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ALLUVIAL CHANNELS REDESIGN PROCEDURE

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ABSTRACT

The Authors have compared Sediment Transport concept and Tractive Force method with Regime Theory as alternative design approaches for Punjab canals. Commonly accepted relations of Regime Theory have been tested on 678 data sets observed by Alluvial Channels Observation Programme (ACOP). Variations in Lacey's silt factor have been studied as useful indicators of behaviour of an existing channel. Alluvial Channels Redesign Procedure (ACRP) has been developed for channels upto 1000 Cs discharges. ACRP uses established relations of Regime Theory without the silt factor, and can be used for existing as well as new channels.

1.0. INTRODUCTION

Lacey's set of equations, accepted by Central Board of Irrigation (India) in 1934, despite some severe criticism, continues to be the basis of design of alluvial channels in Pakistan. Main reason of criticism on Regime Theory, the origin of Lacey's relations, is its pure empirical basis. Sediment Transport concept and Tractive Force method are being considered as possible design alternatives.

This paper compares Sediment Transport concept and the Tractive Force method as alternative design approaches for irrigation channels in Punjab. The Authors are associated with the ISRP Design Cell of the Central Design Office of Punjab Irrigation

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and Power Department, where design work related to the Irrigation System Rehabilitation Project (ISRP) is being carried out. The major part of the design work of ISRP relates to the distributaries with discharge upto 1000 Cs. The Authors have used 678 data sets (for discharge upto 1000 Cs) observed by Alluvial Channel Observations Programme (ACOP) for the analysis. Some of the relations given by Lacey, Bose and Simon-Albertson have been tested on the observed data with the prime purpose of developing criteria for identifying hydraulic problems in the existing channels. The problems resulting from deferred maintenance and the defective working of the outlets are beyond the scope of the present discussion.

It has been observed that various forms of Lacey's silt factor serve as useful indicators of the behaviour of an existing channel. For a new channel a precise criteria for fixing Lacy's silt factor is not available due to which the final geometery and, specially, the slopes of the channels, in many cases, differ significantly from those originally computed by the design engineer. The Authors have developed a design procedure which includes the criterion for fixing channel slopes. The method, called the Alluvial Channels Redesign Procedure (ACRP), uses established relations given by Bose and Lacey without involving the disputed estimation of Lacey's 'f' for design of new channels. ACRP, explained in section 4.8, can be used for problem identification and redesign of existing as well as design of new channels. Design results of Lacey, Simon-Albertson and ACRP for a number of channels with discharges upto 1000 Cs have been given in section 4.9 for the sake of comparison.

2.0. SEDIMENT TRANSPORT APPROACH

In recent years a lot of work has been done to understand the mechanism of sediment transport in alluvial channels. Number of formulae have been developed all over the world to predict sediment carrying capacity of the channels. The formulae are based on basic principles of Fluid and Soil Mechanics, yet most of them carry the empirical colour of statistical correlationing. Equations resulting from statistical analysis tend to reflect typical characteristics of the data and the conditions of their origin. Validity of such equations for different field conditions can, therefore, be rightly questioned.

As will be seen from the following discussion, selection of a suitable sediment transport relation for Punjab Canals is not a matter of obvious choice. Equally importent is the fact that a suitable transport predictor alone does not provide answer to practical design problems of Punjab Canals. The Authors have selected five of better known sediment transport relations to give the reader a feel of difference in their predictions. The relations are :

1. Shields (1936) -- (REL. 1)
2. Einstein-Brown (1950)------------------------------------ (REL. 2)
3. Engelund-Hansen (1967) -------------------------------- (REL. 3)
4. Ackers-White (1973) -------------------------------------- (REL. 4)
5. Karim-Kennedy (1981) ----------------------------------- (REL. 5)

The formula developed by Dr. Mushtaq, in 1962, has not been included in comparison because it shows an appreciable decreasing trend in prediction (in terms of PPM) towards the tail reach. Behaviour of this formula, therefore, does not provide a common base of comparison with the above noted formulae. It may be mentioned that a full fledged research effort is required before one can declare a formula preferable over the rest for Punjab conditions.

2.1. PREDICTINS FOR PUNJAB CANALS

Figures 5 & 6 show sediment discharge (cft/sec) as predicted by the five formulae for d50 of 0.1 and 0.3 mm and discharge range upto 1000 Cs. The channel section and slopes represent typical Punjab Canals for a given discharge. Comparison for a discharge, say 1000 Cs. shows that :

i) Bed load predictors (Shields & Einstein-Brown) differ by 51% and 132% for the two sediment sizes.

ii) Total lod predictors difffer by 11% to -40% with respect to Engelund-Hansen.

iii) Formulae predict 3 to 5.5 times less due to increase in d50 from 0.1 to .3 mm.

It is clear from above data that the sediment load predictors differ significantly and their predictions are highly sensitive to sediment size.

Validity of above formulae for Punjab canals is a separate question. M/s. PRC/Checchi Consultants on ISRP Phase-I, compared predictions of some formulae (including last three of the five relations under discussion) with the sediment data observed by ACOP on Punjab Canals. Table T1 summarises the results. The correlation coefficients indicate a poor correlation and the slopes of best fit line confirm the absence of a reasonable relation between the measured and predicted concentrations. Sediment load predictors developed elsewhere can not be used in Punjab without establishing their validity for local conditions.

CANAL	A&W REL. 3		E&H REL. 4		K&K REL. 5	
	cc	m	cc	m	cc	m
UPPER DEPALPUR	.169	.296	.267	.18	.377	.105
UPPER GUGERA BR.	.06	.305	.007	.007	.053	.046
UPPER GUGERA SYS.	.363	.461	.433	.69	.334	.167
PUNJAB & SIND CANALS	.009	.173	.218	.132	.322	.106

Table T1 : Correlation Coefficients (cc) and Slope of the Best Fit Line (m) for Measured Versus Predicted Concentration.

2.2. PRCTICAL DESIGN ASPECTS

A design approach directly based on incoming sediment must resolve number of issues related with peculiar functioning of Punjab Canals. Following discussion briefly covers practical design aspects of sediment Transport approach in relation to Punjab conditions :

1. Carrying capacity of a channel has to be compard with the incoming sediment to verify the adequacy of design. There is a wide range of variation of sediment inflow in a typical Punjab Canal over the year. Figure 4 shows ten daily discharge and sediment observation for B.S. Link for the year 1985 (Ref. 11). The highest figure of the sediment charge (3920 PPM in August), is over six times the lowest (630 PPM in January). Variation of this magnitude in the incoming sediment is common in Punjab Canals. First practical problem is selection of a representative sediment charge for design. It may be mentioned that the design slopes, as worked out by sediment transport relations, are quite sensitive to the sediment charge. The formula given by Engelund-Hansen, for instance, requires slopes of 1:8612 and 1:5665 for carrying sediment concentrations of 100 PPM and 200 PPM respectively for a discharge of 500 Cs.

2. Sediment distribution at off-take points has a vital influence on the design output. Sediment Transport approach must take into account the silt induction of the outlets and the off-takes in accordance with a carefully established criterion. A good deal of research work is needed to fully understand the

mechanism of sediment distribution at off-take points before using sediment transport concept as a design approach.

3. A relatively flatter slope of the downstream reach will not transport the sediment load conveyed by a steeper slope of the upstream reach. This poses a conceptual problem to the design approach sensitive to the sediment charge. Practically the channel dimensions get adjusted by distributing the effect over an extended length of the channel. But the design engineer, who has to match the design output with the incomming sediment, must show with the help of numbers that the difference in the carrying capacities of the two reaches is acceptable. Topography and the command considerations impose a rather inflexible constraint on changing the bed slopes for most channels of Punjab Canals.

