EFFECT OF SEDIMENT ON RESISTANCE TO FLOW IN COBBLE AND BOULDER BED RIVERS

by

K. S. Al-Shaikh-Ali

D. B. Simons

R. M. Li

Civil Engineering Department

Engineering Research Center

Colorado State University

Fort Collins, Colorado

May 1978

CER-77-78KSA-DBS-RML-46

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INTRODUCTION

On July 31, 1976 the Big Thompson Canyon was subjected to a 10 inch thunderstorm. According to indirect measurements made by the U.S.G.S. (12) the discharge of the Big Thompson River reached a calculated value of 31,200 cfs at the mouth of the canyon near Drake, Colorado compared to an all-time recorded maximum of 8000 cfs.

The bed material, composing the bed of the river, ranges from small to large boulders. Observations of the flood flow in the river by . Simons verified the existance of antidunes, and event never observed before in the channel. This led to the conclusion that the huge amount of sand and gravel sediment carried into the river covered the boulders forming the channel bed and causing it to behave as a sand bed channel during much of the flood event.

The purpose of this paper is to discuss the accuracy of measurement of extreme events in the watersheds, the resistance to flow in large-scale roughness channels and, in particular, the effect of sediment yield on resistance to flow in such channels. This information is necessary to more accurately estimate peak flows and to locate and design safe areas adjoining such water courses.

PREVIOUS WORK

In sand bed channels, when the bed form consists of ripples and/or dunes, form roughness is much greater than the grain roughness. However, with large-scale roughness elements such as boulders, bed forms rarely occur (only when the Froude number, F_r, is less than one and the shear stress, τ, is greater than the critical shear stress, τ_c). The resistance to flow in such channels is mainly due to grain roughness. To predict the stage discharge relationship for large-scale roughness channels, the Darcy-Weisbach, the Manning, the Chezy, or some other resistance equation is used. However, before using these equations it is necessary to estimate the resistance coefficient.

In an attempt to show the similarity between fully developed turbulent flow in pipes and in open channels, Leopold, Wolman and Miller (7) used data from Brandywine Creek and introduced the following relation:

$$\frac{1}{\sqrt{f}} = 2\log \frac{d}{D_{84}} + 1.0 \tag{1}$$

where, f is the Darcy-Weisbach resistance coefficient, d is the average depth of flow and D_{84} is the diameter which is equal to or larger than 84 percent of the bed particles. Strickler (11), Keulegan (5), Meyer-Peter and Müller (8), and Lane and Carlson (6) are among the researchers who suggested the following form of equations for estimating the Manning roughness coefficient:

$$n = a\, D_{x\%}^{1/m} \tag{2}$$

where, n is the Manning coefficient, a and m are constants and $D_{x\%}$ is the diameter which is equal to or larger than $x\%$ of the bed particles. Values of x used ranged between 65 and 90. Furthermore, Chow (3) and Barnes (1) have given a descriptive and illustrated estimate of Manning coefficient for a wide range of bed materials under different conditions. Simons and Richardson (9) introduced a method for estimating the discharge coefficient $\frac{C}{\sqrt{g}}$, where C is the Chezy coefficient and g is the gravitational acceleration, based upon the correction of the depth of the flow. They reasoned that for the same discharge the difference between a flow on a smooth and rough boundary is reflected in a change, Δd, in the depth of flow. The change in depth was related to the depth for different sizes of bed material. Graphs of $\frac{C}{\sqrt{g}}$ versus the shear velocity Reynolds number, $R_* = \frac{U_* d}{\nu}$, was constructed with $\frac{\Delta d}{d}$ as a third variable. The shear velocity U_* is equal to $\sqrt{gRS}$, where R is the hydraulic radius and S is the channel slope and ν is the kinematic viscosity. For natural streams, Simons and Sentürk (10) suggested the use of the following form of the Monomial formula:

$$\frac{U}{U_*} = 8.12 \left(\frac{R}{D_{90}}\right)^{1/6} \qquad (3)$$

where U is the average velocity of the flow. Based upon flume and natural streams data, Judd and Peterson (4) introduced the following relations:

$$\sqrt{\frac{8}{f}} = fn(\lambda) \left(\frac{d}{w}\right)^{7(\lambda - 0.08)} \left(\frac{d}{D_{50}}\right)^{1/3} \qquad (4)$$

where fn is a function of , λ is a roughness spacing coefficient and is equal to $\sum_1^n A_F/A_{bed}$, A_F is the frontal cross-sectional area of roughness elements, A_{bed} is the area of the channel bed and w is the surface width of the flow. Bathurst (2) based upon data from stony bed rivers, showed that the roughness spacing coefficient can be related to the relative roughness by the following equation:

$$\lambda = 0.139 \log \left(1.91 \frac{D_{84}}{R}\right) \qquad (5)$$

He then proposed use of the equation:

$$\sqrt{\frac{8}{f}} = \left(\frac{R}{0.365\, D_{84}}\right)^{2.34} \left(\frac{w}{d}\right)^{7(\lambda - 0.08)} \qquad (6)$$

The previous review is not all inclusive and it is not intended to be so. Nevertheless, it identifies the factors that previous investigators have considered to significantly influence resistance to flow in large-scale roughness channels. These factors are the relative roughness, roughness spacing, and channel shape. Prior to this paper sediment discharge has never been considered to be a significant factor affecting resistance to flow. The following experiment coupled with field observations verify that it can be important.

