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REGIME APPROACH FOR PREDICTING THE ALLUVIAL CHANNEL GEOMETRY

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ABSTRACT : A functional approach for the prediction of channel geometry in alluvium is presented. This approach was developed based on the application of dimensional analysis of the salient variables that control the channel behaviour. The resulting functional equations were then evaluated to obtain numerical relationships by analyzing a large number of data from different sources. A flow depth equation was also established based on the available channel observations. The predictive capacity of the present approach has been tested against independent set of data and found an excellent agreement. Predicted channel dimensions were also compared with those obtained using the Lacey regime equations of canal design. This approach for prediction of channel geometry can be used for proposing suitable channel dimensions in irrigation and drainage projects.

KEY WORDS : Alluvium, channel geometry, functional approach, regime, channel, irrigation projects,

INTRODUCTION

One of the objective of studies on channel geometry is to examine the different combination of controlling parameters that results in a stable condition. It is important that such combination of parameters are known to an engineer when he designs a new channel or plans to channelise a river. Channelisation of natural streams may be required for improvement of navigation and acceleration in the passage of floods, for which widening, deepening and straightening of the channel may be involved. Artificial channels may be constructed for irrigation or navigation projects. In these cases, the problem is to determine the combination of cross-sectional area, shape and slope of channel that will carry a given discharge of water and sediment load and remain in stable condition.

The study of stable alluvial channels in terms of cross-sectional geometry, slope and channel pattern has been a subject of considerable research over a century. Traditionally, an alluvial channel is considered to posses three degrees of freedom to adjust its cross-section for a given flow condition. These three degrees of freedom are in width, depth and slope. In recent years, investigators have agreed that these are all dependent variables in a alluvial channel flow. Thus, there has been the necessity for atleast three equations to express these variables quantitatively. The problem appears more complex when one recognises the fact that sediment transport also affects the channel stability. For describing such effects, other variables such as sediment concentration and its median size are to be taken into consideration.

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The first quantitative study in the determination of shape of a channel was made by Kennedy (1885). By analyzing data of upper Bari Doba canal, he derived relationship between the mean velocity and the depth of flow. Based on data from stable canal observations, Lacey (1930) suggested a set of regime equations in which silt factor was incorporated. For a canal carrying significant discharge and substantial silt loads is usually designed using Lacey's regime approach. This approach is being practised in Bangladesh (EPC, 1989). Many investigators after Lacey had attempted to modified and generalised the regime concept over the past decades. These attempts involved the analysis of large number of data from field sources.

The cross-sectional shape of a channel in equilibrium is approximately a trapezoidal section. Blench (1969) observed that the standard canal section was a trapezoidal with side slope 1/2 : 1, and with dunes of sand on the bed. He also observed that "sides were erodible-depositable, made of silt-clay loam and beautifully maintained so as to be apparently hydraulically smooth." Barr et al. (1981) put forward a similar view that river channels over straight reaches can be considered as trapezoidal section similar to that of a canal. A trapezoidal channel section may be schematised in to two distinct portions. These are main channel section and two side channels. Nishat (1981) analyzed a large volume of data to establish combination of various geometric parameters for stable alluvial channels based on main channel section. Based on this idea and with the application of echelon matrix (Barr, 1985) procedure of dimensional analysis, Kawas (1985) and later Matin (1988) consolidated this work which led to development of an approach for the prediction of channel geometry. This was based on the normalisation of observed cross-sectional data obtained from different sources. In this paper, objective is to demonstrate about the development of this approach to predict the channel geometry in alluvium.

BASIS OF CORRELATION

A potential basis of correlation of a alluvial channel data has been evolved (Matin et al., 1993) by applying the echelon matrix procedure of dimensional analysis. The correlation in terms of non-dimensional functional arrangement is as follows :

$$\left[\frac{B}{H}, \frac{Qg^2}{V_s^5}, \frac{Q_s g^2}{V_s^5}, \frac{V_s}{(gH)^{1/2}}\right]=0 \qquad (1)$$

Primarily neglecting the effect of sediment flow in channel dimension, equation (1) can be expressed as the following functional arrangement :

$$\left(\frac{B}{H}, \frac{Qg^2}{V_s^5}, \frac{V_s}{(gH)^{1/2}}\right) = 0 \qquad (2)$$

DATA

Obviously, the establishment of a functional relationship would depend on analysis of a large volume of data. Table 1 summarises the data used in the present investigation. These data obtained from computerised data bank namely the Strathclyde laboratory data (Hossain, 1984) and Brownlie (1981) data and data from many other sources covered a wide range of flow condition.