4. Heading up, so frequently done at regulation points, generates a back water which affects water surface slope in a considerable length of channel (the effect of heading up of 1 foot for 400 Cs channel extends upto 4800 ft and normal velocity is reduced by 22%). When the channels are run in rotation, the effect of heading up becomes even more significant. A realistic computation of the sediment carrying capacity is not possible without considering the back water effect of the heading up.

An obvious conclusion from the above discussion is the fact that an extensive research effort is required to include the effect of operational conditions of Punjab canals after selecting a suitable relation for an approach which considers the quantity of sediment inflow as a basic design parameter. Such a work is not available at the present stage of research which makes, at least for now, the Sediment Transport approach an inadequate choice as a design alternative.

3.0. TRACTIVE FORCE METHOD

Tractive Force Method has resulted essentially from the study of forces that cause initiation of motion of the particles composing the channel perimeter. Theoretically the movement of particles will take place when the disturbing force (caused by the water past these particles) exceeds the resisting forces of cohesion and gravity. The design procedure involves equating the unit tractive force with the permissible tractive force estimated from curves/relations based on type of soil, its voids ratio, particle size and the content of sediment in water. Depth of flow thus computed and the assumed side slopes are used in the Manning's formula to determine the bed width. The following brief discussion is related to the applicability of the Tractive Force method for Punjab;

1. Experiments on determination of critical shear stress show that the incidence of gusts of sediment motion appears to be random in both time and space. This suggests that the process of initiation of motion is statistical in nature (Ref. 12). Because of the statistical nature of the initiation of motion the critical shear stress for given conditions can not be determined from results of experiments on even a slightly different set of conditions. A wide variation in critical conditions have been observed for sediment free water and that discharging sediment (Ref. 12). Same argument must apply to water discharging varying contents and types of sediment. The charts developed for different flow conditions with sediments sizes of 5mm and even large can not be considered valid for Punjab where sediment size varies from 0.1 to 0.3 mm.

2. Variation of critical shear as a function of mean particle diameter shows a wide scatter for various shear stress formulae (Ref. 12). Diversity of experimental and theoretical results makes the selection of a particular shear stress formula for Punjab an extemely complicated task.

3. The size of the channel section, obtained from the tractive force method using available charts for Punjab conditions, differ significantly from those commonly observed.

4. The Tractive Force method essentially aims at prevention of scour, whhere as in case of Punjab canals the common problem is sedimentation. Topography and command constraints seldom allow the flow velocity to exceed a limit where scour would become a predominent design consideration. The very nature of the method makes it an inedequate choice as a design alternative in Punjab.

4.0 REGIME CONCEPT

The basic difference of the Regime theory from the above noted approaches is that it considers the alluvial periphery of the channel, the fluid and sediment flowing in it as a single whole. The other two approaches take into account the individual effect of the contributing factors in accordance with the Laws of Fluid and Soil Mechanics.

The 'Regime Theory' was basically developed in plains of Indus and Ganges. The empirical work based on the Regime concept started with the brilliant investigations carried out by Kennedy, about the years 1983-1895, into the effect of silt laiden waters of lower reaches of Bari Doab Canal on the relation between the velocity and depth of flow at the final stages of making of a stable section. The work continued to advance, with a characteristic empirical nature, in search of physical relations which would help to determine design parameters of a silt stable section. Decades of work resulted in dozens of quite involved relations by many researchers for predicting slope and cross-sectional geometry of the sediment transporting channels. The intent of this paper is not to trace the history of the development of the Regime Theory, therefore, Lacey's equations have been mainly discussed along with those given by Dr. Bose & Simon-Albertson, in relation to the subject of this paper.

One of the earlier definitions of the "Regime Channels" was given by E.S. Lindly (Ref. 1). He stated;

> "When an artificial channel is used to convey silty water, both bed and banks scour or fill, changing depth, gradient and width until a state of balance is attained at which channel is said to be in regime".

The concept of regime as a state "where there is no silting no scouring" demands a rather precise dynamic balance in flow conditions and all dimensions of the channel. Absence of "objectionable scour or the silt deposit", part of an improved definition of regime given by Lane (Ref. 5), is decidedly a more progmatic attribute of the silt stable channel. Lindly (Ref. 1) made a very significant observation regarding non-silting and non-scouring velocities, he stated; "under any set of conditions, there is some latitude in the difference between velocity that just fails to cause scour and that which just suffices to prevent deposit". Regime of a channel, therefore, reflects a range of favourable conditions and not just one and only one combination of discharge, slope, and geometry of the channel cross-section.

Observations on channels which have run long enough to attain regime indicate significant variations to confirm the above fact. Variations in slopes and velocities in different parts of year along with their effects on the cross-section of the flow are matter of commmon observation. The design approach (ACRP) proposed by the Authors in section 4.8 determines the slope for the regime condition. Steepening of the slope to a certain extent does not, however, disturb the regime.

4.1 SMALL VERSUS LARGE DISCHARGE:

The equations that result from statistical correlations have a built in bias which inherently reflects the characteristic of the data base. The use of such relations in different conditions and beyond the controlling limits of the original data seldom produces satisfactory results. It was due to this reason that Lacey's equations, so successfully used for channels of small discharges, were not found as effective in case of Link Canals in Nineteen Sixties (Ref. 4). Sediment Transport relations developed elsewhere do not produce, for the same reason, reliable results when used under Punjab conditions.

As for the discharges, small discharges attain steeper regime slopes than those attained by large discharges under same conditions of sediment flow and type of soil comprising the wetted perimeter. While statisticcal relations can be developed for any range of discharges, the fact remains that relations developed for relatively limited range will make more realistic predictions when used within the same range. The Authors deal with the redesign of channels which fall mostly within the discharge range of upto 1000 Cs. The data base for the present investigation was, therefore, limited to discharges upto 1000 Cs. The Authors feel that a separate design procedure, developed on the lines suggested in this paper, will be useful for channels with higher discharges.

4.2 SCOPE OF THE PRESENT INVESTIGATION:

Equilibrium data observed by (ACOP) was used. Equilibrium measurements were defined as discharge, slope, and sediment measurements in a selected reach under steady flow conditions at or near full supply discharge. The selected steady reach was free of up or down stream influences (Ref. 11). Total number of data set was 678 with discharges ranging up to 1000 Cs.

Main object of the investigation was to lay down definite criteria for selecting slopes for given discharges to ensure problem free operation of the channels. For a discharge of 100 Cs, for instance, slopes of .00015 & .00022 (observed in running canals) corresponds to lacey's f' of .73 and .922 rspectively. Selection of a suitable f' is same as selection of suitable slope. There is no clear method available for selecting Lacey's f' which points to the need of a criterion for deciding on suitable slope. A data base covering a rather narrow range of discharges, like the one used in present investigations, sufficiently reflects the practical conditions of varying sediment flow and can, as such, produce reliable guidelines for deciding on required slopes for a similar range of discharges.

Lacey's silt factor, as appearing in his different equations, was also examined to interpret the flow conditions in the light of computed values of the silt factors.

4.3. LACEY'S SILT FACTOR

Lacey used data observed by Kennedy and other workers for this investigation. Some of the equations developed by him are as follows :

$$P = 2.67\,(Q)^{0.5} \qquad \text{--------} \quad (1)$$

$$V = 1.155\,(fR)^{0.5} \qquad \text{--------} \quad (2)$$

$$V = 16\,R^{2/3}\ S^{1/3} \qquad \text{--------} \quad (3)$$

$$A = 1.26\,Q^{5/6} / f^{1/3} \qquad \text{--------} \quad (4)$$

$$S = .000542\,f^{5/3} / Q^{1/6} \qquad \text{--------} \quad (5)$$

The silt factor appearing in above equations takes following forms and is denoted by variable subscripts to indicate the equation of its origin.

$$fvr = 0.75\,V^2/R \qquad \text{--------} \quad (6)$$

from equation (2)

$$fsr = 193.1\,R^{1/3}\ S^{2/3} \qquad \text{--------} \quad (7)$$

from equation (2) and (3)

$$fsq = [1844\,S\,Q^{1/6}]^{0.6} \qquad \text{--------} \quad (8)$$

from equation (5)

$$fqr = 0.1051\,Q/R^3 \qquad \text{--------} \quad (9)$$

from equation (1) & (4)

$$fd = 1.76\,(m)^{0.5} \qquad \text{--------} \quad (10)$$

relates 'f' with the mean bed silt diameter in mm.

