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ESTABLISHMENT OF RATING CURVE UNDER SHIFTING CONTROL

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LIST OF SYMBOLS

A = cross sectional area of the channel;
A' = portion of A deriving its resistance from bed skin friction;
A'' = portion of A deriving its resistance from bed form drag;
b = bed width;
C = concentration of bed material;
C_m = coefficient used in Mostafa-McDermid velocity relation;
D = mean depth;
d = flow depth;
d_g = geometric mean size of sediment;
d' = depth of stream in Engelund s velocity equation;
d_{35} = grain size such that 35% of material is finer;
d_{50} = median grain size;
d_{65} = grain size such that 65% of the material is finer;
$E1$ = upstream stage;
$E2$ = downstream stage
F = fall ratio;
= Froude number in Mostafa-McDermid equation;
F_b = bed factor;
F_c = constant fall;
F_m = measured fall;
F_s = side factor;
f = Darcy-Weisbach friction factor;
f_f = friction factor for flat beds (Lovera-Kennedy);
f'' = bed friction factor for form drag;

g = gravitational acceleration;
K = constant of proportionality in Dawdy's equation;
= resistance factor;
K_s = roughness length;
Q = water discharge;
Q_c = constant steady discharge;
Q_m = measured discharge;
$Q1$ = upstream discharge;
$Q2$ = downstream discharge;
q = unit discharge ;
R = Reynolds number;
= hydraulic radius in Dawdy's equation;
r = hydraulic radius;
r_b = hydraulic radius of bed;
r' = porotion of r_b due to grain roughness or skin friction;
r'' = portion of r_b due to form drag;
S = channel slope;
S' = portion of channel slope due to grain roughness;
s = specific gravity of sediment;
T = top width of channel;
U_* = $\sqrt{\tau_0/\rho}$ =shear velocity;
U_{*c} = critical shear velocity ;
U_*' = $\sqrt{\tau_0'/\rho}$ =grain roughness shear velocity;
U_*'' = $\sqrt{\tau_0''/\rho}$ = form drag shear velocity;
V = mean velocity;
w = fall velocity of particle;

x = dimensionless factor in Einstein velocity relation;

δ = thickness of viscous sub-layer;

γ = specific weight of fluid;

μ = dynamic viscosity of fluid;

ν = kinematic viscosity of fluid;

ρ_s = density of fluid;

ρ = density of sediment grain;

ψ' = $^1/\tau'_*$ = dimensionless variable in Einstein $\psi - \phi$ relation;

τ_o = bed shear stress;

τ_* = dimensionless shear stress;

τ'_* = portion of τ_* due to grain roughness.

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ABSTRACT

Various methods are available to establish the rating curve under shifting control which exists due to various factors such as scour and/or fill, alluvial bed form changes, seasonal changes in vegetative growth etc. This report describes and reviews methods to establish the rating curve under shifting control. When shifting is due to aquatic growth, no mathematical or empirical method is available to establish the rating curve and it has to be established for each season and for all ranges of flooding levels. For shifting due to alluvial bed form changes, Dawdy's analysis is suitable. Three methods namely, constant fall method, normal fall method and the method adopted in SSARR model are available for different situations when shifting is due to backwater variation. Overflow situation is tackled by using Stevens method and slope-conveyance method. Also, it is quite practicable to establish the ratings separately for the flow in the main channel and in the overflow area. Methods, have been developed by different researchers based on sediment transport theory, to establish the rating curve under scour and/or fill conditions.

INTRODUCTION

Both the stage and discharge of a stream vary most of the time. The relation of stage to discharge remains valid as long as the physical characteristics of the channel remain stable. In fact, very seldom river maintains such stability and the stage-discharge relation may require periodical modification unless artificial controls are provided. Stage-discharge relation still provides an important method for obtaining a continuous and long-period record of discharges.

A rating curve is said to be under the influence of shifting control when there is a frequent change either gradually or abruptly in the established rating curve, due to changes in the physical features that form the station control. The factors which are responsible for this change are -

i) Seasonal changes in vegetative growth along the channel ;

ii) Alluvial bed form changes ;

iii) Variable backwater from a down-stream tributary, reservoir or tidal estuary ;

iv) Overbank flow and ponding in areas adjoining the stream channel, and

v) Scour and/or fill.

Vegetal growth in the approach channel affects the approaching velocity and hence the rating curve. The shifts associated with vegetative growth are cyclic and therefore change with time. The growth increases as the growing season progresses and declines during the dormant season, but shifts may terminate abruptly if the vegetation is washed out by a stream rise. As the shift is very uncertain, the rating curve should be established for every season. But as the seasonal ratings, covering all ranges of levels are likely to cause significant changes in the weekly/monthly/annual volumes, hence the rating curves should be established for all ranges of flooding stages. There is no mathematical or empirical method available to establish the rating curve under this influencing factor.

In alluvial streams, the bed form changes as the flow increases. On the basis of laboratory investigations, Simons and Richardson (1962) described the bed configuration of sand channel streams as ripples, dunes, plane bed, standing waves and anti-dunes. Under this influencing factor the procedures adopted by Simons and Richardson (1965), Dawdy (1961) for different regimes can be used.

Backwater generally occurs due to the changes in operation of hydro-power plants, construction of weirs, barrages and dams located below gauge station, overbank spills downstream of the gauging site or confluence of two or more streams. If the discharge is affected at all times, fixed or constant fall method is applied. On the other hand if fall reduces below a particular value affecting the discharge, the normal fall method is used. In case the slope of the channel is variable, stage ratio method could be used. If the discharge is being affected by tidal fluctuations, or due to ponding at down-stream, the technique adopted in SSARR model can be used.

At many gauging stations there may be significant out of bankflow and ponding areas on the flood plain adjacent to the stream channel. Under such circumstances complications arise in determining stage-discharge relationship. The Stevens method can be used for such flow situations but it is applicable only in approximately trapezoidal flood plains. This is a simpler method. For more rational approach, slope-conveyance method can be used. The later method can be used to advantage in particularly complicated sections. Also it is frequently practicable to establish seperate discharge rating curves for the flow in main channel and in the overflow area, the total discharge being the sum of them (Herschy, 1985).

Scour and/or fill occur when the sediment is associated with the flow and the bed and banks are erodible in nature. To establish the rating curve under such conditions, Roudkivi (1967) gave a graphical relation between different parameters on the basis of his extensive laboratory experiments. His method is quite straight forward. Alam and Kennedy (1969) proposed an iterative method to establish stage-discharge relation. On the basis of Manning's equation Mostafa and McDermid (1971) gave a graphical relation to establish the rating curve using published field data.

TERMS AND DEFINITIONS:

The terms used in the report are described as below:

Stage:

Refers to the elevation of water surface usually above some arbitrary datum recorded at a gauging station.

Stage-discharge relation:

Ideally, stage- discharge relation or rating curve should define a unique functional relation between stage and discharge that is smooth, continuous and sensitive.

Control:

A control is a site or a section, physical features of which tend to make a stage-discharge curve stable.

A control can be said to be fully effective when discharge for any given gauge remains constant, implying that the relation of stage to river flow also remains unchanged.

Types:

Controls can be of various types depending upon their function and location as described below:

a) Channel Control:

Particular reach of a river would provide a control if the bed and banks are rigid and stable and variation in sectional area due to bed scour and deposition are absent. This is called a channel control.

b) Section Control:

A section control may exist where the control characteristics as of channel control are obtained not over a long reach but only at a particular section, for example, an isolated rocky section.

The controls may be either complete or partial:

a) Complete control :

The control which is effective at all stages:

b) Partial control:

Which is effective over a partial range of stages.

Shifting control:

Bank erosion, bed scour, accretion and formation of bars across a river result in variation of the rating curve. These are called shifting controls.

Temporary Controls:

Controls which exist only part of the year, such as formation of ice, are seasonal control while features like aquatic growth and vegetal cover may be operative only temporarily. These are termed as temporary controls.

Multiple Controls:

The controls which are operative at different stages, are known as multiple controls.

Natural Control :

Natural control may be in the shape of a rocky reach of a river, a local rocky ledge, all across the river with a pool behind it, fall over a rocky cliff etc.

Artificial Control:

It is in the form of artificial structure like dam, spillways, weir at downstream of the gauging station, low sills and notches etc.

REVIEW:

The relation of stage to discharge is usually influenced by the controls, causing the relation to change overtime. Such controls known as shifting controls can be due to scour and/or fill of channel beds, alluvial bed form changes, vegetative growth in the channel etc. Different procedures are suggested by researchers under the influence of above mentioned factors. These are described as below under different heads:

Seasonal Changes in Vegetative Growth:

Vegetal growth in the channel increases the resistance to flow hence the flow is affected. If the weed grows in the approach channel, the approach velocity is reduced and if it is on the weir itself, the head is decreased and thus the stage-discharge relationship is affected. Vegetal growth increases with progressing season and declines when the season is dormant. Herschy (1985) has suggested that the change in weed growth should be closely observed over the growing season and determined by a series of discharge measurements.

Alluvial Bed Form Changes:

In sand channel streams stage-discharge relations are continually changing with time, because of changes in configuration of channel bed. These changes cause the shape and position of the stage-discharge relation to vary from time to time and flood to flood.

Simons and Richardson (1962) described the bed configuration of sand channel streams as ripples, dunes, plane bed, standing waves and anti-dunes. This sequence of bed configurations occurs with increasing discharge. When the dunes washout and the sand is rearranged to form a plane bed, there is a marked decrease in resistance to flow which may result in an abrupt discontinuity in the stage-discharge relation. The sequence of configurations described in table -1 is developed by continually increasing discharge. The lower regime occurs with lower discharges, the upper regime with higher discharges,an unstable dis-continuity in the depth discharge relationship appears between these two more stable regimes.

