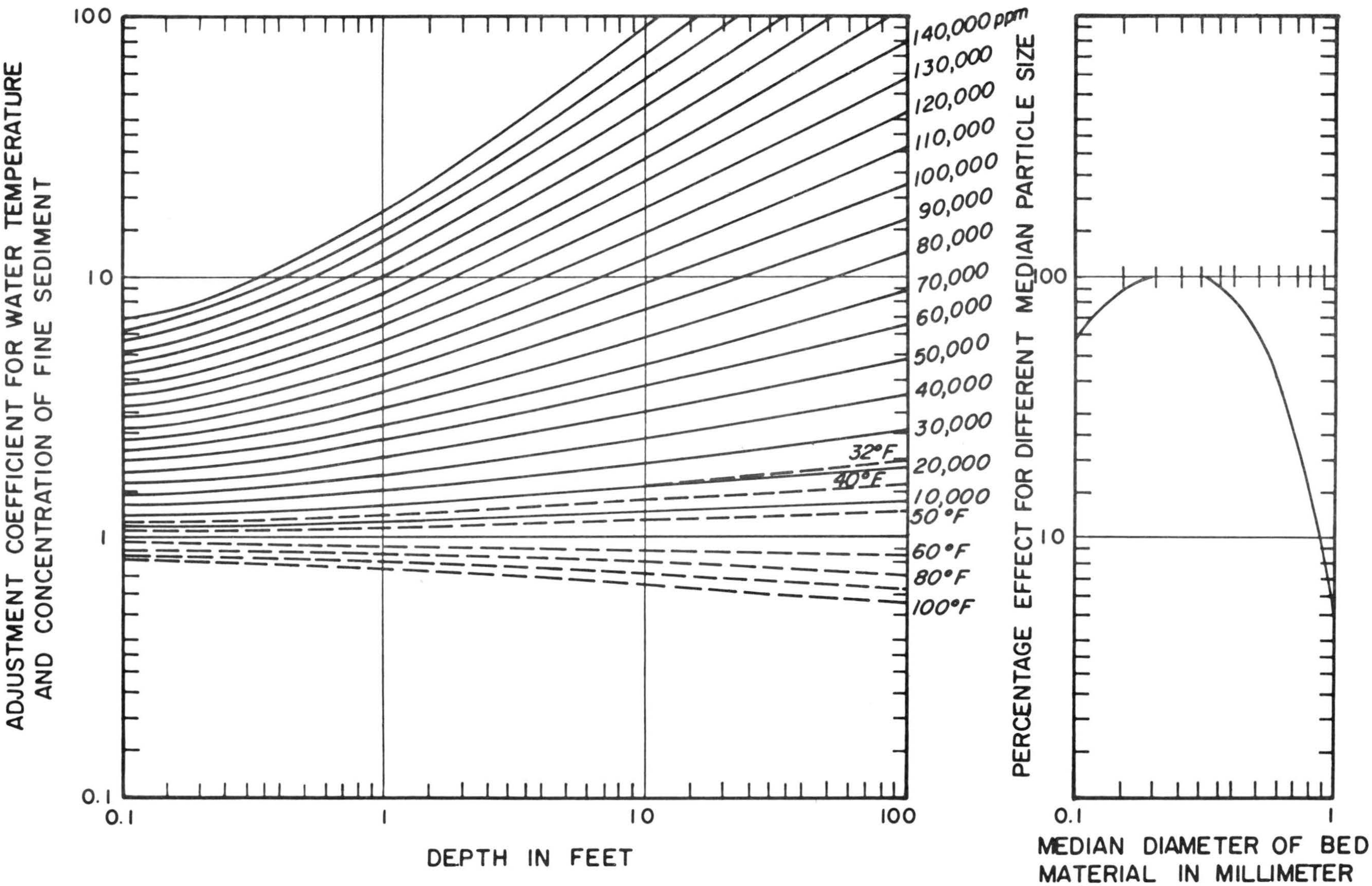


FIG. 9 APPROXIMATE EFFECT OF WATER TEMPERATURE AND CONCENTRATION OF FINE SEDIMENT ON THE RELATIONSHIP OF DISCHARGE OF SANDS TO MEAN VELOCITY, AFTER COLBY