For all data sets fvr and fsr were computed. The data sets were divided into three groups corresponding to fvr > fsr, fvr = fsr (with a 10% difference) and fvr < fsr. The number of data sets for above noted groups were 172, 264 and 242 respectively. The grouping based on two important forms of silt factors proved to be very helpful in studying variations in other forms of the silt factors.

Some researchers have viewed the variatins between different forms of silt factors for existing channels as a drawback in Lacey's approach. Civil Engineering systems seldom behave exactly as invesaged by the designer, and irrigation channels are no exception. The present study has shown that the variations in the relative values of the silt factors for above noted groups yield interesting information for studying interaction of the flow with slopes and geometry of the cross-section. Following discussion will help to interpret the physical behaviour of the channel in the light of above noted variations.

4.3.1. fvr & fsr

Hydraulic mean depth is related with velocity in equation (2) by fvr wheres fsr relates hydraulic mean depth with the slope. Equality of the two values of the silt factors implies satisfaction of the regime velocity equation (3) (the fact can be easily demonstrated by equating fvr with fsr). Mr.C. C. Inglis defined the ratio fvr/fsr as a measure of deviation from regime and showed that observed velocity could be computed by multiplying $16R^{2/3}$ $S^{1/3}$ by $(fvr/fsr)^{0.5}$. Simple algebraic manipulatin leaves V on either sides of equation (3) when right hand side is multiplied by the square root of fvr/fsr. The above noted ratio can be regarded as a measure of divergence from regime provided equation (3) is accepted as expression of the regime velocity.

The value of fvr increases with decrease of R while fsr increases with increase of either R or S or both. Study of fig 1 indicates that for fvr>fsr, the observed R values are less than those predicted by Lacey. For fvr<fsr (Fig. 2), the situation is quite the opposite and for fvr=fsr (Fig. 3), the observed R values reasonably match Lacey's predictions. For fvr<fsr the observed R values are close to those predicted by Simon-Albertson but higher than the predictions of Bose and Lacey. For fvr>fsr the observed values match those predicted by Bose while for fvr=fsr the observed values fall between predictions of Bose and Lacy. In view of the fact that fvr less than fsr is an indication of problem it is obvious that R-Q relation given by Bose is decided better than Simon's relation and mariginally preferable to Lacey's relation.

A value of fvr higher than fsr signifies that the observed velocity is more than the velocity required by cross-section geometry and slope. This, by all means, is a happy sign for Punjab Canals. Deviation from regime on the higher side of fvr can be viewed as problematic only in an extremely rare case where prevailing velocity assumes threatening proportions for the banks. Command consideration coupled with flatter available slopes almost eliminate generation of high velocitis in Punjab canals. The problem of silt deposition is encountered far more frequently than the isolated case of bed scour. The case where fvr<fsr may represent the problem situations in that it implies lesser existing velocities than the cross-section geometry and slope requires.

For an existing channel a comparison of fvr and fsr can yield useful initial information, but their relative values may not be regarded as conclusive pointers of the presence or otherwise of the problems. In a given situation fvr may be small as 0.6 and still greater than fsr which will require further investigation for a possible problem elsewhere in the channel. In general higher values of fvr were observed for data sets where fvr was greater than fsr. Table T2 contains statistics of the observed fvr and fsr values for all the three data groups.

	fvr > fsr		fvr = fsr		fvr < fsr	
	MEAN	STD	MEAN	STD	MEAN	STD
fvr	1.084	0.239	0.864	0.153	0.727	0.164
fsr	0.846	0.165	0.863	0.148	0.924	0.154
fsq/fsr	1.035	0.028	1.012	0.023	0.993	0.028
fsq/fqr	0.759	0.186	0.922	0.181	1.107	0.298

Table T2: Variations of Different Forms of Lacey's 'f' (Mean and Standard Deviation) for three data groups.

4.3.2. fsq & fsr

The silt factor fsq relates slope with discharge in equation (5). The silt factor fsq has been selected as the basis of comparison with other forms of 'f' because of its importance in determining the slope. The two silt factors fsq & fsr vary with about the same power of slope, their equality therefore, requires a fixed relation between discharge and hydraulic mean depth. It is because of existance of a relation between discharrge and hydraulic mean depth, as shown by some researches, that fsq is observed to be equal to fsr. Table T2 shows that the mean value of the ratio fsq/fsr is 1.035 for fvr>fsr, 0.993 for fvr<fsr, and 1.011 for fvr=fsr, with small values of standard deviation in each case. A higher value of fsq/fsr implies fvr>fsr which is, as seen in section 4.3.1, a favourable sign.

4.3.3. fsq & fqr

The value of fqr (equation 9) increases with decrease in R which is also a condition for increase in fvr. For fvr>fsr, therefore, a lower ratio of fsq/fqr. (.759) was observed (Table T2). The same reasoning explains a higher value of fsq/fqr (1.108) for fvr<fsr, and an in between value for fvr=fsr (0.922). It can be seen from equations (6) & (9) that fqr is far more sensitive to change in R than fvr. This explains a wider variations in fqr than fvr and also the other forms & silt factor. Because fqr follows from equations (1) & (4), it can be readily seen that fqr will be equal to fsq (and therefore fsr) if area of the

existing cross-section and the wetted perimeter obey equation (4) and equation (1) respectively. The difference between fqr and fsq in fact is an indication of difference in actual and predicated values of P or A or both.

4.3.4. fd

The silt factor related to the mean diameter of bed silt is given by equation (10) ;

$$fd = 1.76\, m^{1/2}$$

The mean diameter (d50) of bed material for data where fvr = fsr varies from 0.07 to 0.182 mm which gives value of 'f' equal to .46 and 0.75 respectively using the above relation. This is way out of line with the observed values of the silt factors for the data sets. The data sufficiently support the following facts ;

1. Sediment size of bed material decreases in the tail reaches of the channel.
2. Smaller discharges of the tail reach attain a higher 'f' at regime.

Equation 10 predicts higher 'f' in the head reach or channels with larger discharges which is contrary to common observation. This form of Lacey's 'f' deserves no serious attention for any design work.

For an existing channel different forms of Lacey's silt factor, excluding fd, can be regarded as useful indicaters of its hydraulic behaviour. For new channels, however, absence of a clear cut criterion for selecting a suitable silt factor is a problem. The Authors have developed a design procedure, applicable to new as well as existing canals, which uses widely tested equations of Regime Theory without the silt factor. Section 4.5 to 4.7 describe the controlling relations while section 4.8 covers the design procedure.

4.4. SIDE SLOPES

Lacey used side slope of 0.5 horizontal to 1 vertical in his relations. Channels with higher discharges tend to attain flatter side slopes in Punjab (Ref. 4). Correct estimation of the side slopes is essential for the design out put to be a true representative of the final shape of the channel. In order to recommend suitable side slope the data sets were divided into five groups of discharges varying up to 10, 30, 100, 300 and 1000 Cs. The left side slopes were found to be flatter than the right side slopes (for all groups) which appears to be the result of specific mode of observations. The averages of the mean values of the slopes of both sides for the five groups were computed to be 0.59, 0.714, 0.59, .64 & 0.67 respectively. With the exception of second group the side slopes manifest a flatening trend for higher discharges. The average side slope of 0.65 horizontal to 1 vertical has been used in ACRP against a computed average of 0.641.