Colby (1960) developed stage-discharge relation for Pigion Roost Creek, Mississippi, and concluded that the stage-discharge relations might be expected to have a dis-continuity provided the reach had all of the following characteristics:

a) A bed of uniform and readily shifting sediment which does not form distinct pools and riffles;

b) At some flows almost all of the stream-bed is covered with loose sand dunes;

c) At higher flows the bed of the stream is mostly plane or has anti-dunes ;

d) The depth of the flow at the point of dis-continuity can be distinguished from changes caused by small local shift of the channel bottom:

e) The lateral distribution of depths and velocities must be sufficiently uniform for the bed configuration to change across most of the stream-bed

TABLE - 1

Surface and bed description for the various flow regimes

Type of Configuration	Description Bed	 Flow
Lower regime of flow:		
Plane bed	Plane; no sediment movement.	Plane surface little turbulence
Ripples	Small uniform waves; no sediment movement	Plane surface; little turbulence
Dunes	Large, irregular , saw-toothed waves formed by sediment moving downstream; waves move slowly downstream	Very turbulent; large boils
Upper regime of flow:		
Plane bed	Dunes smoothed out to plane bed	Plane surface; little turbulence
Standing waves	Smooth sinusoidal waves in fixed position	Standing sinusoidal waves in phase with bed waves; termed "sand waves"
Antidunes	Symmetrical sinusoidal waves progressing upstream and increasing in amplitude; suddenly collapse into suspension then gradually reform	Symmetrical sand waves progressing upstream in phase with bed waves; amplitude increases until wave breaks, whole system collapses then gradually reforms

in a relatively short time.

The above conditions are very restrictive and generally not applicable to field situations.

Dawdy (1961) established the relationship for upper regime condition in a true sand bed channel ;

$$V = KR^{1/2} \qquad \ldots(1)$$

where,

V = mean velocity

K = Constant

R = hydraulic radius

More recent study (WMO, 1980) has shown that the exponent of R ranges from 2/3 as in Manning equation, to 1/2, the larger exponents being associated with the coarser grain sizes.

Recent studies (WMO, 1980) suggest that the lower regime of bed form will occur when the ratio,

$$\frac{V^4}{g^2 D^{1/2} d_{50}^{3/2}}$$

is less than 1×10^3, that the upper regime of bed forms will occur when the ratio is greater than 4×10^3 and that the bed will be in transition if the ratio is between these values. In the ratio, V is the mean velocity in m/s, g is the acceleration due to gravity in m/sec^2, D is the mean depth in metres, and d_{50} is the median grain size in metres.

Variable Backwater:

Backwater effect is commonly due to the changes in operation of hydropower plants, construction of weirs, barrages, and dams located below gauging station etc. Hiranandini and Chitale (1964) have suggested methods namely constant fall method, normal fall method and stage-ratio method under different variable conditions. These are described as below:

a) Constant fall method :

In absence of any channel control the discharge may be affected by backwater, at all times. Under this condition constant fall method is used.

b) Normal fall method:

If usual simple rating curve is applicable at big falls when backwater effect is absent while for low falls the discharge is affected by backwater, this method is used. Critical value of the fall dividing the two regions is termed as normal fall.

c) Stage-ratio method:

When backwater is due to variable channel slopes, this method is used.

Overbank Flow:

When the flow in the channel exceeds the channel capacity overbank flow occurs. Overbank spills cause lowering of gauges during rising flood and higher gauges during subsidence. Hiranandini and Chitale (1964) suggested to make sufficient observations at overbank stages for preparation of loop curve. Herschy (1985) suggested the same proposition to establish the rating curve under this influencing factor.

Scour and/or Fill:

When sediment is associated with water in natural channels which are erodible in nature, scour and/or fill occurs. The analysis and investigations to establish the rating curves are summarized here in roughly chronological order of their development. The limitations of the various methods and a general evaluation of them will be given:

a) Regime formulation (1895-1970)

The regime formulation traces its origin to British Engineers who were engaged, late in the 19th century, with designing and operating extensive irrigation systems in India. Most regime formulations include three relations that aimed values of the channel width, depth and slope as a function of the water discharge, and bed material size. Some of the more refined ones also take into account bank cohesiveness sediment discharge or concentration and fluid viscosity. A good example of a regime formulation is that of Blench (1970):

The width is given by

$$b = \sqrt{\frac{F_b \cdot Q}{F_s}} \qquad \ldots(2)$$

where,

F_b = bed factor

= g times the Froude number squared = $\frac{V^2}{d}$

and, $F_s = \frac{V^3}{b}$ = side factor

The depth equation

$$d = \sqrt[3]{\frac{F_s \cdot Q}{F_b^2}} \qquad \ldots(3)$$

while the slope is expressed as

$$S = \frac{F_b^{7/8}}{Kb^{1/4}d^{1/8}(1+C/2330)} \qquad \ldots(4)$$

in which,

C = The concentration in ppm of bed material transported by the flow

and

$$K = \frac{3.63q}{\nu^{1/4}} \qquad \ldots(5)$$

F.P.S. System is used here.

F_b and F_s are generally determined largely on the basis of the engineers experience.

In the absence of better information

Blench suggests

$$F_b = 1.9\sqrt{dg} \qquad \ldots(6)$$

where,

dg= geometric mean size of sediment in millimeters

and

F_b = is in foot per second squared

F_s = 0.10 for friable banks

F_s = 0.20 for silty, clay, loam banks

F_s = 0.30 for tough clay banks

Regime relations should never, of course, be applied in cases in which the flow, sediment transport, and channel characteristics differ widely from those from which the particular formulation was derived. In general, they are applicable only to flows at low Froude numbers, in the ripple-dune regime.

b) Einstein-Barbarossa Analysis (1952):

Einstein-Barbarossa (1952) were the first to develop a depth-discharge predictor taking any formal account of the contribution, the bed form make to the channel roughness.

Determination of depth-discharge relations using the method proposed by them for a channel with known cross section, slope and bed material size proceeds as follows:

I. Select a value of r', calculate $U'_* = \sqrt{gr'S}$ and determine V from

a) $$\frac{V}{U'_*} = 7.66 \left(\frac{r'}{K_s} \right)^{1/6} \qquad \ldots(7)$$

b) $$\frac{V}{U'_*} = 5.75 \text{ Log} \left(12.2 \frac{r'}{K_s} x\right) \qquad \ldots(8)$$

when,

$$\frac{K_s U'_*}{11.6\mu} \leq 5 \text{ (approx.)}$$

II. Obtain $\frac{V}{U''_*}$ from fig (1) and calculate r"

III. Calculate $r = r' + r''$

IV. Determine A and d from curves of r versus A and d based on known channel section dimensions

V. Calculate $Q = VA$

where,

A = cross sectional area

r = hydraulic radius, consisting of two additive parts

i) One section with area A' and corresponding hydraulic radius r' in which a component of the gravitation force exerted on the grain roughness, and

ii) A second section of area A" and hydraulic radius r", for which the gravity force is balanced by the

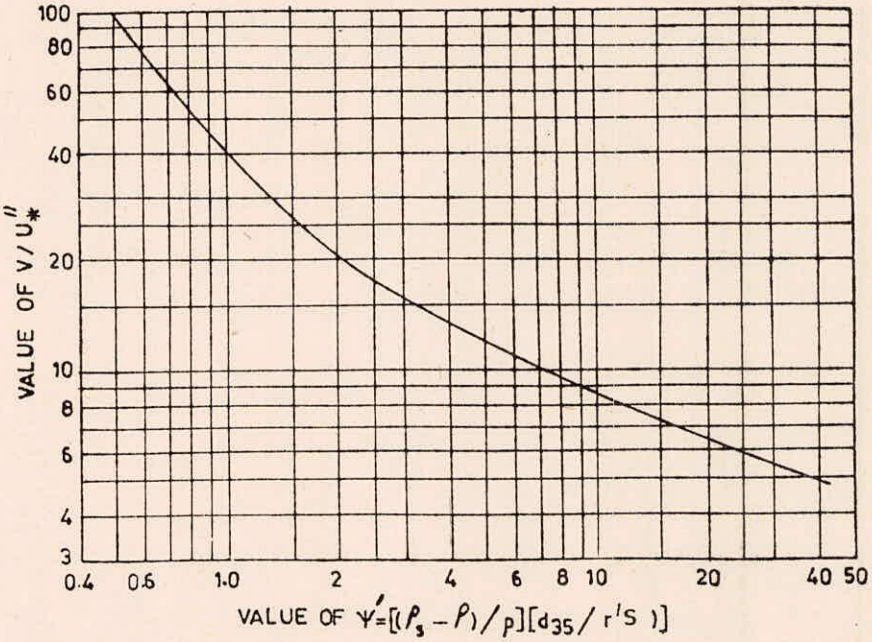


FIG. 1–EINSTEIN BARBAROSSA (1952) BAR RESISTANCE GRAPH

drag exerted on the bed form and other channel irregularities.

U_* = shear velocity corresponding to the grain roughness

K_s = the equivalent sand grain roughness diameter taken to be d_{65}

V = mean velocity

x = a function of $K_s U'_*/11.6$) is a correction factor accounting for the effects of viscosity.

$$\psi' = \frac{\rho_s - \rho}{\rho} \times \frac{d_{35}}{r\ S} \qquad \ldots(9)$$

in which,

ρ_s and ρ = densities of the sediment and fluid, respectively

S = slope of the channel

d_{65}&d_{35} = sediment size such that 65% and 35% of the material is finer respectively.

Shen (1962) undertook to improve the Einstein-Barbarossa method, and in particular to extend it to materials other than sand and to eliminate the systematic deviation that had been found to exist between the Einstein-Barbarrosa curve (fig.1) and flume data. He found that for $\frac{wd_{50}}{\nu} > 100$ (approx), $\frac{U''_*}{V}$ may be expressed as a function of ψ' alone, but for $\frac{wd_{50}}{\nu} \leq 100$ (approx.), $\frac{U''_*}{V}$ is a function of ψ' and $\frac{wd_{50}}{\nu}$.

Veiga da Cunha (1967) analysed data from a Portugese river with a bed composed of relatively coarse material. He concluded that for ψ' greater than about five, $\frac{U''_*}{V}$ is a double function of ψ' and presented a graphical relation between these two quantities. w is the fall velocity of the particle.

c) Garde and Raju's Analysis (1966):

Garde and Raju (1966) collected a large body of laboratory and field data obtained by other investigator and used it to evaluate the depth-discharge predictors proposed by Einstein and Barbarrosa (1952), Shen (1962). They concluded that an equation of the Manning form with a variable coefficient should be adopted.

$$\frac{V}{\sqrt{\frac{\rho_s - \rho}{\rho} \, g . d_{50}}} = K \left(\frac{r}{d_{50}}\right)^{2/3} \left[S . \frac{\rho}{\rho_s - \rho}\right]^{1/2} \qquad \ldots(10)$$

where,

$$K = \text{a function of } \frac{V}{\sqrt{[(\rho_s - \rho) / \rho] . g . r}}$$

defined in graph they developed from field and laboratory data for sand bed channels.