EXPERIMENTAL PROCEDURE

A recirculating plastic flume was used to study the effect of sediment on resistance to flow in large-scale roughness channels. A layer of rocks having a maximum size of about 1 inch (25.4 mm) was placed along the flume bed (Fig. 1 and 2). Then a water discharge which barely covered most of the rocks was allowed to circulate (Fig. 3). Henceforth, this discharge, Q_o , shall be called the subflow discharge. After measuring the subflow discharge and recording its elevation, a relatively large channel discharge, Q , was circulated through the flume (Fig. 4). The depth of flow, corresponding to the difference between the channel and subflow discharges, Q_1 , was measured. Keeping the discharge constant, sand-size sediment was then fed to the flume and the resulting changes in the depth of flow were recorded. It was predetermined that the developing sand bed channel would fall in the upper flow regime (plane and antidune beds forms). Sediment was fed to the system until the rock roughness was submerged in sand and antidunes started to develop. Figure 5 and 6 show the bed, completely covered with sand, in the plane and antidune phases, respectively. After measuring the depth of flow the sediment supply was stopped the bed was allowed

FIG. 1. - Plan View of the Rock.

FIG. 2. - Side View of the Rock.

FIG. 3. - The Subflow Discharge.

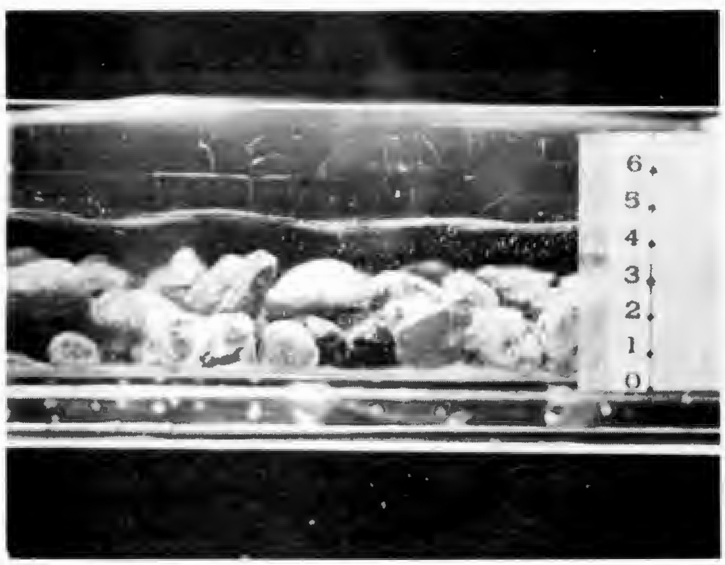

FIG. 4. - The Channel Discharge.

FIG. 5. - Plane Bed.

FIG. 6. - Antidunes Bed.

to scour exposing the normal rock roughness. Figures 7, 8 and 9 show the upstream, middle and downstream channel bed conditions, respectively, sometime after scour of the bed was initiated by halting the inflow of sand to the system.

RESULTS AND DISCUSSION

Results of the experimental work are schematically illustrated in Fig. 10. Although the depth of flow above the rock bed, d_r, was produced by 90 percent of the channel discharge, it was almost twice the depth above the sand bed, d_s, produced by the entire channel discharge, under extreme conditions.

The total discharge and energy slope before and after sediment feeding are the same. Furthermore, if one assumes that the hydraulic radius can be replaced by the depth of flow, Manning's equation can be used to derive the following relation:

$$n_s = n_r \left(\frac{d_s}{d_r}\right)^{5/3} \qquad (7)$$

where n_s and n_r are the Manning coefficients corresponding to sand and rock bed channels, respectively. By substituting the value $d_s = 2\ d_r$ into Eq. 7, it reduces it to the following:

$$n_s = 0.314\ n_r \qquad (8)$$

Equation 8 shows that resistance to flow in a rock bed channel can become more than three times smoother if there is enough sand and gravel size sediment to fill the spacing between its roughness elements during the flood event.

FIG. 7. - Upstream Portion of the Bed.

FIG. 8. - Middle Portion of the Bed.

FIG. 9. - Downstream Portion of the Bed.