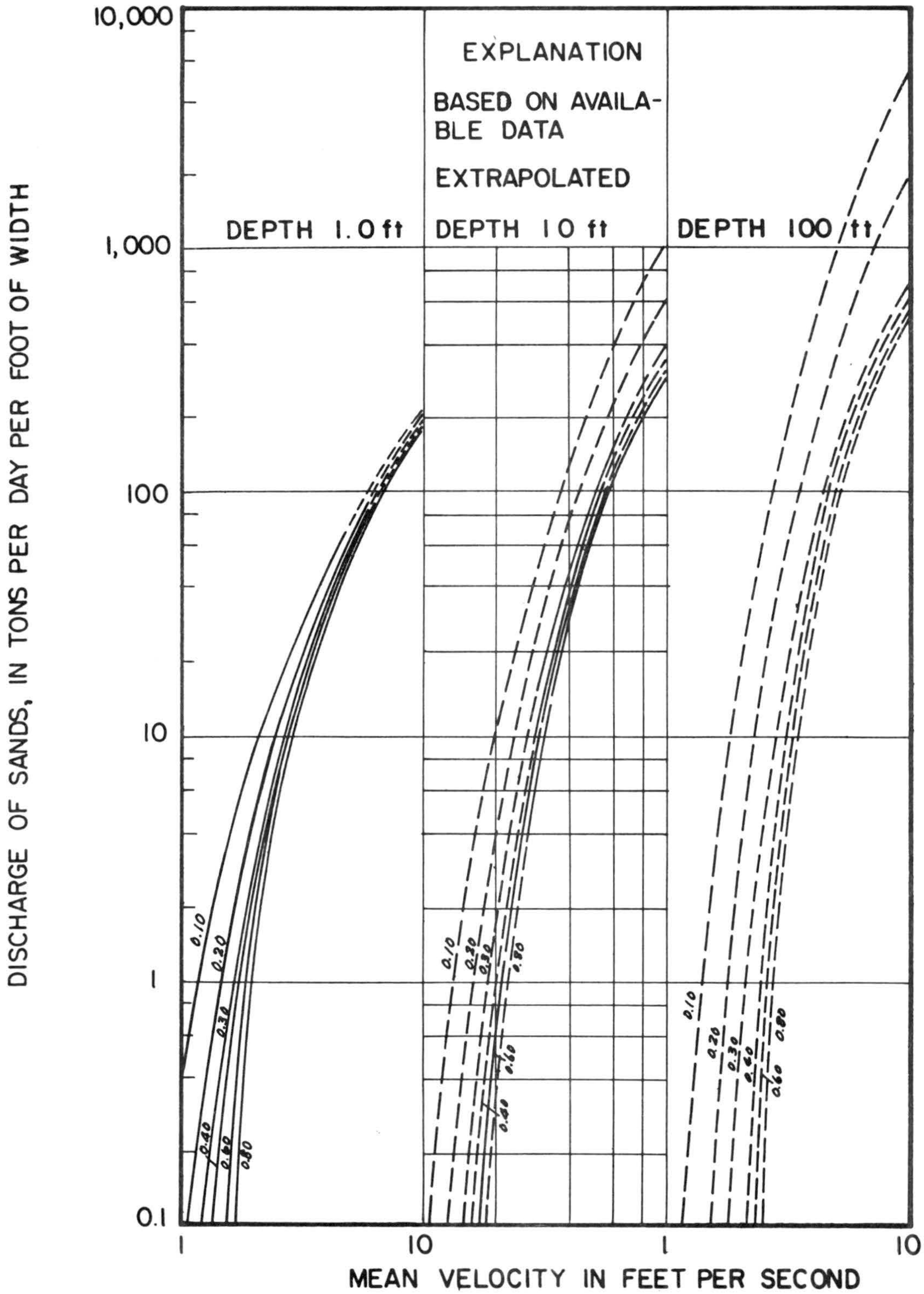


FIG. 10 RELATIONSHIP OF DISCHARGE OF SANDS TO MEAN VELOCITY FOR SIX MEDIAN SIZES OF BED SANDS, FOUR DEPTHS OF FLOW, AND A WATER TEMPERATURE OF 60° F, AFTER COLBY