K = 3.2 for ripples

and K = 6.0 for the antidune & transition regimes.

Alam (1967) calculated the depth-discharge predictors on the basis of their proposed technique and found poor depth-discharge relationship. He concluded that the analysis by Garde and Raju (1966) does not support its validity.

d) Simons and Richardson and Haynie and Simons' Analysis (1966-1968)

They analysed the data obtained in natural streams and irrigation canals by several investigations with the goal of obtaining an improved friction factor predictor for alluvial channels. Application of the results of their analysis for calculation of depth-discharge relations proceeds as follows:

I Select values of r,d and S and obtain Δ V from fig.(2)

II Compute $U_* = \sqrt{grS}$, $\frac{\Delta V}{U}$ and $\frac{U_* d}{\nu}$

III Compute the velocity , V* that would obtain if the boundary were smooth, $\frac{V}{U_*} = 5.75 \text{ Log } \left(\frac{V_* d}{\nu}\right) + 2.5$ ...(11)

IV Calculate the velocity to be expected in the alluvial channel $V = V + \Delta V$

V. Calculate the stream power, $\rho g VdS$ and for the known value of d_g ascertain from Symons and Richardson's (1966) empirical graphs if the flow is expected to be in the ripple or dune regimes. If not, the estimate of V should be disallowed, since fig.(2) is valid only for these bed configurations.

Where U_*,V,r,d,ν and S are same as discussed previously

ΔV = velocity corrections

= calculated as the difference between the actual velocity and that predicted by Tracey and Lesters' (1961) friction factor relation for smooth rectangular channel as:

$$\frac{\Delta V}{U_*} = \frac{V}{U_*} - 5.75 \text{ Log } \frac{U_* d}{\nu} + 2.5 \qquad \text{...(12)}$$

The absence of any dependency of V on bed material size would appear to be a serious deficiency since it is well known (Simons and Richardson, 1966) that f is heavily dependent on the size of the bed sediment.

e) Engelund's Analysis (1966-67).

Engelund (1966) proposed a new line of analysis based on similarity considerations. The calculation of the depth-

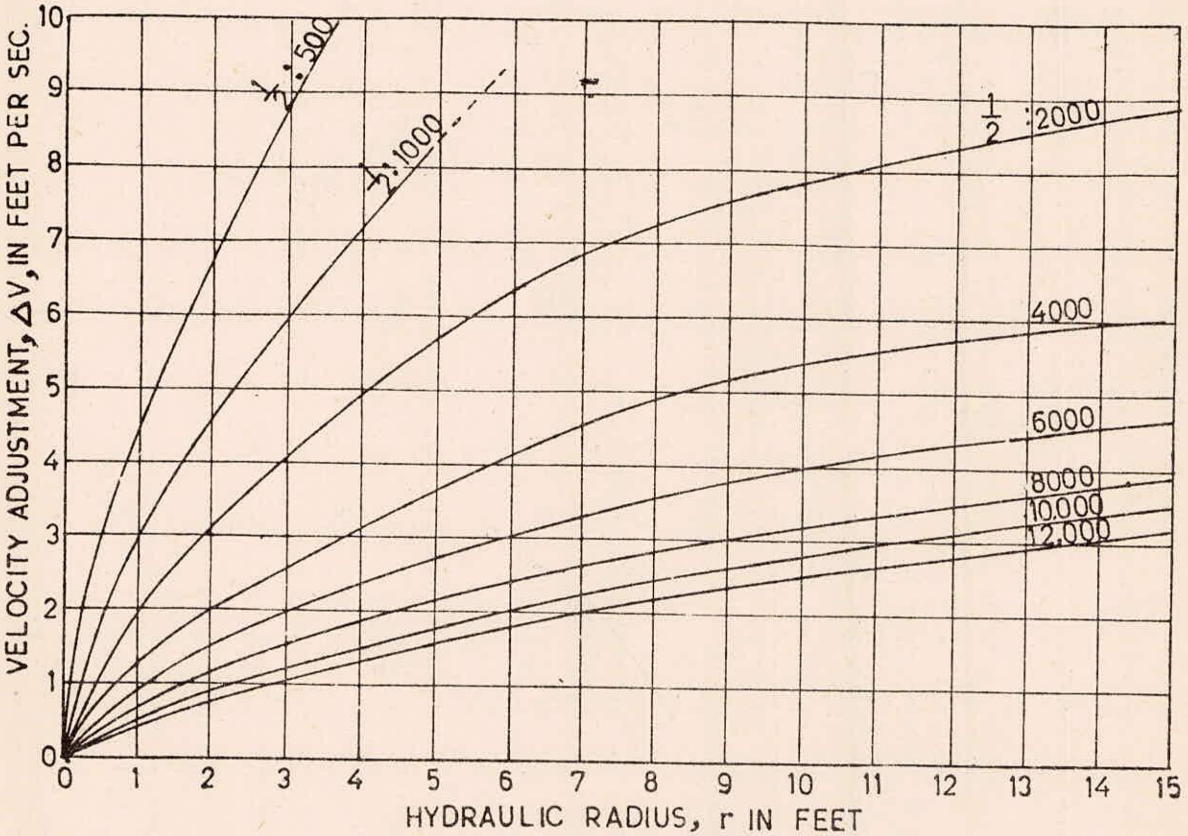


FIG. 2— HAYNIE AND SIMONS (1966) EMPIRICAL RELATION BETWEEN VELOCITY ADJUSTMENT ΔV, HYDRAULIC RADIUS AND SLOPE.

velocity relation for a stream with known slope and distribution of bed particle sizes proceeds as follows:

I. Select a value of d' and calculate the corresponding values of τ'_* using d_s = dg and V

$$\tau'_* = \frac{\tau_0}{\gamma\,(s-1)\,d_s} = \frac{dS'}{(s-1)d_s} = \frac{d'S}{(s-1)d_s} \qquad \ldots(13)$$

and

$$\frac{V}{\sqrt{gd'S}} = 6+2.5\ \ln\frac{d'}{2d_{65}} \qquad \ldots.(14)$$

II. Obtain τ_* (dimensionless shear stress) from fig.(3)

III. Compute $d= [\tau_*(s-1)d_s]/S$, again taking $d_s=d_g$

IV. Calculate the unit discharge (discharge per unit width, $q = Vd$)

where,

γ = specific weight of the fluid

d' = depth of stream in Engelund's velocity equation (analogous to r'')

= portion of τ_* due to grain roughness

S' = portion channel slope due to grain roughness

S = channel slope

d_s = size of particle

The validity of Engelund's analysis rests heavily upon his similarity hypothesis, which has not yet been verified. The depth-discharge relation presented in his closing discussion (Engelund, 1967) tend to corroborate the reliability of his approach . The method does not, ofcourse, take account explicitly of the effects of temperature and suspended-sediment concentration on the channel roughness.

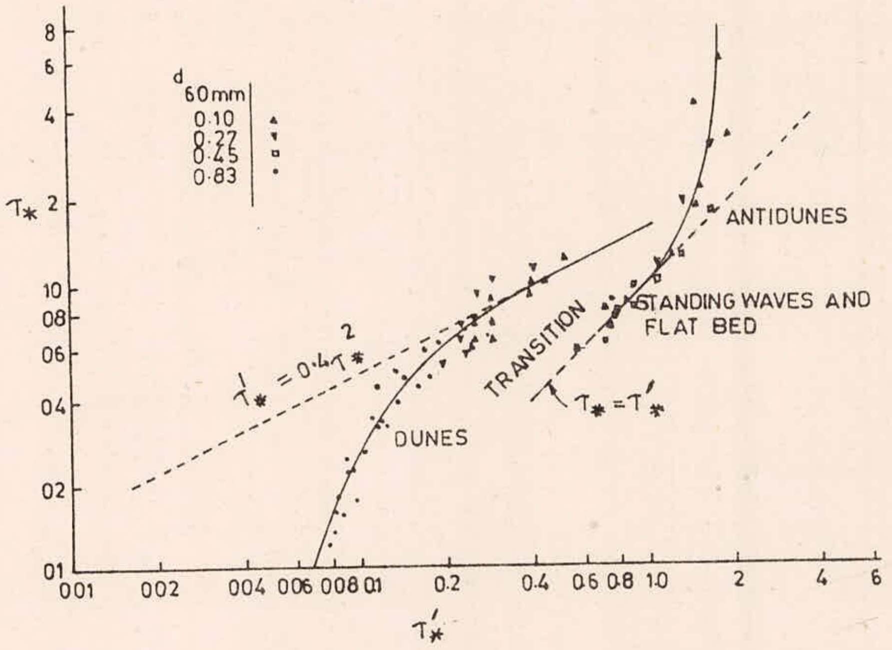


FIG.3–ENGELUND'S(1967) UNIVERSAL RELATION BETWEEN NORMALIZED GRAIN-ROUGHNESS SHEAR STRESS $\tau'_* = \tau'_o/[\gamma(s-1)d_s]$ AND NORMALIZED TOTAL SHEAR STRESS $\tau_* = \tau_o/[\gamma(s-1)d_s]$

PROBLEM DEFINITION

This report describes the available procedures which are suitable for establishment of rating curve under the following shifting control situations.

i) Seasonal changes in vegetative growth

ii) Alluvial bed form changes

iii) Variable backwater

iv) Over bank flow

v) Scour and/or fill

METHODOLOGY

Different methods proposed by researchers are described below:

Growth and decay of aquatic (weed) growth:

Vegetal growth in the approach channel of the control or on the control itself will affect the stage-discharge relation. Aquatic vegetation in the approach channel will affect the velocity of approach, and if the vegetal growth encroches on the control it may reduce the effective length of the control. Aquatic growth on the control itself will reduce the discharge corresponding to any given stage by reducing the head on the weir and increasing the resistance of flow, and/or by reducing the effective length of the control. The shifts associated with vegetal growth are cyclic and therefore change with time. The growth increases as the growing season progresses and decline during the dormant season, but shifts may terminate abruptly if the vegetation is washed out by a stream rise.