4.5. THE P-Q RELATION

Lacey's P-Q relation (Equation 1) is widely accepted. A number of reserchers have concluded that the wetted perimeter is directly proportional to the square root of the discharge. The constant (2.67 in Lacey's equation) may vary a little. Following three P-Q relations were tested by the Authors;

$P = 2.67\ Q^{1/2}$ Lacey ------ (11)
$P = 2.6\ Q^{1/2}$ Simon-Albertson ------ (12)
$P = 2.8\ Q^{1/2}$ Bose ------ (13)

Regression analysis on 678 data sets produced following relations ;

$P = 2.85\ Q^{1/2}$ where $fvr = fsr$ ------ (14)
$P = 2.78\ Q^{1/2}$ where $fvr > fsr$ ------ (15)
$P = 2.90\ Q^{1/2}$ where $fvr < fsr$ ------ (16)

The P-Q relations of Lacey's, Simon, and Bose were compared with the observed data by computing the slope of best fit line with zero intercept. Coefficient of correlation was nearly one (.99987) in all three cases where slope of best fit line came out to be 0.9509, 0.9260 and 0.9972 for Lacey, Simon and Bose respectively. It is obvious that the relation given by Bose is marginally preferable.

4.6 THE SURFACE ROUGHNESS & THE REGIME VELOCITY

The surface roughness of the channel perimeter plays a significant role in formation of its longitudinal slope and the cross-section. The recent practices of channel design, other than the Regime Theory, consider surface roughness as a basic design parameter. The most widely used velocity relation is the one given by Manning. The flow conditions all over the world manifest enormous variations in the surface roughness of the channel perimeter. Some of prominent factors that influence roughness are, the size of the bed load material, bed shapes (ripples, dunes etc), vegitation, channel irregularities and alignment, sedimentation and scouring etc.

Attempts have been made to device methods of estimation of Manning's 'n' in a variety of situations for materials ranging from soil to all lining materials used anywhere in the world. All these estimations are essentially empirical in nature. The pure empirical methods, extensions of Strickler's Method (Ref. 6), correlate 'n' with representative size of bed material. These methods resulted from data of bed materials of much larger size than found in Punjab canals. No wonder then, that the 'n' values predicted by these methods do not match with the commonly observed range for Punjab canals.

An important observation about Manning's formula is the fact that it resulted from curve fitting based on purely empirical approach. The formula (in British Units) is ;

$$V = 1.485\, R^{2/3}\, S^{1/2}/n \qquad \text{----------}\ (17)$$

If a representative value is assigned to 'n' which coresponds to regime condition in Punjab canals (which is realistic considering the narrow range of discharges covered by this investigation) the shape of Manning's formula changes to;

$$V = K\, R^{2/3}\, S^{1/3} \qquad \text{----------}\ (18)$$

The regime condition as represented by equation (3) matches closely with the above equation. The constant in the regime equation may well be regarded to include the effect of surface roughness. The next criterion to determine preference of one equation over the other is a better fit in the relevant data. Simon used data from the sub-continent and testified to the validity of Lacey's regime equation (Ref. 7). Another confirmation of the validity of Lacey's regime equation came from Mushtaq/Rehman (Ref. 8). From above discussion it can be safely concluded that Lacey's regime equation is valid for use in design of channels in Punjab.

When Mannings equation is applied for regime condition, where velocity is given by equation (3), the value of 'n' works out to be equal to 0.0926 $S^{1/6}$ by simply equating the two expressions of velocity. Considering the ratio (fvr/fsr) as a measure of divergence from regime and the reciprocal effect of roughness on velocity, the value of 'n' may be estimated for channels out of regime by the following expression ;

$$n = 0.0926\, S^{1/6}\, (fsr/fvr)^{1/2} \qquad \text{-------}\ (19)$$

The above relation was found to hold for observed values of the entire data of this investigation. The reason is simple. Substitution of expressions for fsr and fvr in equation (19) yield the Mannings' equation. Since any design based on Lacey's approach must satisfy his regime equation, the designer has two options;

1. Use Lacey's regime equation.
2. Use Manning's equation with $n = 0.0926\ S^{1/6}$

The result in both the cases will be the same. The Authors have prefered to use Lacey's regime equation in the design approach proposed in section 4.8.

4.7. FROUDE NUMBER : A USEFUL CRITERION

The ratio of inertial forces to gravity forces represent the effect of gravity upon the state of flow. Froude Number gives this ratio and is defined as ;

$$Fr = V/(g^{*}D)^{0.5} \qquad \text{------------} \quad (20)$$

where V & g have usual meanings of velocity and accelleration due to gravity while D represents area of cross-section divided by the top width.

Kennedy related regime velocity with the depth of flow. Lindly (Ref. 1) developed similar relations with slightly changed co-efficient and power of depth of flow. Lacey's fvr (equation 6) can be regarded as a statement that for a given type of sediment, regime velocity bears a fixed relation with hydraulic mean depth. The velocity relations developed by Kennedy, Lindly and Lacey, therefore carry the same meanings. Some other researchers have also developed depth velocity relations.

The ratio between slope and Darcy-Weisbak friction factor 'fo' is related to V^2/R by following expression;

$$S/fo = V^2/(8gR) \qquad \text{----------} \quad (21)$$

The variable slope being a manifestation of roughness V^2/R must be constant for a silt stable channel. It is clear that Lacey's selection of fvr has a sound scientific basis.

Close resemblence of fvr with Froude number has drawn attention of many researchers. Blench obvserved that for channels with coarse silt, Froude Number was practically constant. Lacey found that Froude number was also constant for channels with finer silt but its value was lesser than those carrying coarse silt (Reg. 5). Lacey used the resemblence of the ratio V^2/R with Froude Number and little variation in Froude Number for stable channels to assert that V^2/R was a criterion for regime.

The Frude Number was studied for the three data groups of this investigation. The mean value of Fr is 0.162 for data where fvr<fsr, 0.176 where fvr=fsr and 0.197 where

fvr > fsr. Because of the similarity between Fr and fvr they share the reasons of their variations.

It is clear from the above statistics that the value of the Froud Number is a useful indication of the direction of deviation from the regime condition. A lower value represents deviation towards fvr < fsr which is indicative of problem situation. This leads to the further conclusion that for a representative flow condition of Punjab Canals (specially for small discharges), there exists a "regime range" of Froude Number, with a more useful lower limit. The fact that larger discharges attain flatter regime slopes necessitates correlation of the lower end of the "regime range" of the Froude Number with the discharge. Based on the lower value of the Fr from the discharge group of the data where fvr > fsr, the Authors have developed the following relation from regression;

$$LFr = 0.195\ Q^{-0.025} \qquad \text{---- (22)}$$

The above formula gives the minimum recommended value of Fr for a Punjab canal. For instance for discharges of 20 and 1000 Cs., Fr worked out by above formula is 0.181 and 0.164 respectively.

In the opinion of the Authors the Froude Number provides a much needed criterion for checking the regime condition for an existing as well as a new channel. For the new design the coondition fvr = fsr exists for the output based on any discharge and slope. For instance, a channel designed on Lacey's approach with a discharge of 100 Cs and slope of .0001 gives the Froude Number = .146, change of slope to 0.000187 for the same discharge gives a Fr = 0.174 which equals the number given by the above formula. The regime condition fvr = fsr is satisfied for both design outputs, but the Froude Number shows that the second design is better than the first. For existing canals therefore, the regime has two pre-conditions:

1. fvr not less than fsr
2. Fr not less than .195 $Q^{-0.025}$ (LFr)

As discussed before fvr > fsr, and for that matter, Fr > Lfr is not problem for Punjab canals almost in all cases.