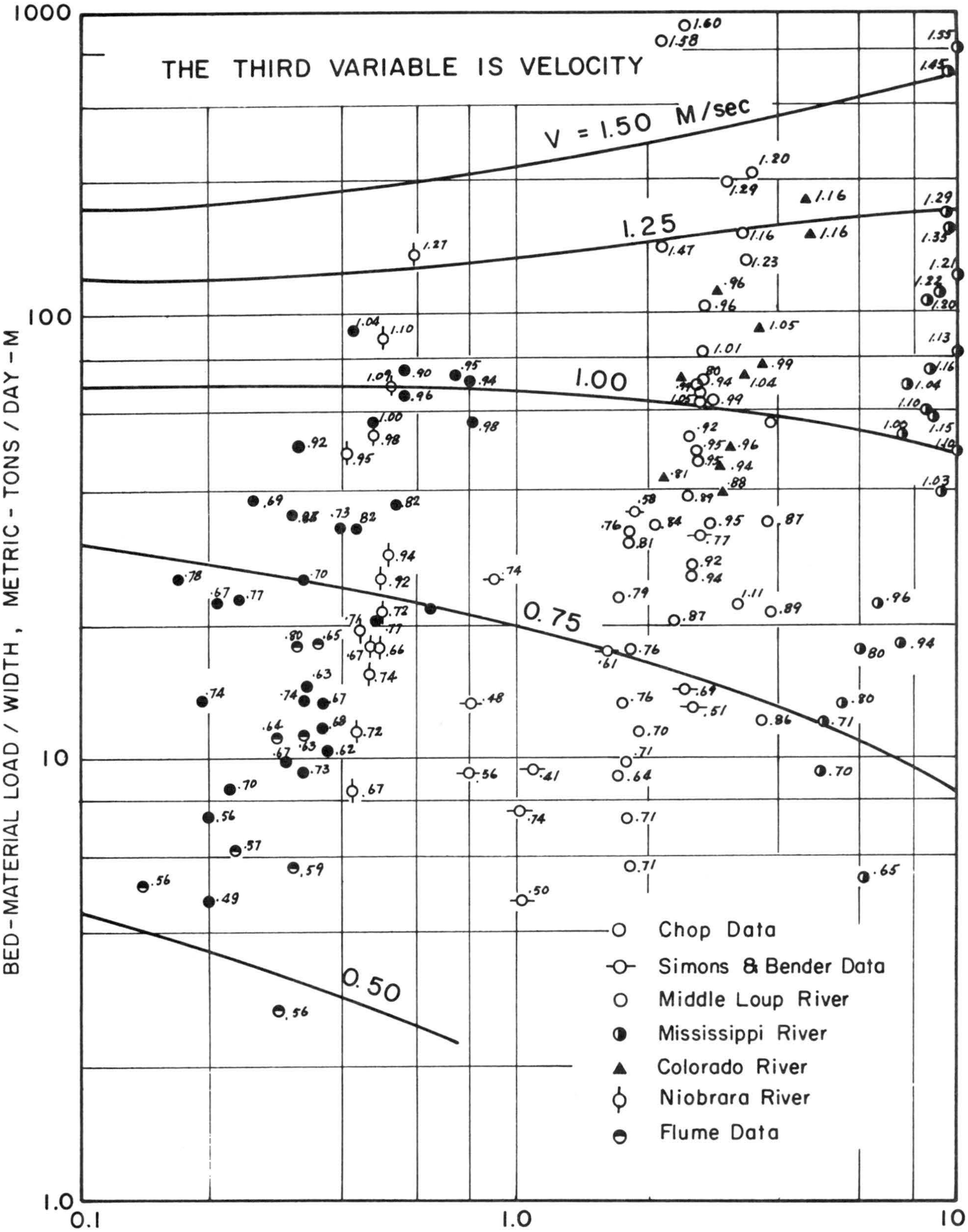


FIG. 11 RELATION BETWEEN BED MATERIAL DISCHARGE, BED DEPTH AND AVERAGE VELOCITY

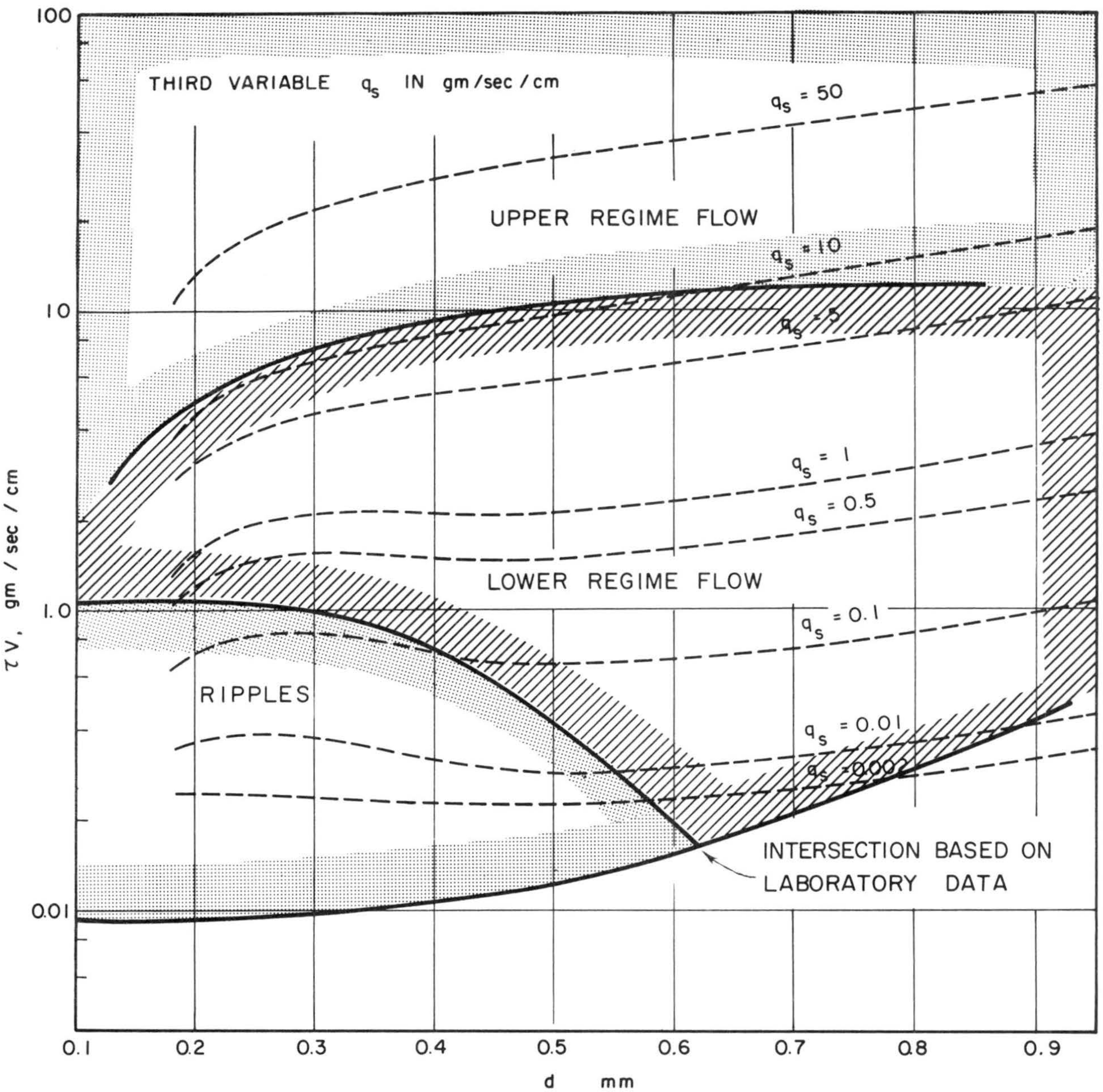


FIG. 12 RELATION BETWEEN STREAM POWER, MEDIAN DIAMETER OF BED