NORMALISED CHANNEL SCHEMATISATION

The normalised channel is taken within sequence of a trapezoidal section where there is imposed a constant ratio of top width to bottom width. The difference between the discharge in the normalised section and the real section is in respect of flow associated in the side channels. The average velocity of side channel sections can be assumed as 2/3 that of main channel velocity. Thus the concept of normalisation of cross-section and relevant expressions can be defined as follows :

$$B_n = C_1 B_m \qquad (3)$$

$$Q_n = V_m H B_m + C_2 V_m [(B_n - B_m)/2H] O \qquad (4)$$

Here, C_1 and C_2 are the constant factors. The value of C_1 was assumed as 1.22. However, this assumption was based on an assessment of field data for cases where the value of side slope was known. According to Nishat (1981), the value of C_2 was assumed as 2/3.

EVALUATION OF RELATIONSHIPS

Expression for relative width

The relevant functional form of the relative width of a channel is given by equation (2). This correlation can be expressed by the application of the following expression :-

$$\frac{B_n}{H} = 10^{a} \left(\frac{Q_n g^2}{V_s^{\,5}}\right)^{b} \qquad (5)$$

Where,

$$a = 1.88\,(0.00097 + F_s)^{-0.23}, \qquad \text{for } F_s < 0.025 \qquad (6)$$

$$= 1.18\,(0.0165 + F_s)\ -0.40 \qquad \text{for } F_s > 0.025$$

$$b = 0.625 + 0.526\,F_s \qquad (7)$$

$$F_s = V_s/(gH)^{1/2}$$

Flow Depth Equation

Using same data (Table 1), it was possible to obtain a relation between depth (H) and longitudinal gradient (S), for different values of discharge as third variable. This relation can be expressed as follows :

$$H = 0.067\, Q^{0.284}\, S^{-2.44} \tag{8}$$

Equation (8) was established primarily under conditions where it was considered possible to neglect the effect of sediment concentration in the flow. However, number of laboratory tests conducted by author and Hossain (1984) in trapezoidal flume with mobile bed revealed that the greater the rate of sediment, the lesser the equilibrium depth of flow(Fig. 1). Thus the revised form of flow depth equation in which the allowance for the influence of sediment concentration is included, can be expressed as follows :

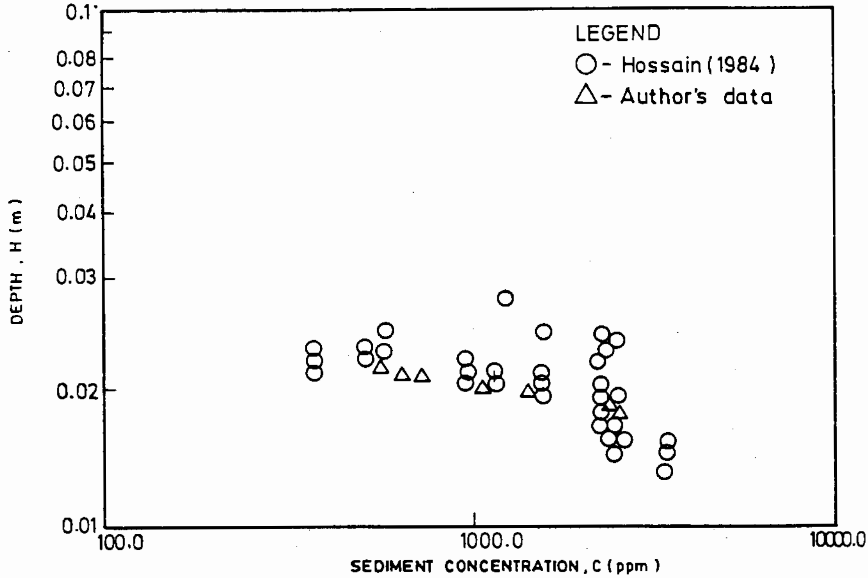

Fig 1. Variation of Channel Depth with Sediment Concentration for trapezoidal Flume Data at Discharge Q = 0.00167 m^3s^{-1}

$$Hc = \frac{H(1+\psi_c)}{1+0.13{*}C^{0.32}\psi_c} \tag{9}$$

in which $\psi_c = 3.432\,(540/C)^{-5.682}$ (10)