Seasonal ratings, covering all ranges of levels are also, likely to cause significant changes in the weekly/monthly/ annual volumes. Hence it is suggested that the rating curves should be established for every season and for all ranges of flooding levels. No mathematical or empiricial method is available to define the rating curve relationship.

Alluvial bed form changes:

In sand channel streams, stage-discharge relations are continually changing with time, because of scour and fill and because of changes in the configuration of the channel bed.

On the basis of laboratory investigations, Simons and Richardson (1962) described the bed configuration of sand channel streams as ripples, dunes, plane bed, standing wave, and antidunes. This sequence of bed configuration occurs with increasing discharge. When the dunes wash out, and the sand is rearranged to form a plane bed, there is a marked decrease in resistance to flow which may result in an abrupt discontinuity in the stage-discharge relation see fig.4. The lower regime occurs with lower discharges, the upper regime with higher discharges, an unstable discontinuity in the depth-discharge relationship appears between these two more stable regimes.

Changes in bed forms don't occur instantaneously with increasing or decreasing discharge. The time lag between change in bed form and change in discharge may result in loop rating curve.

A plot of stage against discharge in sand channel streams often obscures any underlying hydraulic relationship because neither the bottom nor sides of these streams are fixed. The relation between stage and discharge is indeterminate. The effect of variation in bottom elevation is eliminated by replacing stage by mean depth or hydraulic radius. The effect of variation in width is eliminated by using mean velocity, see fig.5 & 6.

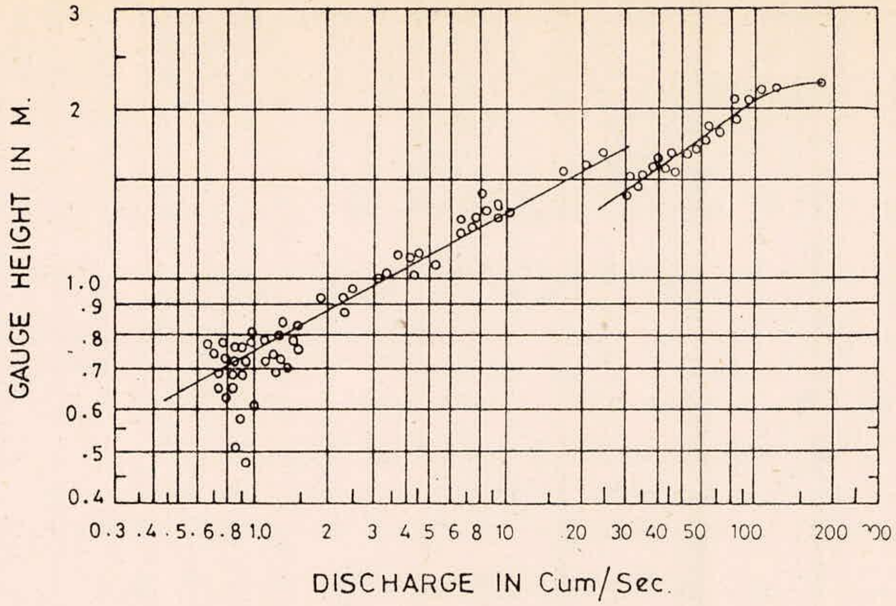


FIG. 4—STAGE-DISCHARGE RELATION FOR STATION 34 ON PIGEON ROOST CREEK.

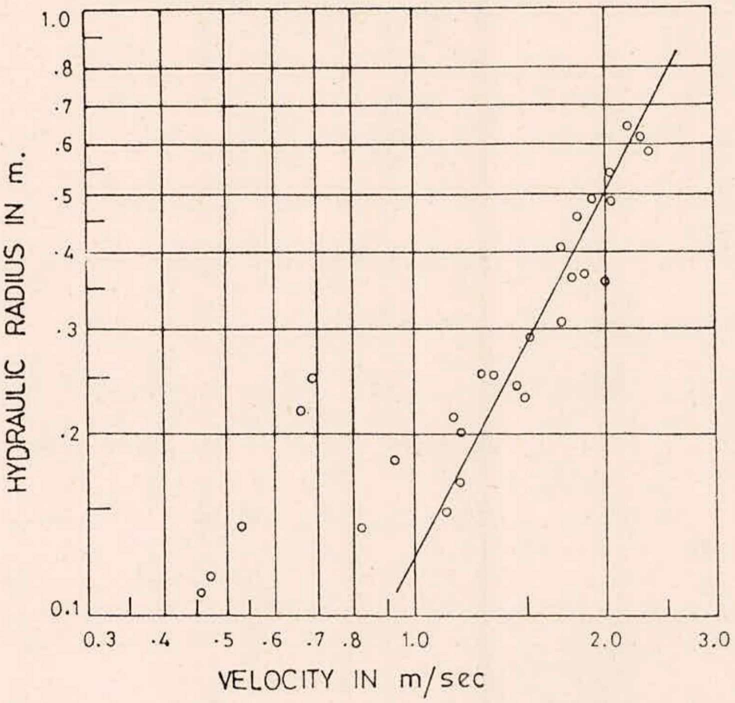


FIG. 5—RELATION OF VELOCITY TO HYDRAULIC RADIUS FOR HUERFANO RIVER NEAR UNDERCLIFFE, COLO, FROM DAWDY(1961).

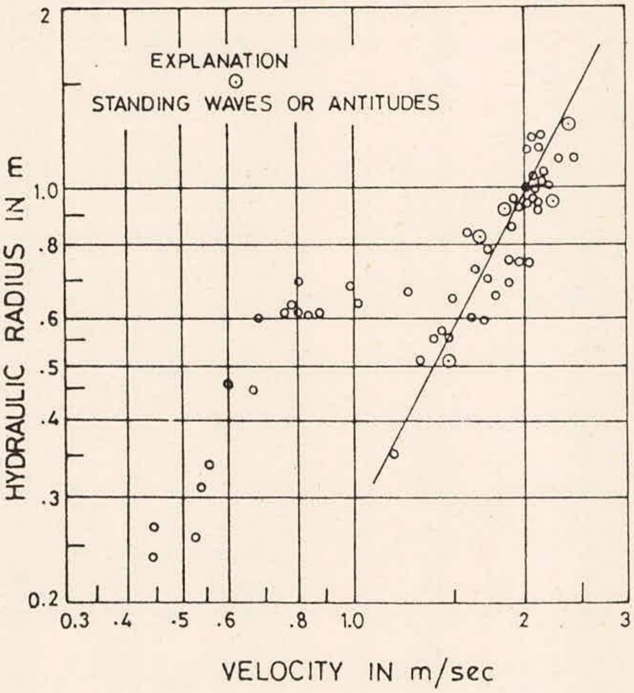


FIG. 6–RELATION OF VELOCITY TO HYDRAULIC RADIUS FOR RIO GRANDE NEAR BERNALILLO N. MEX FROM DAWDY (1961).

According to Dawdy (1961) the curve representing the upper regime in a true sand bed stream usually fits the following relation.

$$V = KR^{1/2}$$

where,

V = mean velocity

K = constant

R = hydraulic radius

He found this relation applicable for 26 of the 27 streams used in his study.

More recent study (WMO, 1980) has shown that the exponent of R range from, 2/3 as in the Manning equation to 1/2. The large exponents being associated with the coarser grain sizes.

Backwater Variation:

Backwater phenomena is commonly due to the changes in operation of hydro-power plants, construction of weirs, barrages and dams located below gauge station, over bank spills downstream of the gauging site or confluence of two or more streams. For variable slope due to backwater, the flow may be considered to be steady & non-uniform. The discharge is affected by variable slope due to backwater either at all stages or else, the gauge gets affected only when fall reduces below a particular value. As backwater reduces the fall increases and a channel control may then become effective. In absence of any channel control the discharge may be affected by backwater at all times. Establishment of rating curve under this condition is dealt by fixed or constant fall method. On the other hand when fall reduces below a particular value affecting the discharge the normal fall method could be applied.

i) Constant Fall Method :

It involves drawing of rating curve for a constant fall (F_C). This fall is generally selected as one unit since then the relation

$$\frac{Q_m}{Q_c} = f\left(\frac{F_m}{F_c}\right) \qquad \ldots(15)$$

simplifies to $Q_m = f(F_m) . Q_c$, where $F_c=1$. Here subscript m pertains to actual or measured values while C pertains to constant values corresponding to steady discharge.

Rating curve is prepared using observed data of discharge against gauges is plotted. At each point, corresponding fall between the upper and lower gauges is indicated. Curve for a constant fall of one unit can then be drawn.

In addition to this curve another curve of Q_m/Q_c against F_m/F_c, called a relation of discharge ratios to fall ratios, is prepared. In this plot Q_m and F_c are the observed values while Q_c i.e. discharge at constant fall F_c of one unit is read from the rating curve. Accuracy of the two curves can be checked by working backwards using observed data of Q_m. These values are reduced to Q_c with the help of the curve of discharge ratios to fall ratios and plotted on the rating curve of unit fall. If the two curves are accurate all values of Q_c will fall on the rating curve. If on the other hand scatter is observed, further refinement is indicated. The curve of discharge ratios to fall ratios is then redrawn on basis of the new rating curve. One or two trials will result in sufficiently accurate relation curves.