MATERIAL, FORMS OF BED ROUGHNESS AND BED MATERIAL DISCHARGE

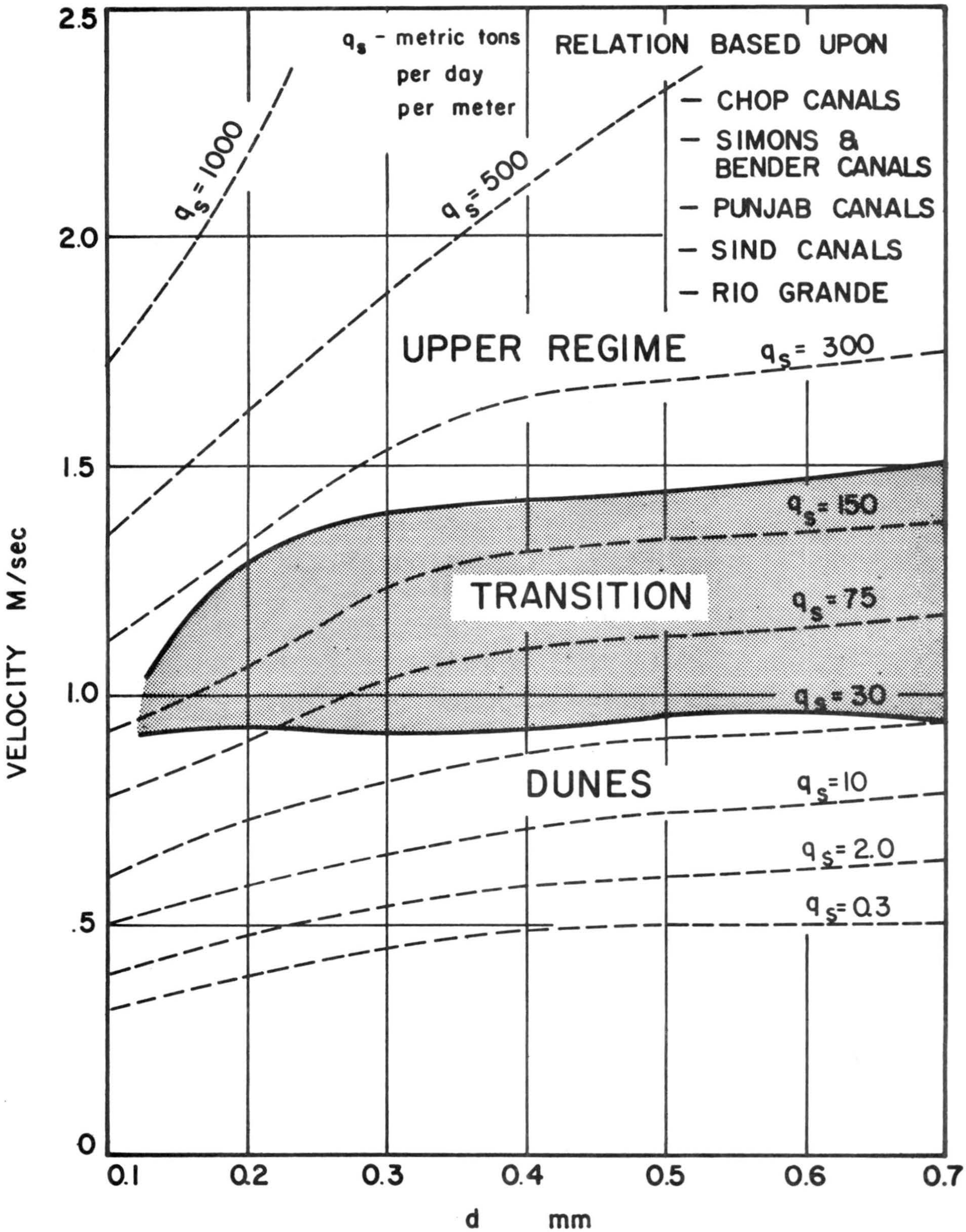


FIG. 13 RELATION BETWEEN AVERAGE VELOCITY, MEDIAN DIAMETER OF BED MATERIAL, DISCHARGE OF BED MATERIAL AND FORM OF BED ROUGHNESS.