Table 1. Summary of the basic data sets used for the investigation. (Source : Matin, 1988)

Source Description	No. of Data Sets used	Discharge (m^3s^{-1})	Sediment concentration (ppm)	Slope x 1000	Sediment median size (mm)
Strathclyde lab.	53	0.0005-0.015	525.0-9250.0	1.000-32.00	0.150-0.300
R. Raju et al	4	0.018-0.015	150.0-2425.0	0.750-2.830	0.27
Ackers	14	0.028-0.151	10.0-476.0	0.410-9.200	0.150-0.200
Ikeda	3	0.008-0.010	57.0-121.0	1.810-2.020	1.30
Simons Bender	7	4.14-29.19	52.0-447.0	0.058-0.330	0.096-0.715
UP Canals	28	0.42-281.9	58.0-2010.0	0.102-0.434	0.110-0.410
CBIP (India)	18	1.15-242.0	670.0-1518.9	0.700-0.100	0.051-0.820
CHOP	30	27,52-427.57	115.7-1316.9	0.051-0.254	0.090-0.311
NEDECO	33	28.90-3089.90	8.3-2000.5	0.015-0.620	0.100-1.300
Atchafalaya River	40	2044.40-14186.30	12.5-567.0	0.020-0.504	0.105-0.303
Colorado River	28	77.53-408.35	18.0-572.0	0.030-0.304	0.160-0.695
Leopold's Data	37	83.33-454.30	49.0-516.0	0.053-0.346	0.140-0.443
Middle Loup	27	9.03-13.61	437.8-2269.2	0.920-1.570	0.270-0.430
Mississippi River	25	1885.84-28825.67	7.4-329.1	0.020-0.133	0.173-1.129
Mountain Creek	19	0.07-15.10	40.8-686.0	1.370-1.790	0.200-0.899

Slope Equation

The channel longitudinal slopes (S) were correlated with the discharge (Q) as shown in Fig. 2. This correlation was expressed by the simple power law :

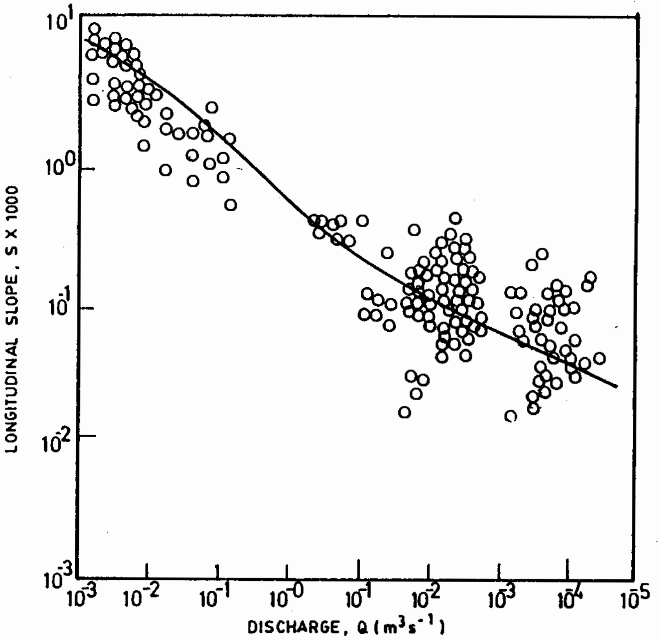

Fig 2. Slope-Discharge Relation

$$S = 10^{-3}\left(\frac{1+1.56Q^{1.36}}{1+5.06Q^{1.36}}\right)Q^{-0.255} \qquad (11)$$