4.8. ALLUVIAL CHANNELS REDESIGN PROCEDURE (ACRP)

Flow chart on page 24 explains in detail the Alluvial Channel Redesign Procedure (ACRP) developed by the Authors for channels up to 1000 cs. discharge. ACRP can be used for problem identification and redesign of existing as well as design of new channels. The controlling relations used in ACRP are;

$P = 2.8\,Q^{1/2}$ ---- Bose

$V = 16\,R^{2/3}\,S^{1/3}$ ---- Lacey

$Lfr = .195\,Q^{-0.025}$ ---- Authors

For an existing channel reach, the relevant procedure of the flow chart may be summarised as follows;

1. If
    (i) $fvr > fsr$ and
    (ii) $LFr < Fr < 0.3$, the channel reach has no hydraulic problem.
2. If above conditions do not exist the channel reach must be redesigned.

The following design procedure is applicable for both new as well as existing channels.

STEP-1 Assume a design slope from considerations of command and Topography.

STEP-2 Compute

$P = 2.8\,Q^{1/2}$

$A = 0.286\,Q^{0.5}/S^{0.2}$

$B = P-2.385D$

$D = (P-(P^2-6.94A)^{0.5})/3.47$

$Fr = V/(gA/Tw)^{0.5}$

$LFr = .195\,Q^{-0.025}$

STEP-3 If $Fr < LFr$ then

(i) Increase the slope, if possible, and go to Step 2.

(ii) Line the reach if slope can not be increased.

STEP-4 If $Fr > LFr$ but less than 0.3, the design is complete.

STEP-5 If $Fr > 0.3$ and the existing channel shows an objectionable scouring trend, then select a flatter slope (by introducing a fall in the reach) and go to step 2. An existing channel, as an isolated case, may show scouring trend with Froude Number greater than Lfr but less than 0.3 which would require flattening of the slope. For new channels Fr may be keept well below 0.3.

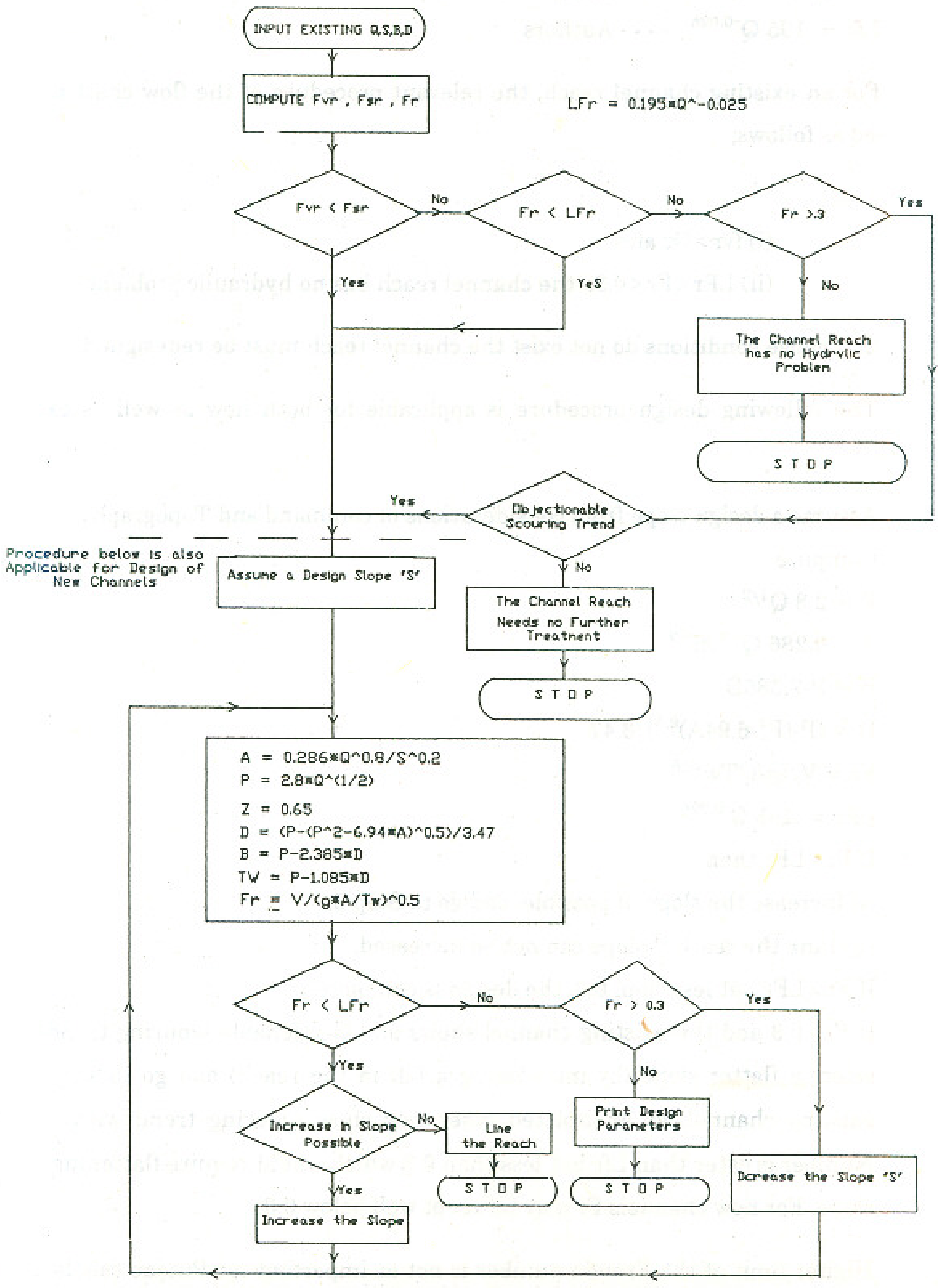
Higher limit of the Froude number is not as important for Punjab canals as the lower limit (LFr) is. The available slopes do not generate high velocities. A discharge of

FLOW CHART

ALLUVIAL CHANNEL REDESIGN PROCEDURE (A C R P)

ALSO APPLICABLE TO DESING OF NEW CHANNELS

(FOR CHANNELS UP TO 1000 cfs DISCHARGE)



5.0. CONCLUSIONS:

The discussion presented in the paper leads to following conclusions.

1. Sediment transport relations predict widely varying transport capacities of canals and show a poor correlation with sediment data observed in Punjab.
2. Huge variations in the sediment inflow over the year and lack of research work to account for operating conditions of Punjab Canals make the Sediment Transport concept an inadequate choice as design approach at its present stage of research.
3. Tractive Force method does not effectively deal with the more common problem of sedimentation in Punjab canals. It does not, as such, qualify for a reliable design alternative.
4. Regime Theory is a dependable design tool for Punjab canals. There is a need for improvement of design equations being used by Punjab Irrigation and Power Department.
5. For an existing channel, variations in different forms of Lacey's f serve as useful indicators of the channel behaviour.
6. Alluvial Channel Redesign Procedure (ACRP), developed by the Authors, uses accepted relations of Regime Theory, without the disputed estimations of Lacey' 'f' and produces results quite comparable with approaches given by Lacey and other researchers.