For any observed gauge and fall, discharge can now be found with the aid of these two curves. Referrring to the rating curve discharge for unit fall is first obtained, knowing the fall ratio ($\frac{F_m}{F_c} = F$) actual discharge corresponding to F_m is then read from the curve of discharge ratio to fall ratio. This single plot would enable discharge to be estimated for given stages and fall at upper and lower stations by direct reading. The curves are plotted against the upper gauge height as ordinate and discharge as abscissa. The application of constant fall method is illustrated through fig.7.

ii. Normal Fall Method :

This method is adopted if usual simple rating curve is applicable at big falls when backwater effect is absent while for low falls discharge is affected by backwater. Critical value of the fall dividing these two regions is termed the normal fall. Value of normal fall at any discharge can be determined by studying the plot of gauge against discharge. The example of the method used is shown in fig.8.

iii. Stage_Ratio Method:

Besides constant and normall fall methods another simple method applicable for correcting discharges in case of variable slopes is the stage-ratio method. In this all discharge measurements are plotted against corresponding

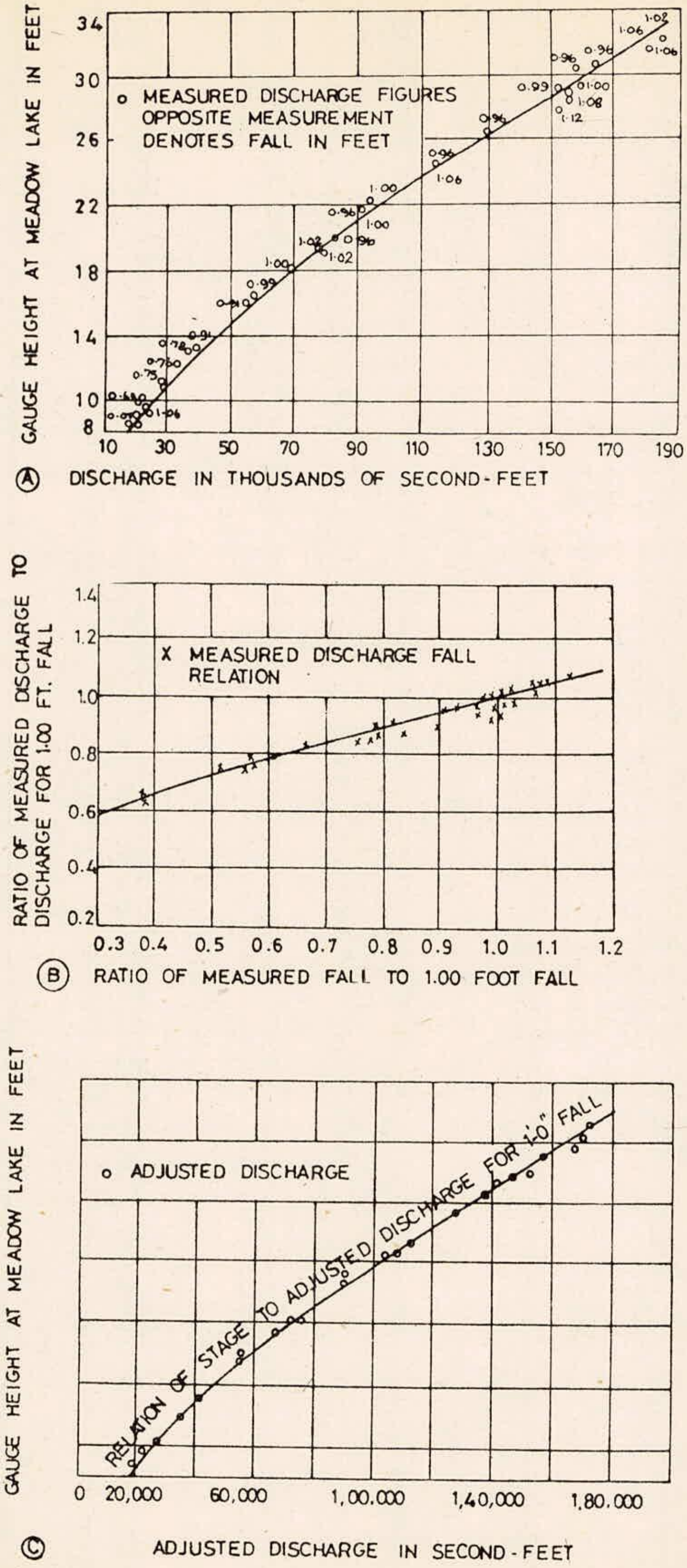
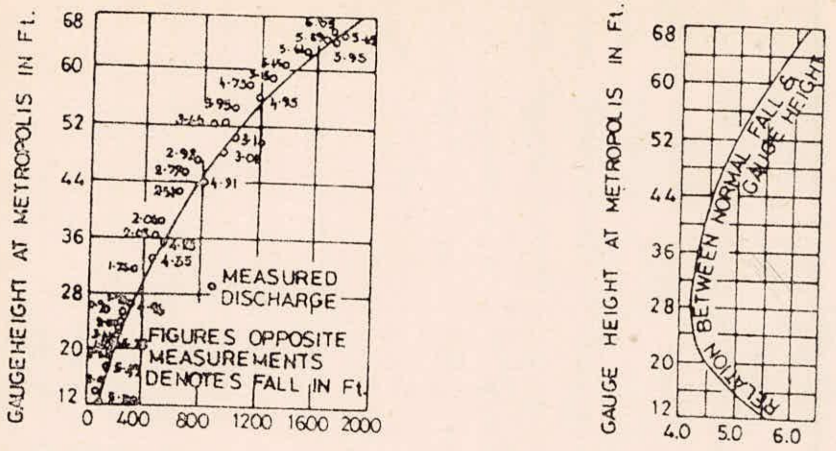
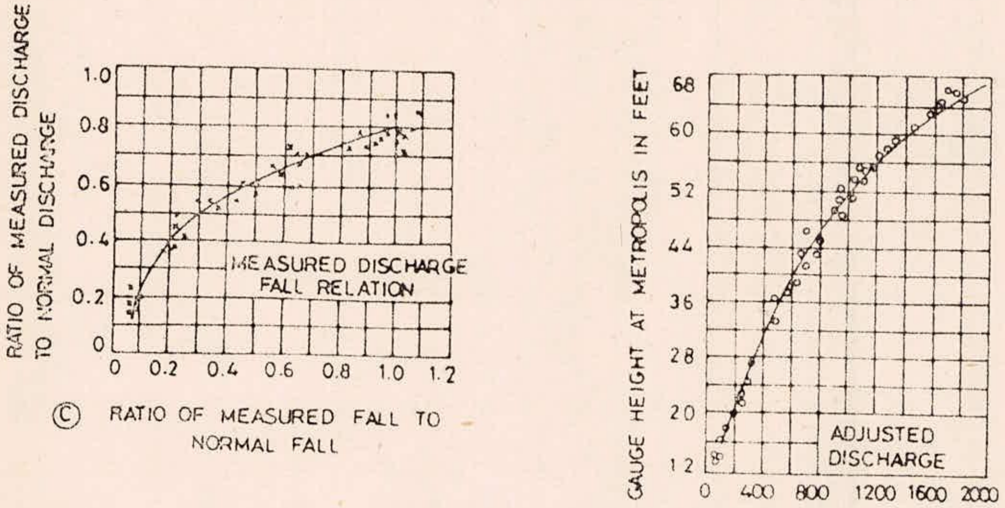


FIG. 7– CURVES OF TENNESSE RIVER AT CHATTANOOGA, TENNESSE, U.S.A.



Ⓐ DISCHARGE IN THOUSANDS OF SEC-Ft

Ⓑ NORMAL FALL IN FEET



Ⓒ RATIO OF MEASURED FALL TO NORMAL FALL

Ⓓ DISCHARGE IN THOUSANDS OF SEC Ft

FIG. 8 – CURVES OF OHIO RIVER AT METROPOLIS, ILLIONIS, U.S.A.

gauges at the upper gauge station and a curve is drawn which is lower than any of the discharge measurements but parallel to them. This is called effective gauge height curve. The ratio of actual gauge height and that given by the curve is next determined for each discharge. This is called stage-ratio. These stage ratios are then plotted against gauge ratios which are the ratios of upper and lower gauge heights read to common datum. On this plot of stage ratios against gauge ratios, a mean curve is drawn. Further refinement will be possible by using stage ratios from the curve. The two curves, one of effective gauge height ratio, permit of obtaining the corrected discharge.

iv) SSARR Model Technique :

There are cases where stage-discharge relations are affected by backwater from a downstream time variant source. Examples of such occurrences are river estuaries affected by tidal fluctuations, river reaches upstream from a junction with a major tributary, and the upstream reaches of a reservoir or a lake whose outflow is affected by the elevation of another lake just downstream. For such situations, stage-discharge relations can be accomplished by the 'back-water mode' of the SSARR model. This model utilises a three variable relationship between upstream stage (E1), downstream stage (E2) or flow (Q2) and discharge from the upstream location (Q1).

$$Q1 = f\ (E_1,\ E_2) \qquad \ldots(16)$$

or $$Q1 = f(E1, Q2) \qquad \ldots(17)$$

An example of such relationship is illustrated in fig.(9). The model treats the flow at any period of the upstream station as dependent upon the water surface elevation (or flow) of the downstream control station and also the water surface elevation of the upstream station.

Overbank Flow:

Streams with large over bank flow present many complications in stream flow measurement, and in determining stage-discharge relation, particularly during rising and falling stage. Two methods namely Stevens method and slope conveyance method are available to tackle these situations, these are described as below:

a) Stevens Method (1907):

This method is applicable only in approximately trapezoidal floow plains.