CALCULATION PROCEDURE

The basic input variables are the discharge Q, the sediment median size (D_{50}), the sediment concentration (C). All these variables should be in SI units. Other input data are the kinematic viscosity (V) for calculation of fall velocity (V_s) and the channel side slope (Z). The calculation for channel width and depth are carried out as follows : First an assumption has to be made that the discharge within the normalised channel is equal to the actual discharge. The the initial values of fall velocity Froude number, width and depth of the normalised channel are to be calculated by using the equations (5) to (10). Now the continuity of flow should be checked for these values of channel dimensions. For continuity check, the initially assumed value of normalised channel discharge (Q_n) to be replaced by that of calculated discharge value. This process has to be repeated until Q/Q_{cal} tends to unity.

Degree of Compliance of Prediction Procedure

The geometry of alluvial channels as predicted from the authors approach was tested against wide range of channel data. The degree of compliance was tested by comparing the values of predicted geometry variables with those of observed variables. Results of the prediction are shown in Fig.3 for width and in Fig.4 for depth. These figures indicate a reasonable agreement between observed and predicted values.

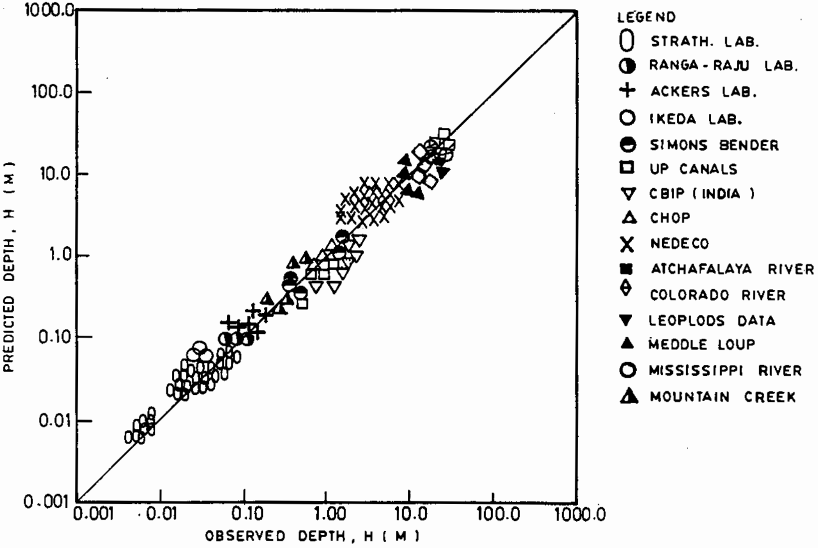

Fig 3. Predicted Versus Observed width for Author's Approach

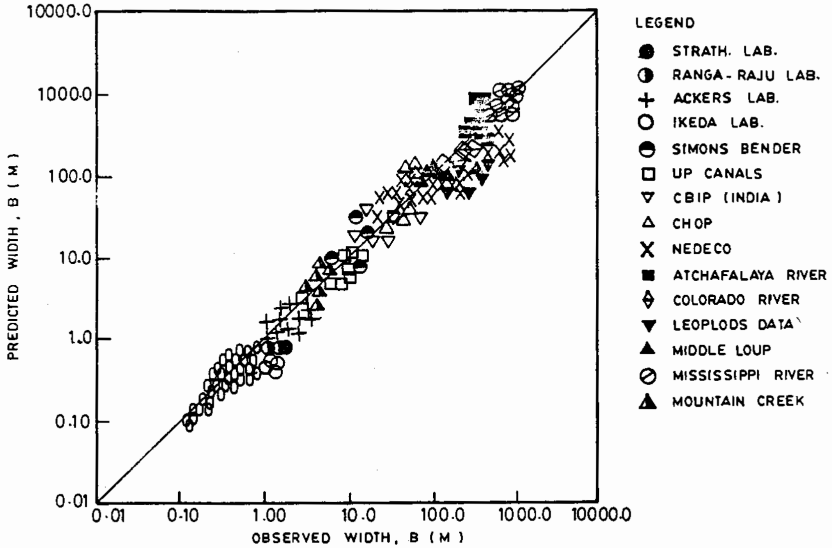

Fig 4. Predicted Versus Observed Depth for Author's Approach

VERIFICATION WITH FIELD CANAL DATA

Data used for the initial assessment includes the same data that were utilized in the formulation of various geometry relationships. However verification of the degree of compliance of the relationships against independent data is necessary. In particular, it is most desirable to utilize field data for such verification. This is because, it is to such circumstances that the practical design application has to be made.