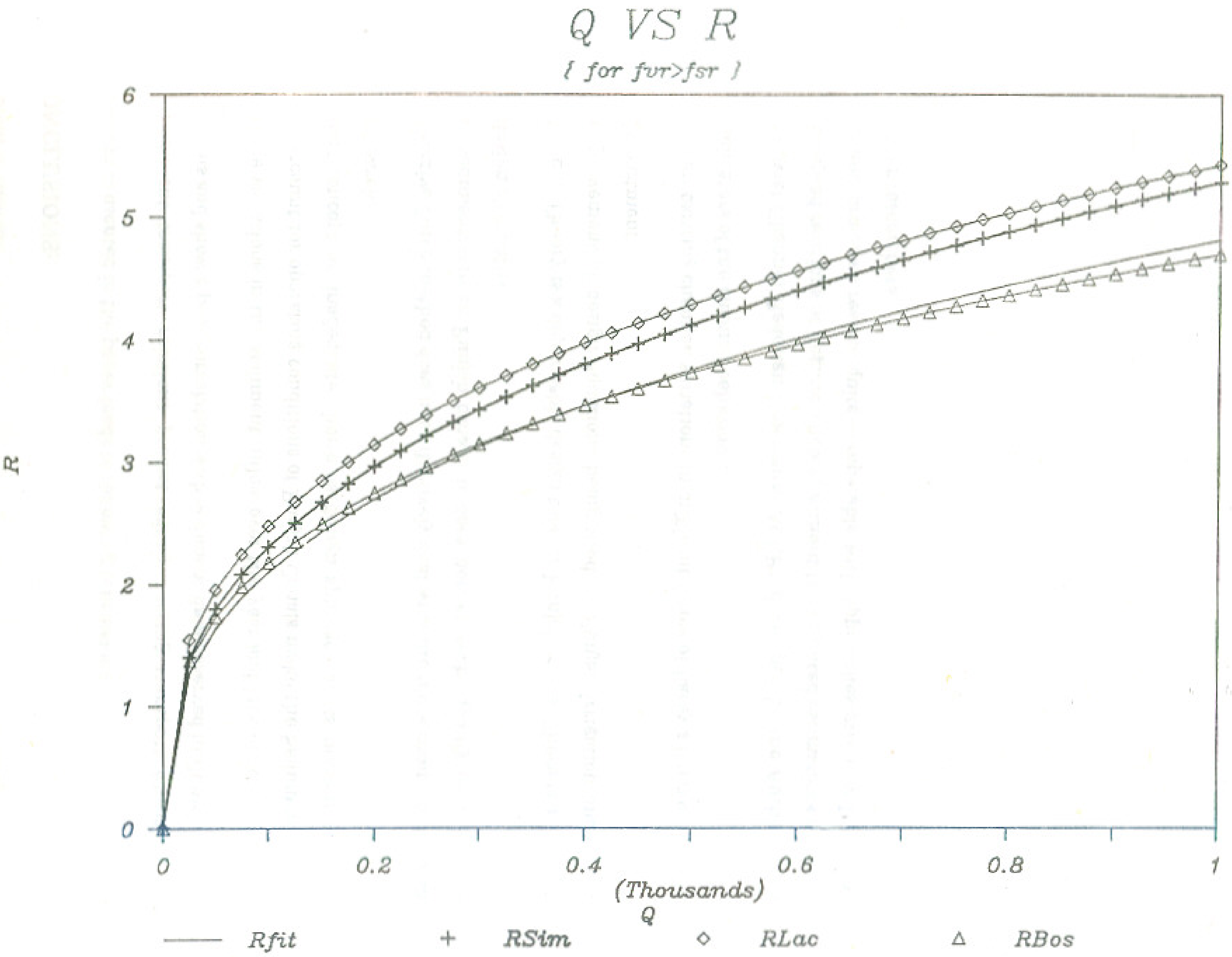

Q VS R
{ for fvr>fsr }
R
0
1
2
3
4
5
6
0
0.2
0.4
0.6
0.8
1
(Thousands)
Q
Rfit
+ RSim
◇ RLac
△ RBos

FIG:-1

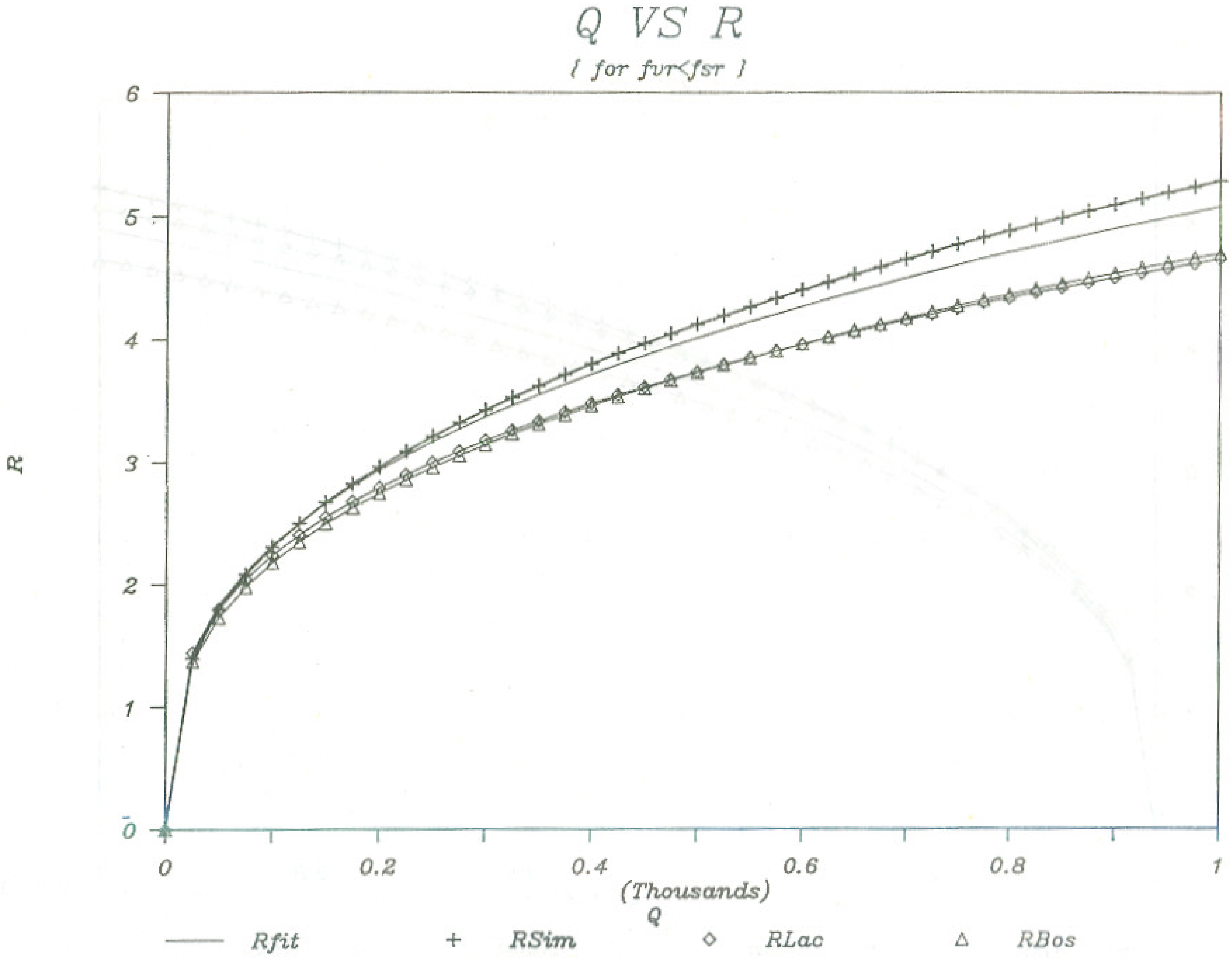

Q VS R
{ for fvr<fsr }
R
6
5
4
3
2
1
0
0
0.2
0.4
0.6
0.8
1
(Thousands)
Q
— Rfit
+ RSim
◇ RLac
△ RBos