The method is based on Chezy formula:

$$Q = AV = A.C\sqrt{RS} \qquad \ldots(18)$$

where,

Q = discharge

A = cross-sectional area

V = mean velocity

R = hydraulic radius

S = slope of water surface

C = Chezy coefficient ,which Kutter defined as below:

$$C = \frac{(41.6 + 0.0028/S) + 1.81/n}{1 + (41.6 + \frac{0.0028}{S})\frac{n}{\sqrt{R}}} \qquad \ldots(19)$$

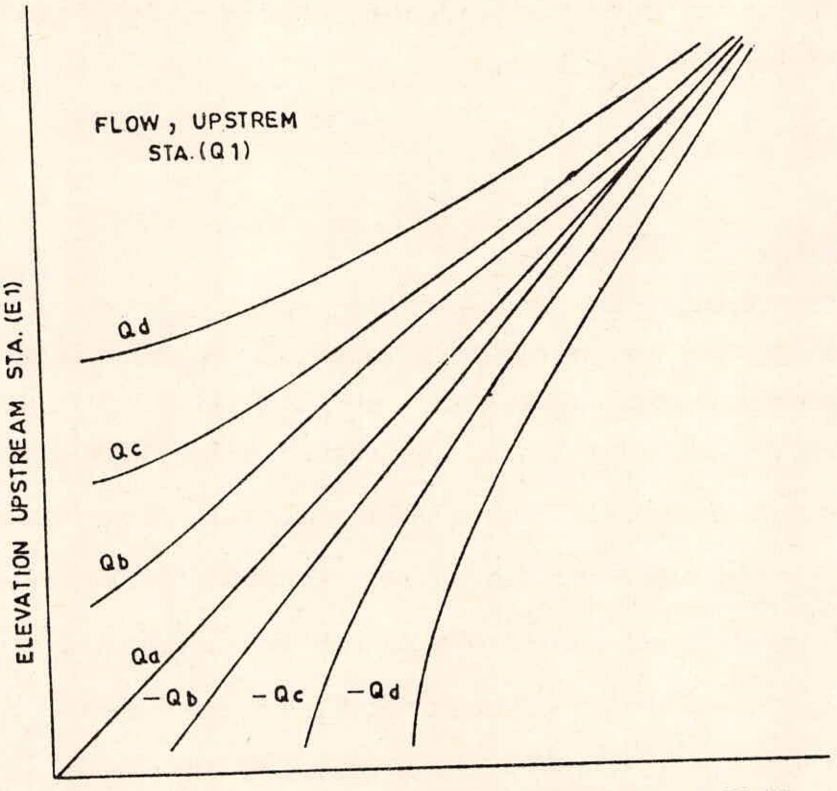


FIG. 9– EXAMPLE OF DISCHARGE–ELEVATION RELATIONSHIPS HANDLED BY THE SSARR BACKWATER MODE

F.P.S. system is used.

Where, n is roughness coefficient. Its variation is neglected. Stevens assumed that $C\sqrt{S}$ is constant throughout the range of stage under consideration. He also assumed that the mean depth of the cross-section, D_m was a suitable substitute for the hydraulic radius, R. In a river channel, where the ratio of horizontal distances to vertical distances is great, this substitution is obviously satisfactory. Therefore, after modification ,

$$Q = C_1 A\sqrt{D_m} \qquad \ldots(20)$$

where,

C_1 = assumed constant

To apply the method, the cross-section survey is used to compute $A\sqrt{D_m}$ for various stages extending as high as designed and a graph between Q & $A\sqrt{D}$ is plotted. This method has been applied to river Naugatuck at Beaken Falls, Conn, for the year 1955 flood. (see fig.10 & 11).

Stevens recognised that where considerable quantities of over bank flow were present, no hydraulic formula applied to the entire section would give correct results, and cautioned against the use of his method in these cases.

b) Manning's Formula or Slope-conveyance Method :

The problem can also be solved by direct application of the Manning formula as follows:

$$Q = \frac{1.486}{n} A.R.^{2/3} S^{1/2} \qquad \ldots(21)$$

The roughness coefficient, n, is the same as that used by Kutter (eqn.19). In using the Manning formula the section must be broken down into trapezoidal sections, each are analysed seperately, and the discharge summed.

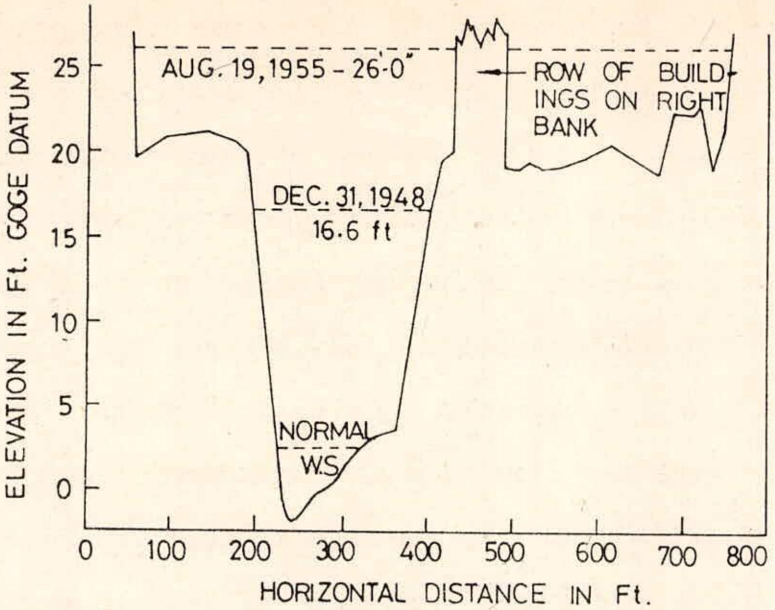


FIG.10–CROSS-SECTIONAL DETAILS OF THE NAGATUCK RIVER AT BEACON FALLS, CONN.

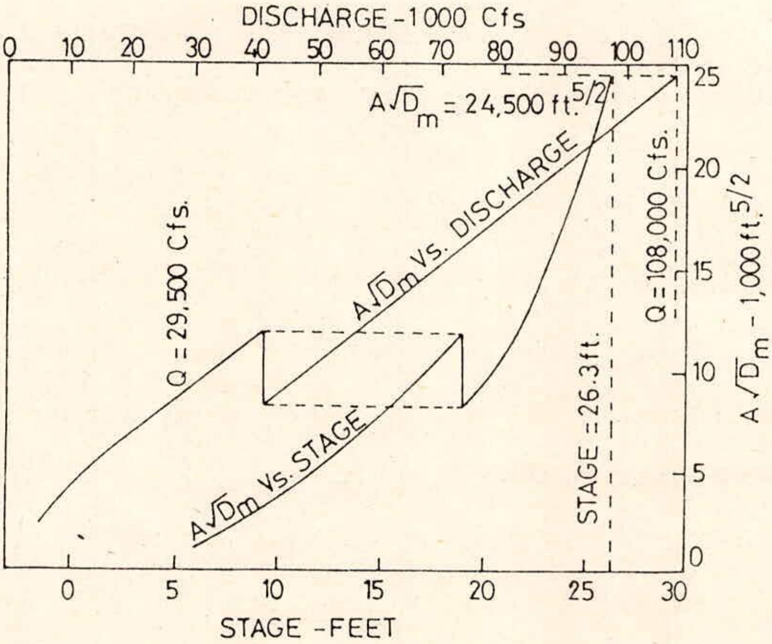


FIG. 11– RATING EXTENSION BY STEVENS' METHOD FOR THE NAGATUCK RIVER AT BEACON FALLS, CONN.

The slope is assumed to be the same throughout the cross-section, and may be equated to the measured bed slope without serious error. If the range of existing rating involves flow in only one trapezoidal section, the formula may be solved for the value of n applicable to this section. Values of n for overflow sections may either be assumed the same or varied, as conditions indicate. If the existing rating involves overflow, the total discharge is the sum of the flow in two or more trapezoidal sections. A simple trial and error solution will produce values of n that will have the proper relative values and that will yield the correct total discharge. Fig.12 provides an example of this method.

Also, it is frequently practicable to establish seperate discharge rating curves for the flow in the main channel and in the overflow area, the total discharge being the sum of them. Bridging over the overflow area is a practical solution, where possible and gauging can be made from the bridge.

Scour and/or Fill:

Some selected methods are described here for the establishment of rating curve when scour and/or fill occurs. These are as below:

a) Raudkivi's Graphical Relations (1967):

Raudkivi (1967) conducted a set of laboratory flume experiments using 0.4 mm dia sand, and analyzed the data obtained in his investigation together with those reported by others for field and laboratory streams. Dimensional

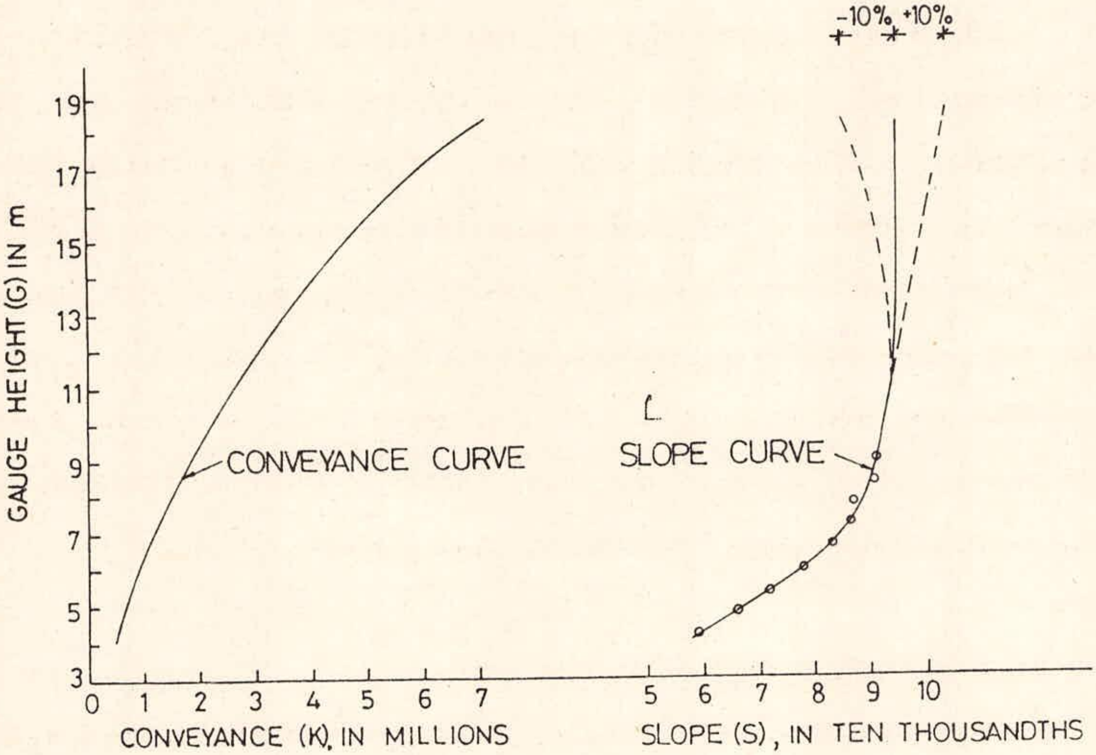


FIG. 12– HIGH FLOW EXTRAPOLATION BY USE OF CONVEYANCE SLOPE METHOD, KLAMATH RIVER AT SOMES BAR, CALIFORNIA, U.S.A.

analysis and physical reasoning, guided largely by his experiments on the distribution of shear stress and pressure over-dunes and ripples, led him to a graphical relation that he later modified slightly (Raudkivi., 1971). Over a significant range of abscissa (fig.13).

$$\frac{V}{\sqrt{U_*^2-U_{xc}^2}} = f\left(\frac{\rho V_*^2}{\gamma(s-1)d_{50}}\right) \qquad \ldots(22)$$

In this region of the graph the bed configuration is undergoing transition from ripples and dunes to flat bed. Most of the points to the right of the multi-valued range correspond to the flat bed or antidune regimes.