In recent time, a notable effort has been made by Mahmood et al. (1987) who have assembled observations from large sand bed channel of link and irrigation canal systems of Pakistan in order to verify the existing theories and relationships for design of stable channels. This data base is referred here as Washington data. The characteristics of the Washington data are summarised as follows :

Discharge, Q (m^3/sec)	:	0.30 to 617.0
Width, B (m)	:	2.224 to 157.58
Depth, H (m)	:	0.306 to 4.437
Longitudinal Slope, S	:	0.013×10^{-3} to 0.333×10^{-3}
Sediment concentration, C(ppm)	:	5. 0 to 2233.0

The results of the degree of compliance against the Washington data are shown in Fig.5 and Fig. 6. Regarding the capacity of predicting channel width, it is found that the author's approach have a compliance of 38% within the range 0.833-1.20. For depth prediction, with the range of discrepancy ratio between 0.833 to 1.20 about 37% data is in agreement with the observed data. From these results, it may be said that the prediction obtained by the authors' approach show satisfactory performance in predicting channel width and depth.

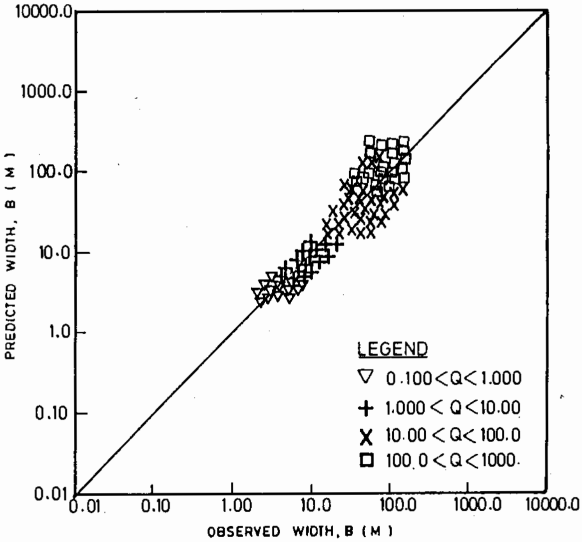

Fig 5. Predicted vs. Observed width for Author's Approach Against the Washington Data

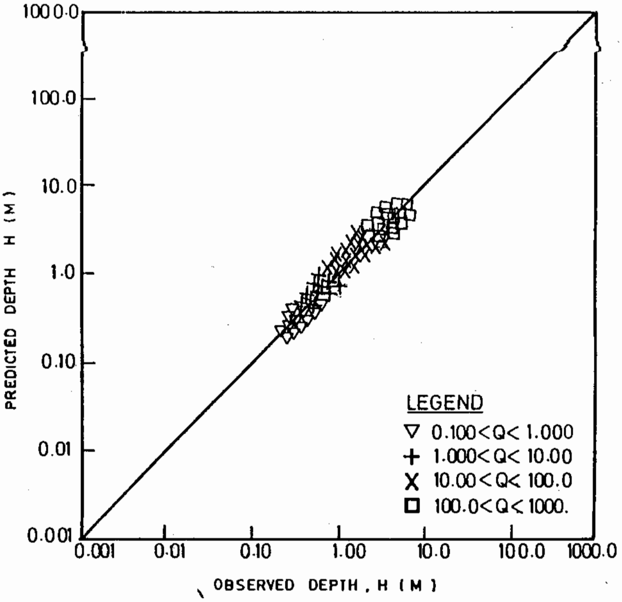

Fig 6. Predicted vs. Observed Depth for Author's Approach Against the Washington Data

COMPARISON WITH LACEY'S REGIME EQUATIONS

The most well-acknowledged Lacey's regime equations in S.I. units are as follows :

$$P = 4.75\,Q^{1/2} \tag{12}$$

$$R = 0.473\,(Q/f)^{1/3} \tag{13}$$

$$S = (f^{5/3}Q^{-1/6})/3340 \tag{14}$$

where $f = 1.76\,D_m^{1/2}$

For design of a canal by Lacey's approach, the inputs required are the discharge and mean diameter (D_m) of bed material.