FIG:-2

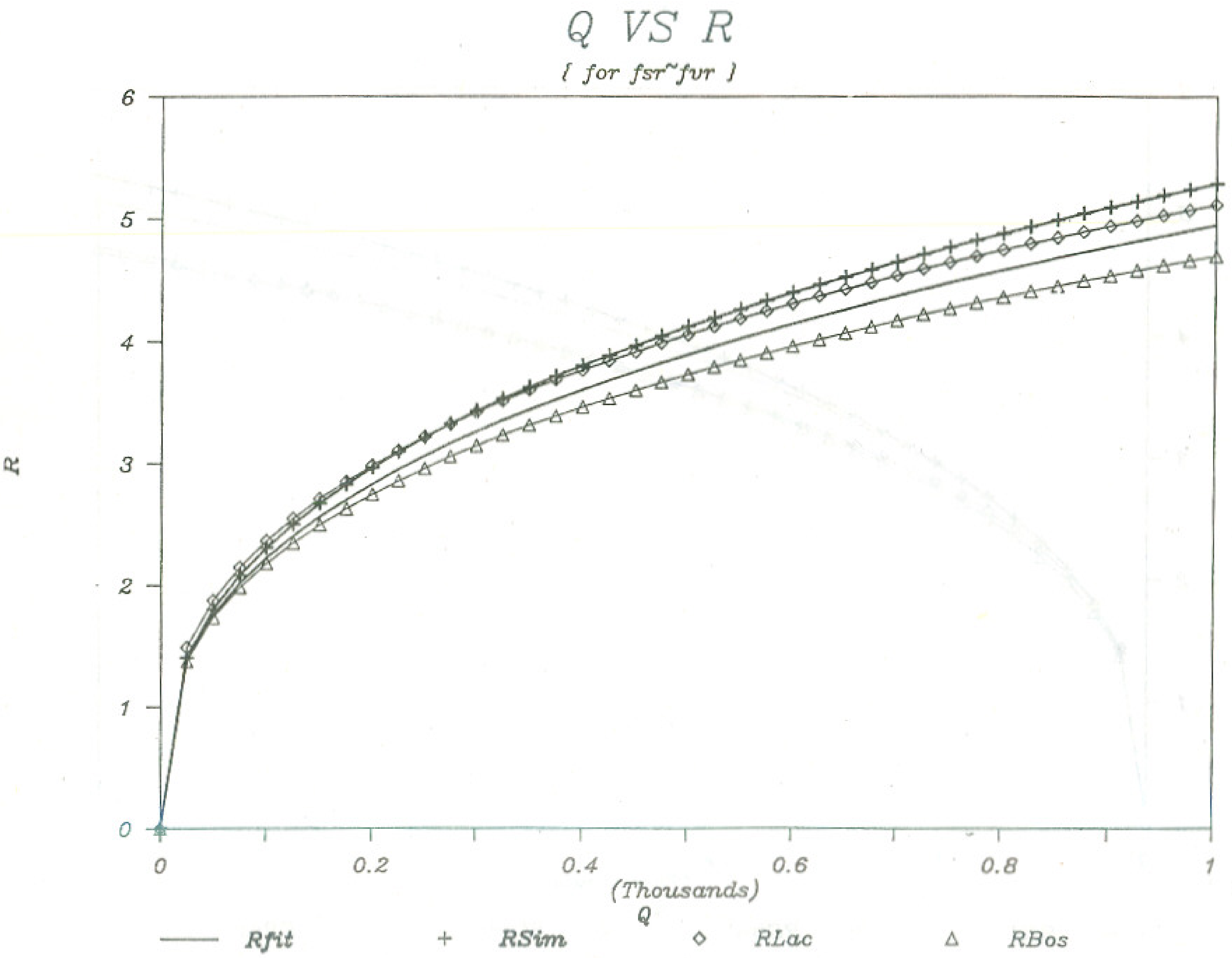

Q VS R
(for fsr~fvr)
R
6
5
4
3
2
1
0
0
0.2
0.4
0.6
0.8
1
(Thousands)
Q
Rfit
+ RSim
◇ RLac
△ RBos

FIG:-3

Table - T-3

Comparison of the design out put of Simon - Albertson, and Lacy (with slopes predicted by former)

Simon & Albertson						Lacey with Simon's Slope					
Q (Cfs)	S (%)	B (ft)	D (sft)	V (ft/s)	Fr	Q (Cfs)	S (%)	B (ft)	D (ft)	V (ft/s)	Ft
20	0.340	7.71	1.75	1.33	0.186	20	0.340	8.17	1.69	1.316	0.187
50	0.258	13.25	2.30	1.51	0.183	50	0.258	13.90	2.23	1.496	0.183
100	0.210	19.62	2.83	1.67	0.180	100	0.210	20.50	2.77	1.648	0.180
200	0.170	28.80	3.56	1.84	0.176	200	0.170	30.00	3.47	1.816	0.177
300	0.151	35.94	4.07	1.94	0.174	300	0.151	37.38	3.96	1.922	0.174
400	0.138	42.00	4.47	2.02	0.173	400	0.138	43.65	4.36	2.001	0.173
500	0.129	47.37	4.81	2.09	0.172	500	0.129	49.20	4.70	2.065	0.172
600	0.123	52.25	5.11	2.14	0.171	600	0.123	54.24	4.99	2.110	0.171
700	0.117	56.75	5.38	2.19	0.170	700	0.117	58.89	5.26	2.164	0.170
800	0.112	60.95	5.63	2.23	0.169	800	0.112	63.23	5.50	2.205	0.169
900	0.109	64.91	5.86	2.27	0.169	900	0.109	67.31	5.72	2.242	0.169
1000	0.105	68.65	6.07	2.30	0.168	1000	0.105	71.18	5.93	2.275	0.168

Table - T-4

Comparison of the design out put of ACRP and Lacey (with slopes predicted by former)

ACRP Approach						Lacey with ACRP's Slope					
Q (Cfs)	S (%)	B (ft)	D (sft)	V (ft/s)	Fr	Q (Cfs)	S (%)	B (ft)	D (ft)	V (ft/s)	Ft
20	0.291	8.56	1.66	1.25	0.180	20	0.291	7.99	1.77	1.275	0.177
50	0.227	14.57	2.19	1.43	0.177	50	0.227	13.72	2.31	1.457	0.176
100	0.181	21.45	2.75	1.57	0.173	100	0.181	20.26	2.88	1.600	0.172
200	0.140	31.41	3.43	1.73	0.170	200	0.149	29.74	3.59	1.768	0.169
300	0.133	39.15	3.92	1.84	0.168	300	0.133	37.11	4.09	1.874	0.168
400	0.124	45.75	4.29	1.92	0.168	400	0.124	43.39	4.48	1.958	0.167
500	0.117	51.59	4.62	1.98	0.167	500	0.117	48.95	4.81	2.024	0.166
600	0.111	56.87	4.91	2.03	0.166	600	0.111	53.98	5.11	2.077	0.166
700	0.106	61.73	5.17	2.08	0.165	700	0.106	58.61	5.38	2.122	0.165
800	0.103	66.33	5.39	2.12	0.165	800	0.103	62.97	5.61	2.167	0.165
900	0.101	70.66	5.59	2.17	0.165	900	0.101	67.11	5.81	2.212	0.165
1000	0.097	74.70	5.81	2.19	0.164	1000	0.097	70.94	6.04	2.240	0.164