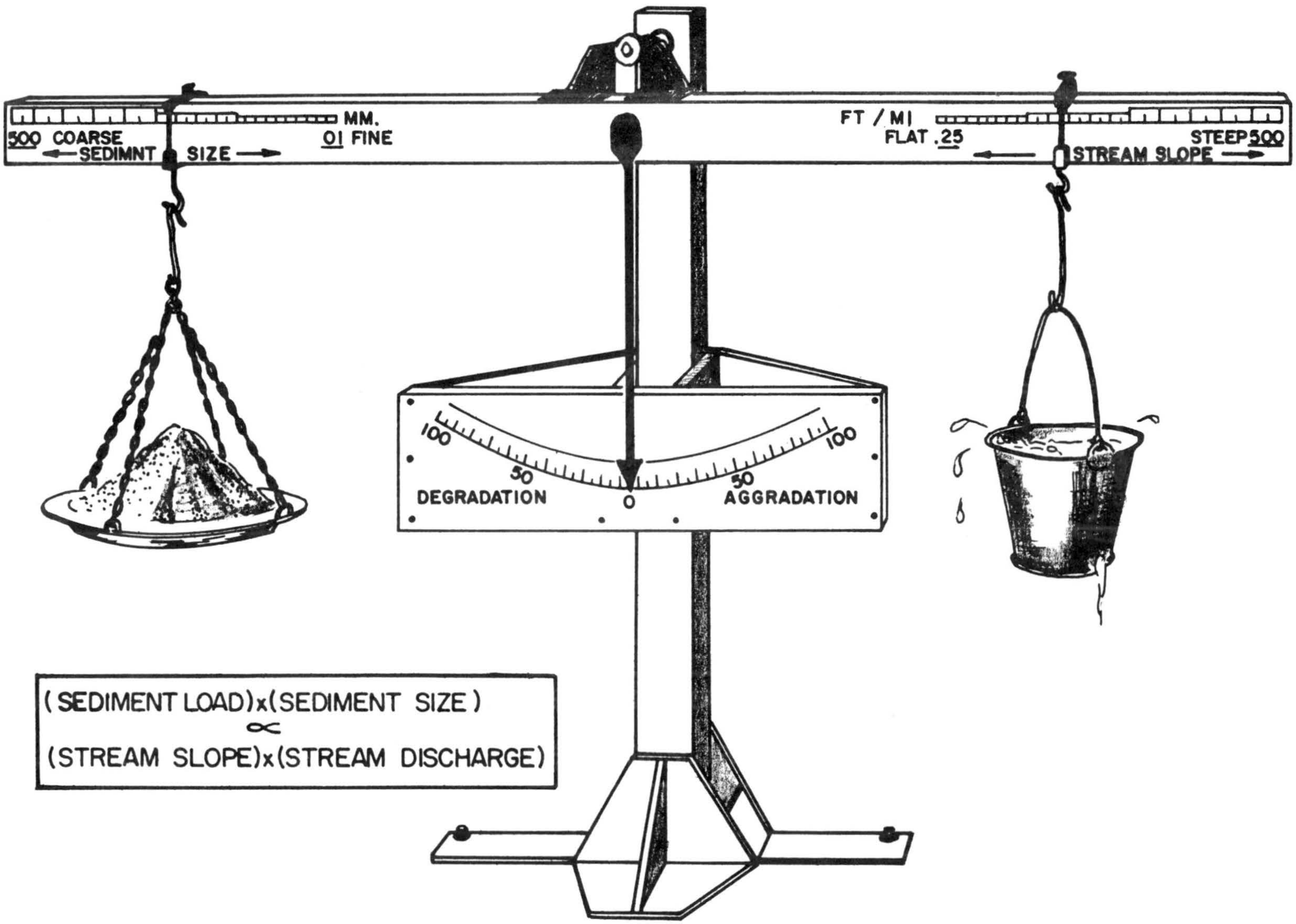


FIGURE 14 STABLE CHANNEL BALANCE
(After E. W. LANE)