Prior to make comparison, the applicability of Lacey's regime approach in predicting channel perimeter (P), hydraulic mean depth (R) and longitudinal slope (S) were verified against the available data. The channel cross-sections were schematised as a trapezium with side slope Z as imposed using Smith relation (Smith, 1974). Thus the actual P, R, S were computed from known values of Q, B and H from the data base. Predicted values are obtained from equations (12) to (15). It has been found that these parameters differ significantly from Lacey's equations. Therefore an attempt has been made to adjust perimeter values for the improvement of depth and width prediction. The corrected coefficients of the equation (12) and (14) are found to be 5.65 and 2910 instead of 4.75

and 3340 respectively. After the adjustment of the Lacey equations improvement of the predicted capacity is shown in Table 2. Matin and Islam (1989) compared the width and depth prediction from the present approach and the Lacey regime approach of canal design against ACOP canal data. Results of the comparison are shown in Table 3. From these results, it is evident that the performance in predictive capacity of the present approach against the field data is satisfactory. However, significant improvement of the Lacey equations can be achieved **(Table 2)** after the adjustment in coefficients of said equations.

Table 2. Assessment of Lacey's approach on the basis of percentage error and percentage of data coverage in selected discrepancy ratio range

Channel geometry variables	Lacey's Approach	% error*	% data coverage in discrepancy ratio** range	
			0.91-1.10	0.83-1.20
width	original	29.98	8.55	25.0
	adjusted	21.01	31.58	32.63
Depth	original	35.15	11.18	30.26
	adjusted	15.05	18.03	57.08
Slope	original	33.37	13.12	26.97
	adjusted	31.58	15.79	26.73

$$\text{*\% error} = \sqrt{\frac{(\text{Predicted-observed})^2}{\text{No. of observed data}}}$$

***Discrepancy Ratio = Predicted / Observed*

Table 3. Comparison with Lacey's approach on the basis of percentage error and percentage of data coverage in selected discrepancy ratio ranges.

Channel geometry variables	Approach	% error	% data coverage in discrepancy ration range	
			0.91-1.10	0.83-1.20
width	Lacey	29.98	31.58	32.63
	Authors'	27.19	38.71	40.05
Depth	Lacey	35.15	18.03	57.08
	Authors'	14.69	40.13	75.66
Slope	Lacey	33.37	15.79	26.73
	Authors'	37.27	11.18	20.39

DISCUSSION

There is benefit to be achieved by applying dimensional analysis in problems related to study of the alluvial channels behaviour. However dimensional analysis must be carried out in conjunction with the physical understanding to the process involved. Together with the physical arguments, the application of dimensional analysis provide towards formulation of reliable basis of correlation between pertinent parameters. In authors findings, it is demonstrated that the shape factor (B/H) of an alluvial channel is a function of non-dimensional discharge (Qg^2/V_s^5) and the fall velocity Froude number $V_s/(gH)^{1/2}$. The role of sediment fall velocity Froude number is also significant that quantifies interrelationship between the fall velocity and the depth.

A flow depth equation has been deduced and applied to the basic functional equation for the purpose of channel geometry prediction. In prediction procedure, the input variables were the water discharge, the sediment size, the sediment concentration. The channel longitudinal slope may be considered as dependent variable and can be calculated from the discharge values using equation (11). On testing the applicability and efficacy of authors' approach, it has been found that this can be applied successfully over a wide range of channel sizes. Comparing the predicted geometry variables with Washington data file, it was found that about 38% and 37% data falls within discrepancy ratio range 0.833 to 1.20 for width and depth respectively.