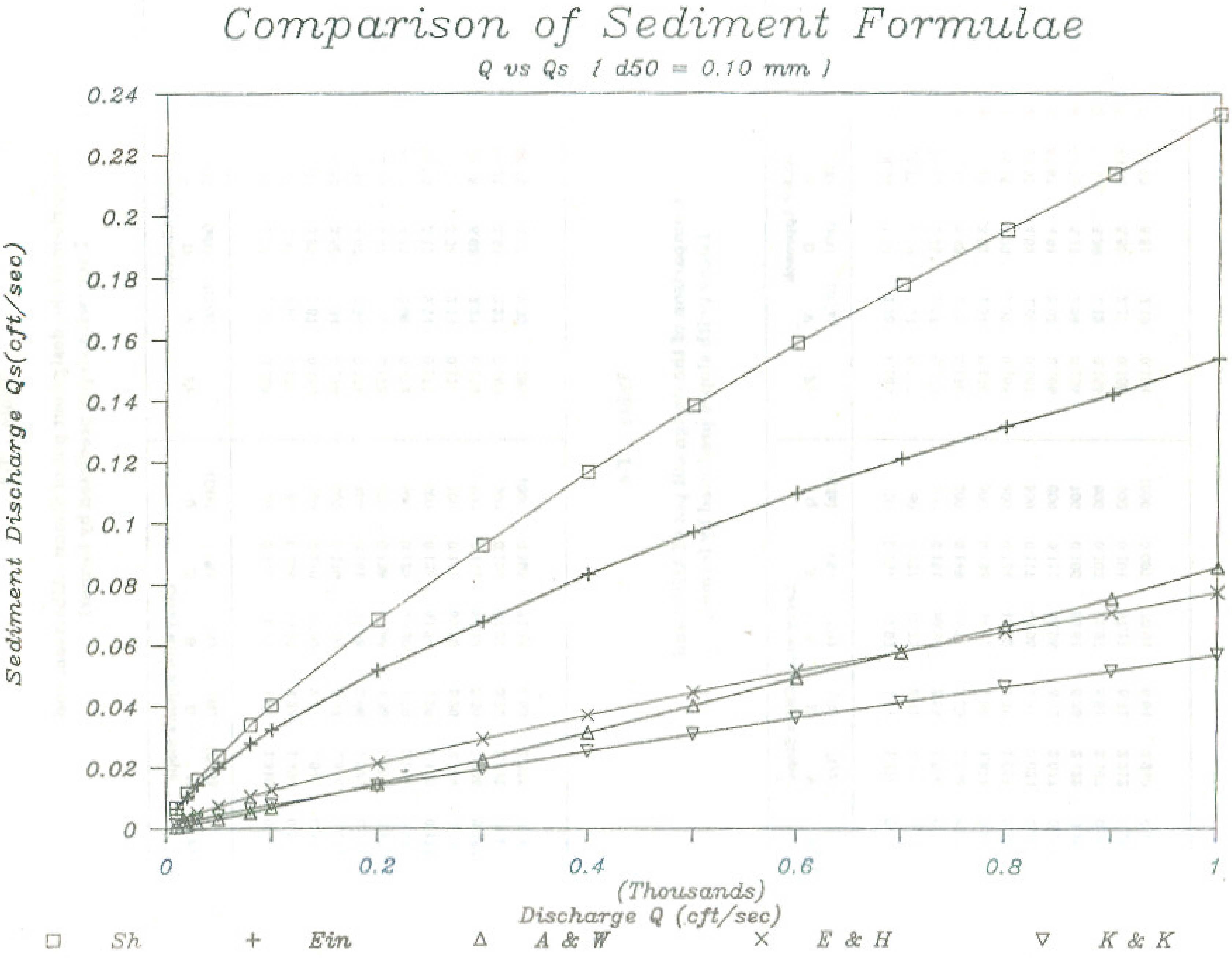
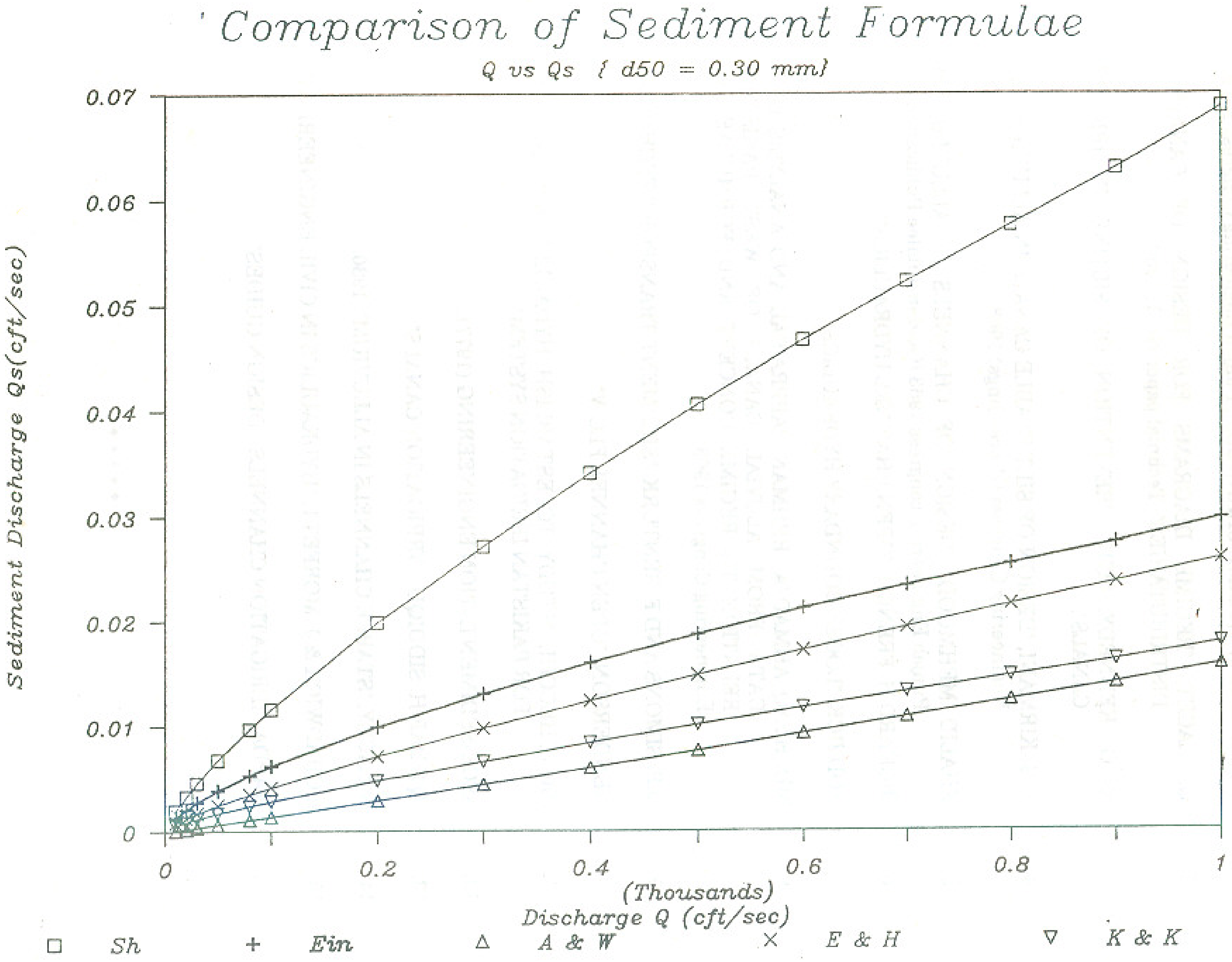

Comparison of Sediment Formulae
Q vs Qs (d50 = 0.10 mm)
Sediment Discharge Qs(cft/sec)
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.2
0.4
0.6
0.8
1
(Thousands)
Discharge Q (cft/sec)
□ Sh
+ Ein
△ A & W
× E & H
▽ K & K

FIG:-5



Comparison of Sediment Formulae

Q vs Qs { d50 = 0.30 mm}

FIG:-6

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