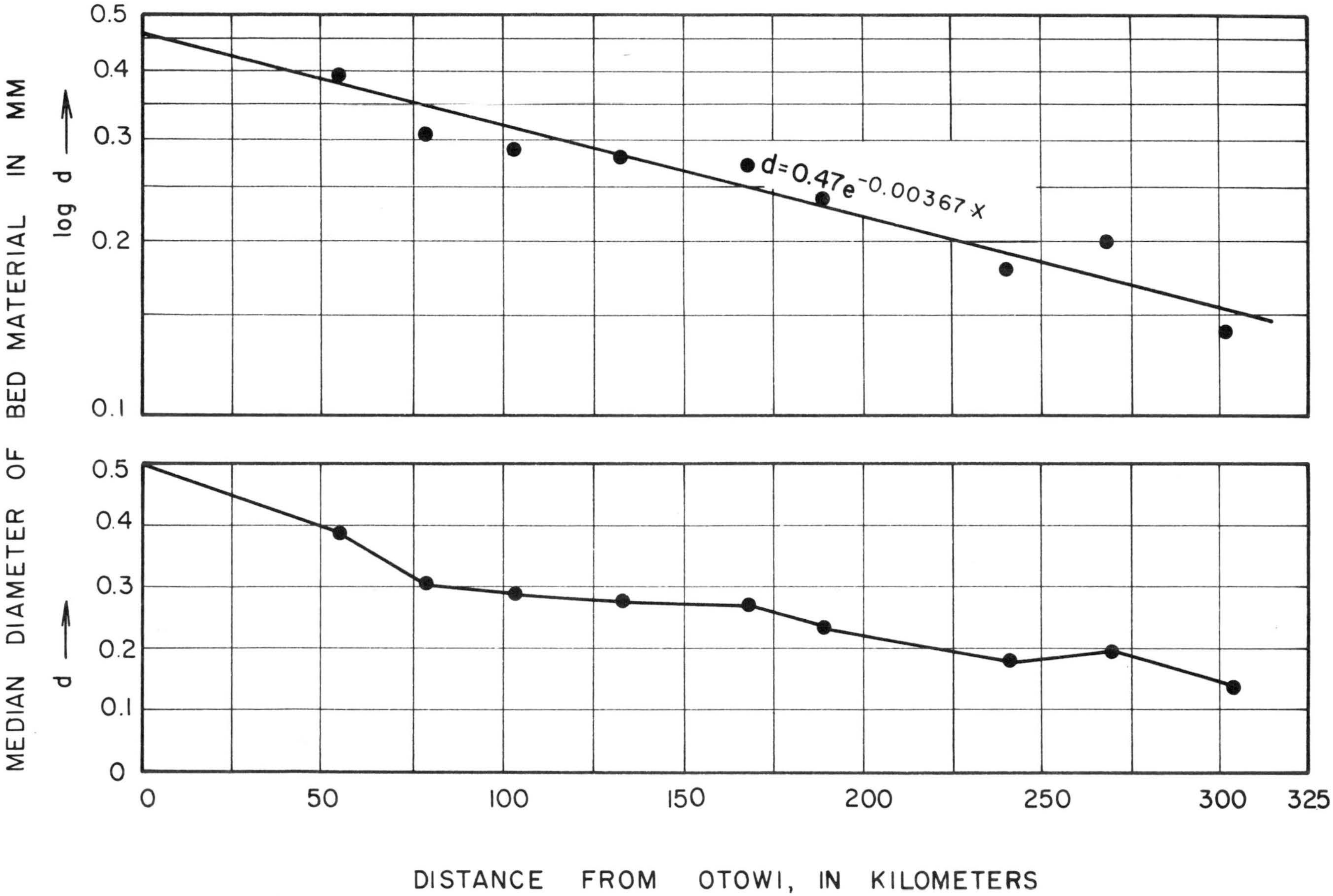


FIGURE 15 PARTICLE – SIZE REDUCTION ALONG RIO GRANDE

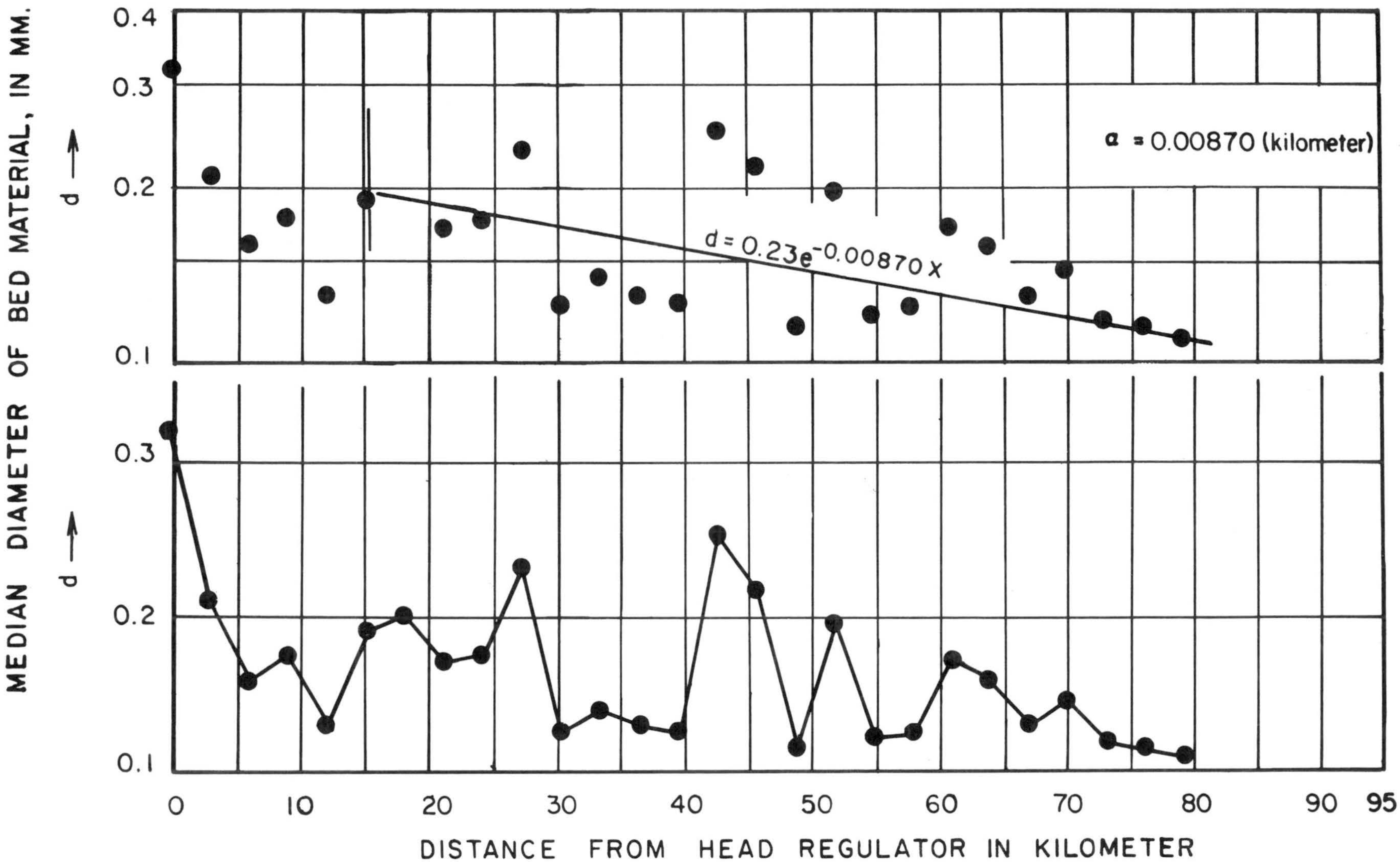


FIGURE 16 PARTICLE - SIZE REDUCTION