It is evident that the Lacey's method of canal design is widely practised in this Indian subcontinent due to its satisfactory performance. Using this method, the main and branch canals of Teesta irrigation and drainage project of Bangladesh water Development Board had been designed. The usage of this method is rather simple and based on explicit empirical relations. It is, however, emphasised that if proper calibration can be made in Lacey's equations against data from different old canals, better design of canals could be possible in future. The author's approach, on the other hand, is based on the non-dimensional parameters for defining the shape factor. Equations (5) to (10) expressing the channel geometry variables are interdependent and require few iteration to satisfy continuity condition. It is to be worth mentioned that the author's approach considers the effect of sediment concentration to predict the channel dimensions. This is demonstrated in Fig. 7 and Fig. 8. It is observed that the influence of sediment concentration on channel dimension is found to be significant for the cases of sediment flow greater than about 500 ppm. For higher rates of sediment inflow it appears that a predicted channel becomes to be relatively shallower and wider for its stability.

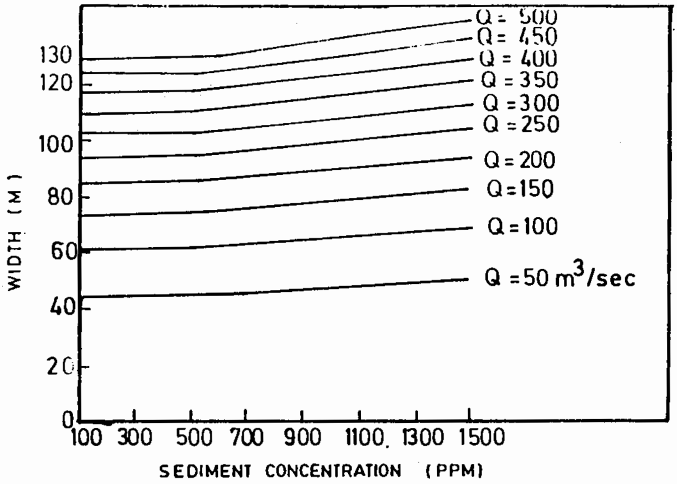

Fig 7. Variation of Channel Width Against Sediment Concentration for D_{50} *= 0.20mm, T = 20°c*

CONCLUSIONS

The usage of this approach for the prediction of channel geometry is simple and gives reasonable accuracy in the predicted results, when compared with prototype data. Predictions obtained from this system lead to a suitable cross-sectional area and shape factor for long term stability. For use in design work, the proposed approach can be adopted for determination of stable channel size of irrigation and drainage projects.

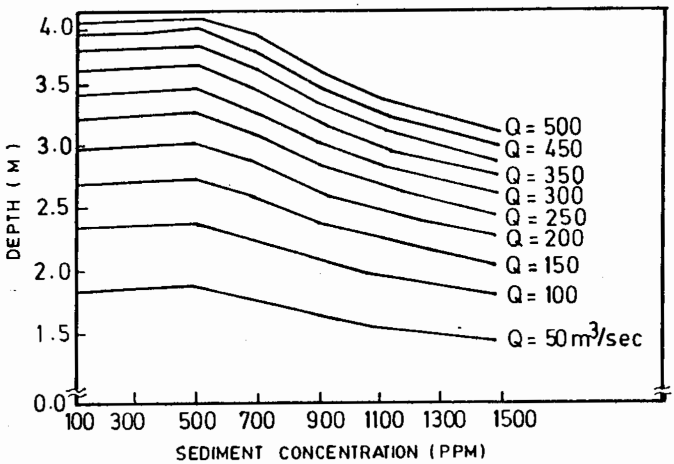

Fig 8. Variation of Channel Depth Against Sediment Concentration for D_{50} *= 0.20mm, T = 20°c*

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NOTATION

B : Channel width

B_n : Width of normalised Channel

C : Sediment concentration

D_m : Sediment mean diameter

D_{50} : Sediment median diameter

F_s : Fall velocity Froude number

f : Silt factor

g : Acceleration due to gravity

H : Depth of flow

P : Wetted perimeter

Q : Discharge

Q_s : Sediment discharge

Q_n : Discharge through normalised channel

R : Hydraulic radius

S : Channel longitudinal slope

T : Temperature

V_s : Fall velocity

Z : Channel side Slope