The application of Raudkivi's graphical relation, fig.(13) to calculate depth-velocity relations is quite straight forward in principle. However, it is not always altogether clear which of the various curves through the points should be used in a particular case.

b) Alam and Kennedy's (1969) Analysis:

Depth-discharge relations are calculated from fig.(14) and (15) in the following way:

I. From known values of ν and d_{50}, a selected value of V, and an assumed value of r_b, calculate $\frac{V}{\sqrt{gd_{50}}}$, $\frac{r_b}{d_{50}}$, and $\frac{Vr_b}{\nu}$

II. Obtain f_f from fig.(14) and f'' from fig. (15). Use the value of f_f corresponding to smooth boundaries if the $R - \frac{r_b}{d_{50}}$ intersection would fall below the smooth boundary relation.

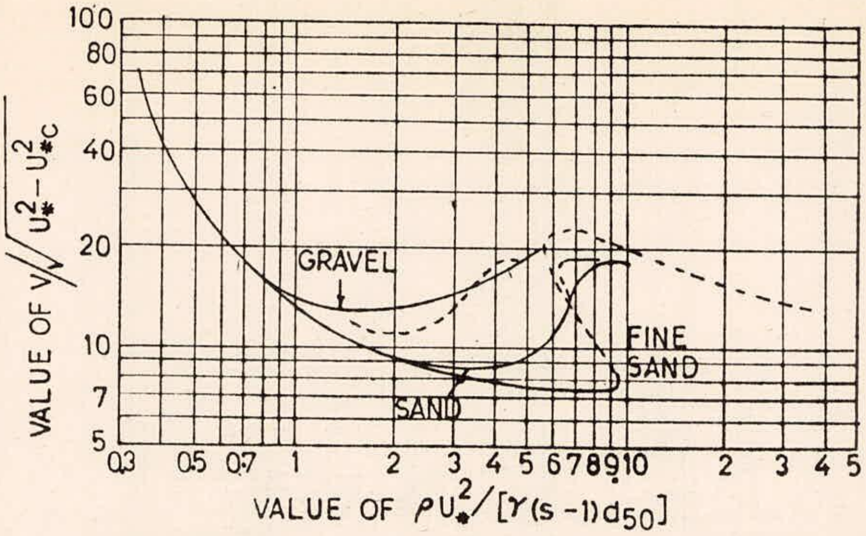


FIG. 13- RAUDKIVI'S (1971) GRAPHICAL RELATION GIVING MEAN VELOCITY AS FUNCTION OF SHEAR VELOCITY

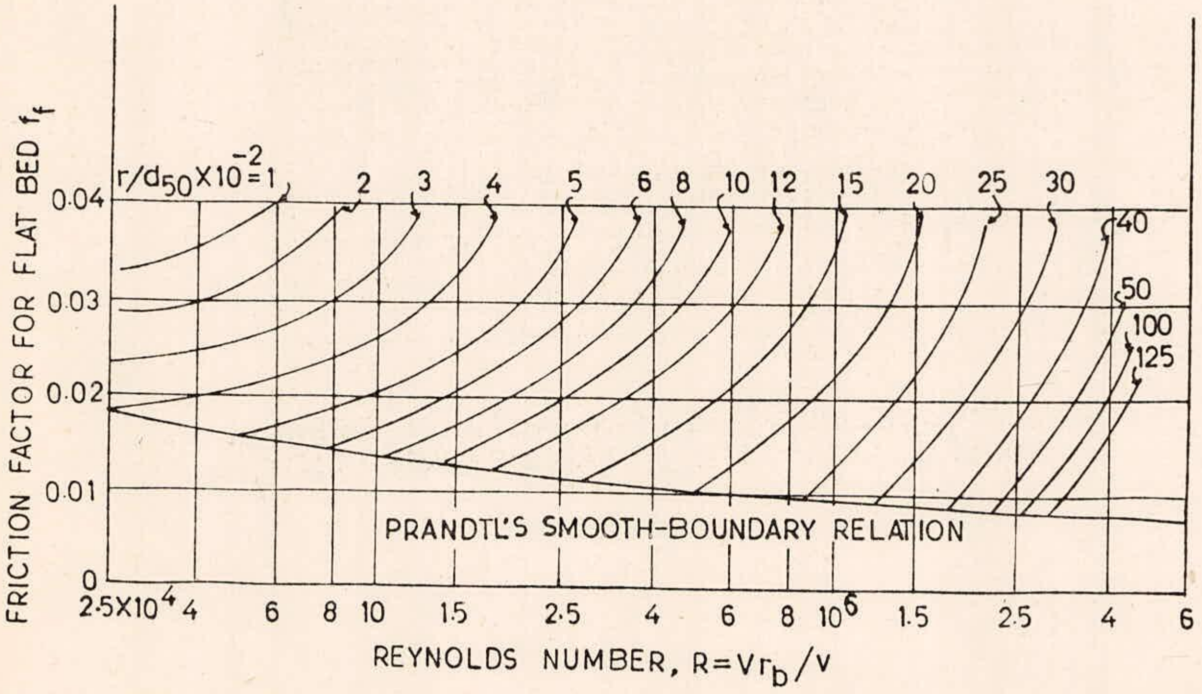


FIG. 14-LOVERA AND KENNEDY'S (1969) FLAT BED FRICTION FACTOR DIAGRAM FOR ALLUVIAL STREAMS.

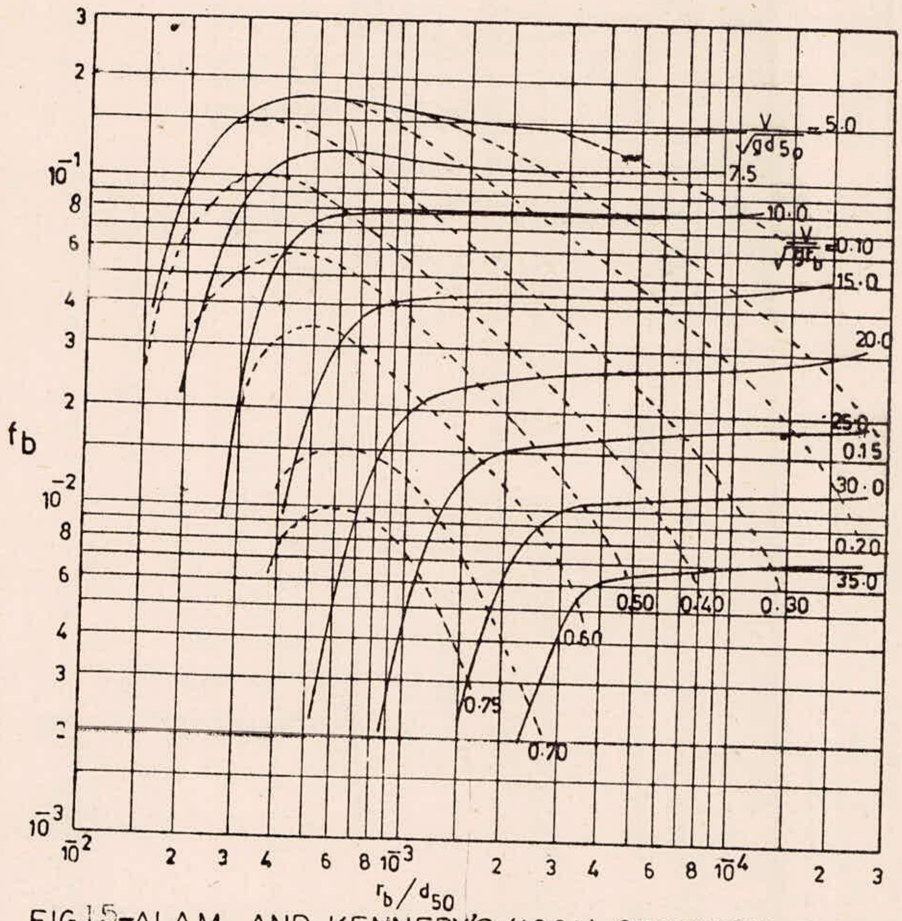


FIG.15-ALAM AND KENNEDY'S (1964) GRAPHICAL EXPRESSION OF f_b'' AS FUNCTION OF FROUDE NUMBER AND r_b/d_{50}

III. Calcuate $f = f_f + f''$

IV. Calculate the corresponding hydraulic radius using f and the known values of S

$$r_b = f \frac{V^2}{8\ gS} \qquad \ldots(23)$$

V Compare the calculated and assumed values of r_b. If they are not in satisfactory agreement, use the values of r_b calculated from equation given previously and repeat the procedure. Iterate until the assumed and calculated values of r_b are equal.

where,

r_b = hydraulic radius of bed

f_f = friction factor for flat beds

f'' = bed friction factor for form drag

f = friction factor (from Darcy-Weisbach)

R = Reynold's Number

and others same as previously discussed

c) Mostafa and McDermid s (1971) Method:

They sought to avoid the questionable step of dividing the hydraulic radius, slope or friction factor, or both into components associated with the grain roughness and bed form resistance. They expressed the Manning equation in dimensionally homogeneous form as:

$$C = \frac{\sqrt{g}}{C_m(d_{50})^{1/6}} . r^{2/3}\ S^{1/2} \qquad \ldots(24)$$

in which the Cm = the non-dimensional Manning coefficient that is related to the Darcy-Weisbach friction factor.

$$f = 8\ C_m^2\ \left(\frac{d_{50}}{r}\right)^{1/3} \qquad \ldots(25)$$

They concluded on the basis of physical and dimensional considerations, that

$$Cm = Cm\ \left(\frac{V}{\sqrt{\frac{gA}{T}}} \qquad \frac{d_{50}}{\delta}\right) \qquad \ldots(26A)$$

in which T is the width of the channel at the level of the free surface; and

δ = thickness of the viscous sublayer.