ALONG MORALA - RAVI LINK CANAL

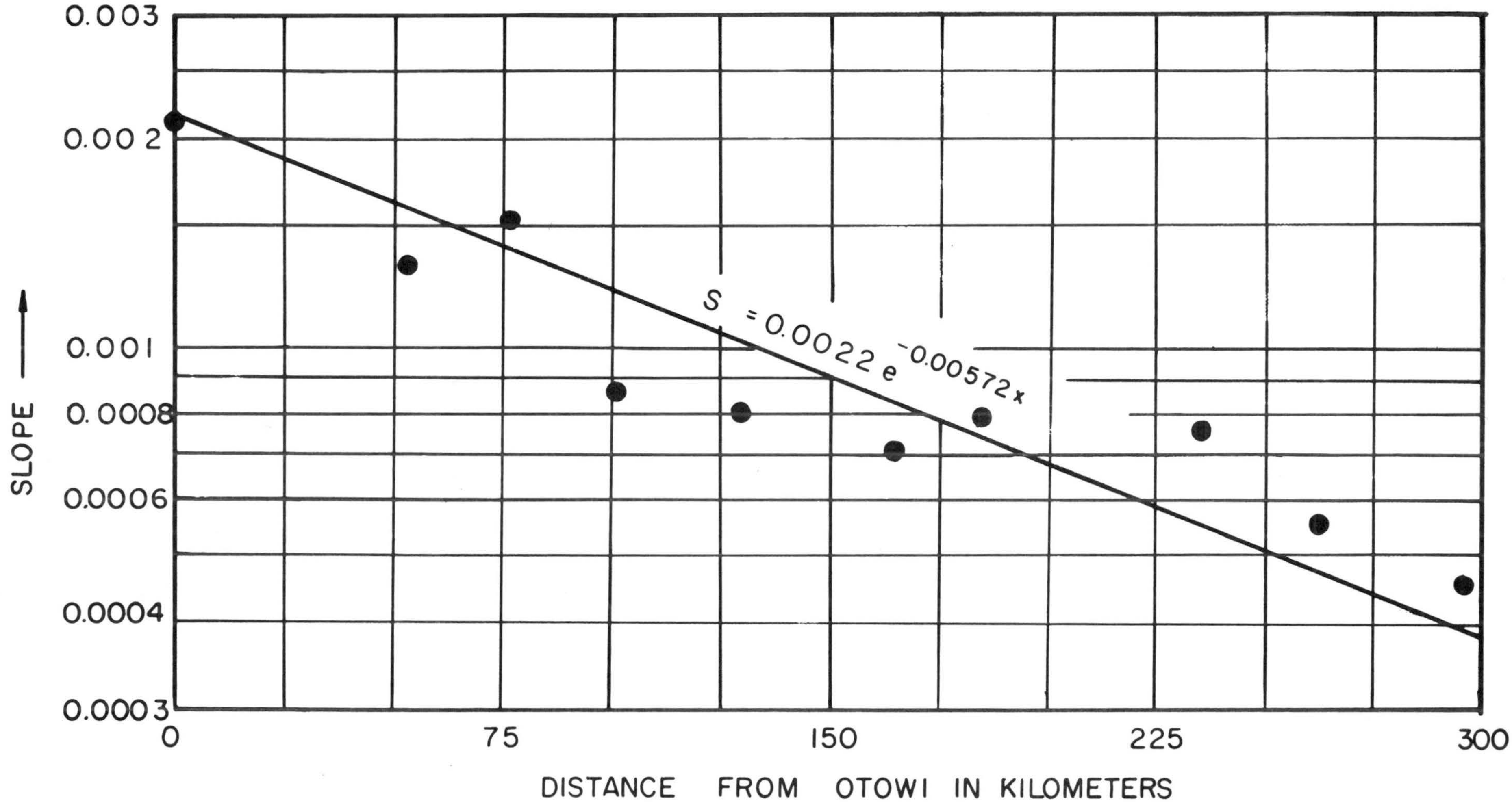
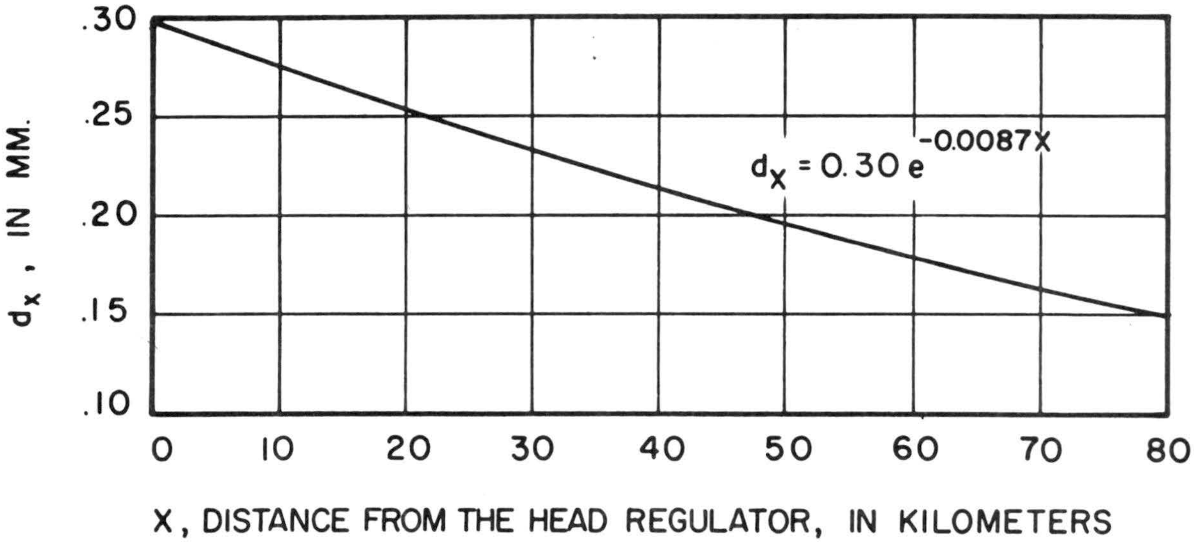
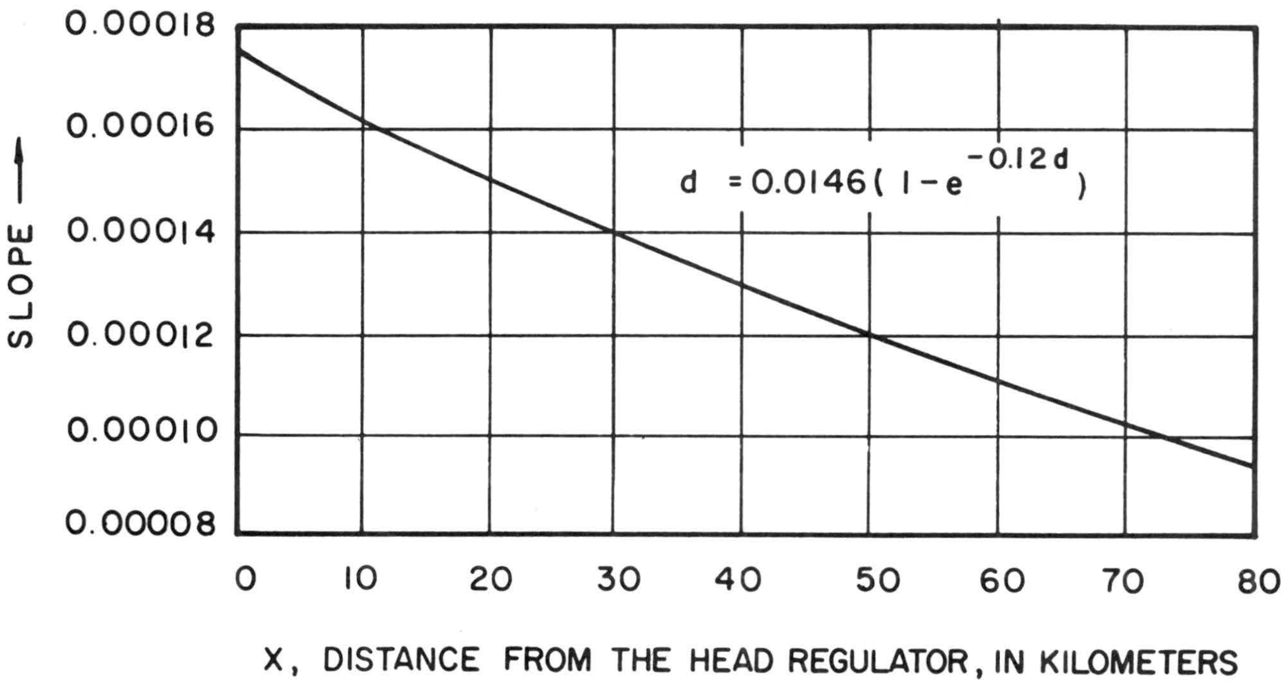


FIG. 17 SLOPE VARIATION ALONG RIO GRANDE



(a) Size of bed material variation along the channel



(b) Slope variation along the channel

FIGURE 18 DESIGN OF CHANNEL - EXAMPLE PROBLEM