To apply their method to a wide river for which the depth and hydraulic radius are nearly equal, equation (24) can be rewritten as:

$$\frac{V}{\sqrt{gd}}\ C_m = FC_m = \left(\frac{d}{K_s}\right)^{1/6} . S^{1/2} \qquad \ldots(26b)$$

Procedure:

I. Calculate FC_m for selected values of $K_s = d_{50}$, S and $\frac{d_{50}}{\delta}$

II. Superimpose equation (26B) on fig.(16) for the conditions chosen and the intersection of this curve with the $\frac{d_{50}}{\delta}$ curve for the same flow gives C_m and F (Froude number).

III. Calculate V from C_m and F.

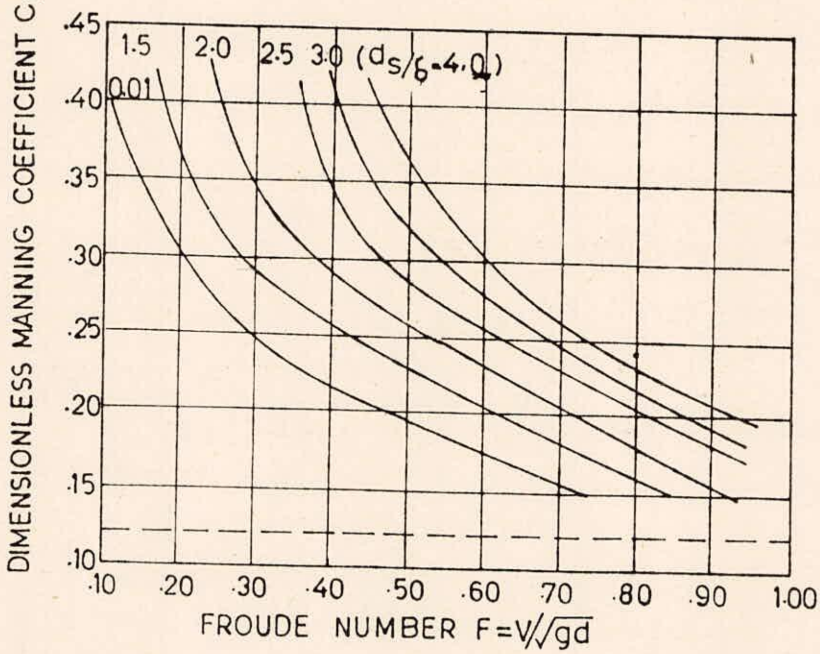


FIG. 16-MOSTAFA AND MC DERMID'S (1971) CHART FOR DETERMINATION OF NON-DIMENSIONAL MANNING COEFFICIENT

CONCLUSION

Various methods under different influencing factors have been given by different authors. This report describes those methods available to establish rating curve under shifting control. The following methods are recommended for establishing, rating curves under different shifting control situations.

Growth and decay of Aquatic growth:

No empirical or mathematical way to establish rating qurve under such condition is yet available. Hence rating curve should be established for every season for all ranges of flooding levels.

Alluvial bed form changes:

On the basis of experimental results Dawdy (1961) established a relation representing the upper regime in a true sand bed stream which is given below:

$$V = K.R^{1/2} \qquad ...(1)$$

where,

V = mean velocity

K = constant

R = hydraulic radius

exponent of R ranges from 2/3 as in Manning's equation to 1/2, the lower exponents being associated with the coarser grain sizes.

Backwater Variation:

If the discharge is affected at all times, fixed or constant fall method is applied. On the other hand, when fall reduces below a particular value affecting the discharge, the normal fall method is used. In case the slope of the channel is variable, stage-ratio method should be used. If discharge is being affected by tidal fluctuations, or due to ponding at down stream, SSARR model technique is better to use.

Overbank flow:

Two methods namely Stevens method and Manning formula are available. The main practical difference between the two methods is the degree of flexibility. The Stevens method includes certain simplifying assumptions that must be retained through-out the problem. The Mannings formula may be used with analogous assumptions, but also permits a more rational approach when needed. It can, therefore, be used to advantage in particularly complicated sections.

Scour and/or Fill:

Raudkivi's (1967) graphical relations are suitable for establishing the rating curve, when the flow in the channel is in low regime. This method is quite straight forward but it is not clear which of the curve should be used in a particular case. Alam and Kennedy's (1969), analysis is useful in establishing the rating curve, but is valid only for sand and water. Mostafa and McDermid's (1971) Manning coefficient graph can also be used for establishing the rating curve.

While using the methods suggested above, one should be guided to the extent possible by the available experience with similar streams in the same locale and preferably the stream being analysed.

Stage - discharge relation is an indirect method of discharge measurement. This is also an essential item in developing secondary data information such as the mean daily, weekly/monthly volumes etc. Irrespective of the engineering applications such as water availability, forecasting etc., It is always advisable to obtain secondary data information from rating curves of individual floods which may assume any level within the cross-section sometimes extending far beyond the bank edges. In case of inadequate discharge observations, seasonal ratings are of great importance. This must be dealt with carefully in site specific coupled with level specific situations as much as possible. Methodologies described and discussed in this report provide useful guideline and should be used with proper judgement and care to deal with particular situations.

REFERENCES

1. Alam, A.M.Z., discussion of "Resistance Relationships for Alluvial Channel flow", by R.J.Garde and K.G.Ranga Raju, Journal of the hydraulics Division, ASCE, Vol.93, No.HY2, Proc., Paper 5129, Mar.,1967, pp.91-96.

2. Alam, A.M.Z. and Kennedy, J.F., "Friction Factors of Flow in Sand bed Channels", Journal of the Hydraulics Division, ASCE, Vol.95, No.HY6, Proc. Paper 6400, Nov.,1969, pp.1973-1992.

3. Blench, T.,"Regime Theory Design of Canals with Sand Beds", Journal of the Irrigation and Drainage Div., ASCE, Vol.96, No.IR2, Proc. Paper 7381, June, 1970, pp.205-213.

4. Colby, B.R.,"Discontinuous Rating Curves for Pegion Roost and Cuffawa Greeks in Northern Mississippi", U.S.Deptt. Agr.ARS 41-36, 1960, pp.31.

5. Cunha, Veiga da L.,"About the Roughness in Alluvial Channels with Comparatively Coarse bed Material", Proc.,Twelth Congress of the International Assoc. for Hydraulic Research, Vol.1, Paper No.A10, Sept., 1967, pp.76-84.

6. Dawdy, D.R., "Depth Discharge Relation of Alluvial Streams-Discontinuous Rating Curves", Water-Supply Paper 1948-C, USGS, Washington, D.C.,1961.

7. Einstein, H.A., and Barbarossa, N.,"River Channel Roughness", Transactions, ASCE, Vol.117, Paper No.2528, 1952, pp. 1121-1146.

8. Engelund, F.,"Hydraulic Resistance of Alluvial Streams", Journal of the Hydraulics Div.,ASCE, Vol.92, No.HY2, Proc. Paper 4739, March, 1966, pp.315-327.

9. Engelund, F., Closure to "Hydraulics Resistance of Alluvial Streams", Journal of the Hydraulics Div., ASCE, Vol.93, No.HY4, Proc. Paper 5304, July 1967, pp.287-296.

10. Garde, R.J., and Raju, K.G.R.,"Resistance Relationships for Alluvial Channel Flow", Journal of Hydraulics Div., ASCE, Vol.92, No.HY4, Proc. Paper 4869, July 1966, pp.77-100.

11. Haynie, R.B., and Simons, D.B.,"Design of Stable Channels in Alluvial Materials," Journal of the Hy-

draulics Div.,ASCE, Vol.94, No.HY6, Proc. Paper 6219 Nov., 1968, pp.1399-1420.

12. Herschy, R.W.,"Stream Flow Measurement", Elsevier Applied Science Publishers, 1985.

13. Hiranandani, M.G., and Chitale, S.V.,"Stream Gauging" CWPRS, Poona, India.

14. Mostafa, M.G., and McDermid, R.M., discussion of "Sediment Transportation Mechanics: F. Hydraulic Relations for Alluvial Streams", by the Task Committee for Preparation of Sedimentation Manual, Committee on Sedimentation of the Hydraulics Div., Vito A.Vanoni, Chmn., Journal of Hydraulics Div. ASCE, Vol.97, No.HY10, Proc. Paper 8407, Oct.,1971., 1777-1780.

15. Raudkivi, A.J.,"Analysis of Resistance in Fluvial Channels", Journal of the hydraulics Div., ASCE, Vol.93, No.HY5, Proc. Paper 5426, Sept.,1967, pp.73-84.

16 Raudkivi, A.J.,discussion of "Sediment Transportation Mechanics: F. Hydraulic Relations for Alluvial Streams", By the Task Committee on Preparation of Sedimentation Manual, Committee on Sedimentation of the Hydraulics Div., Vito A. Vanoni, Chmn., Journal of Hydraulics Div., ASCE, Vol.97, No.HY12, Proc. Paper 8552, Dec., 1971, pp.2089-2093.

17. Shen, H.W., "Development of Bed Roughness in Alluvial Channels", Journal of Hydraulics Div., ASCE, Vol.88, No.HY3, Proc. Paper 3113, May,1962, pp.45-58.

18. Simons, D.B., and Richardson, E.V.,"The Effect of Bed Roughness on Depth-Discharge relation in Alluvial Channels", USGS Water Supply Paper 1498-E, 1962, pp.26.

19. Simons, D.B., and Richardson, E.V.,"Resistance to Flow in Alluvial Channels", Professional Paper 422U, USGS, Washington, D.C.,1966.

20. Stevens, J.C.,"A Method of Estimating Stream Discharge from a Limited number of Gaugings", Engineering News, Vol.58, No.3, July 1907.

21. W.M.O.,"Manual on Stream Gauging", Vol.II "Computation of Discharge", Report No.13, 1980.