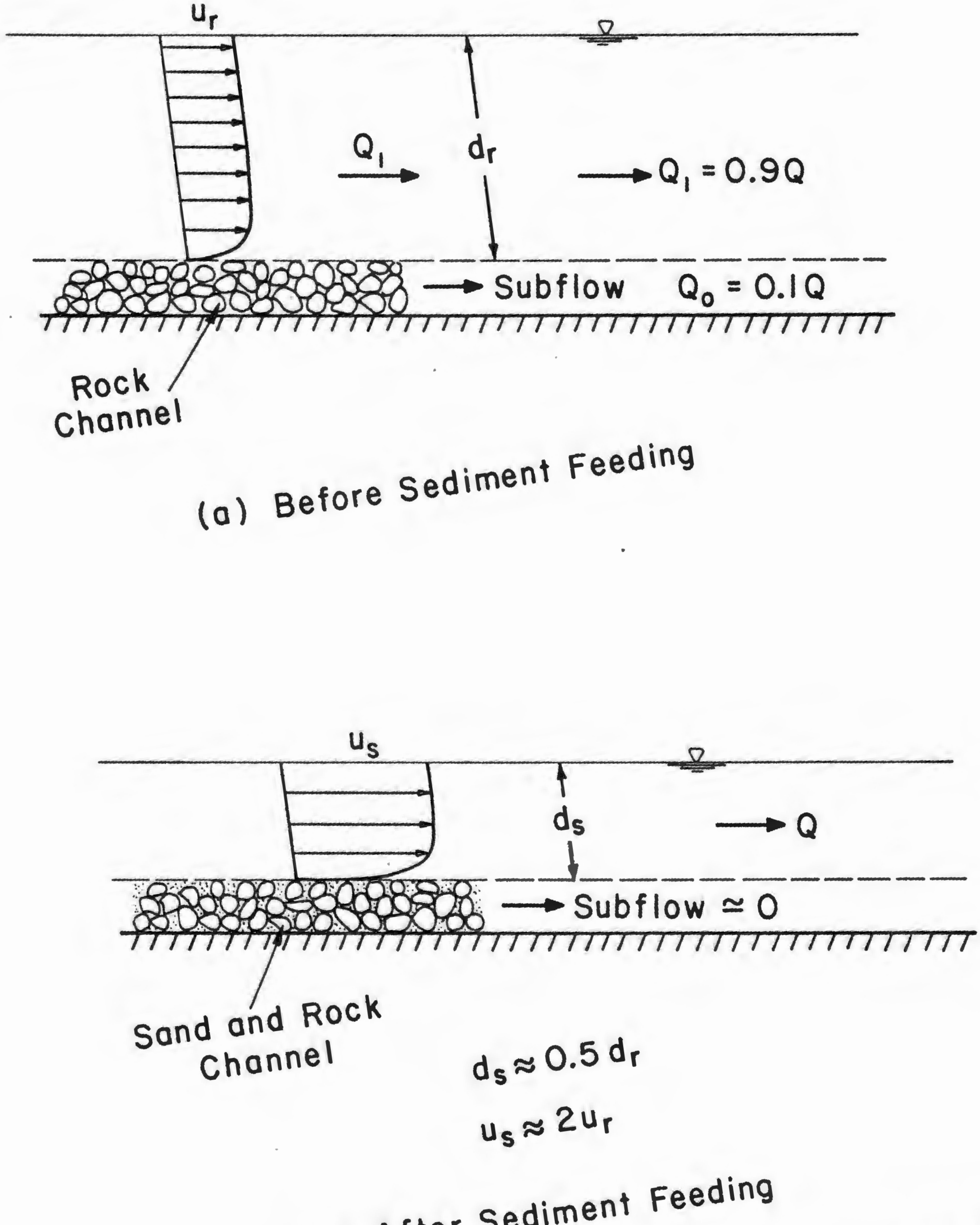

FIG. 10.- Schematic Illustration of a Rock Channel Before and After Sediment Feeding.

Figure 11 is a plot of Manning coefficient versus the discharge for channels with medium and large-scale roughness elements. It is prepared from Barnes' work (1). The manning coefficients were calculated for various rivers in the United States after the occurrence of a major flood. Discharges were either measured by the current-meter method or determined from well-defined stage-discharge relation. As the discharge increases both the Manning coefficient, the range of variation and the size of bed material decrease. Furthermore, solid lines join two values of Manning's coefficient for the same channel under different flow conditions. As the depth of flow increases the value of Manning's coefficient decreases drastically. This decrease cannot be attributed entirely to a change in relative roughness resulting from a change in depth. Sand and gravel size sediments carried out by the higher discharges are partly responsible for this decrease in resistance to flow. Further evidence verifying the effect of sand and gravel size sediment on rock and cobble roughness elements can be obtained from studying streams number 2, 3 and 6. Streams 2 and 6 have smaller bed material and higher discharges than stream 3. In spite of that, stream 3 has a lower value of Manning coefficient. Comparison of other streams in Fig. 11 lead to the same conclusion. When sand and gravel size sediments from watersheds deposit between the rock and cobble elements there is significant reduction in resistance to flow and a comparable decrease and increase in the depth and velocity of the flow, respectively. This fact can be used to explain what appears to be an inconsistency in Barnes' (1) work.

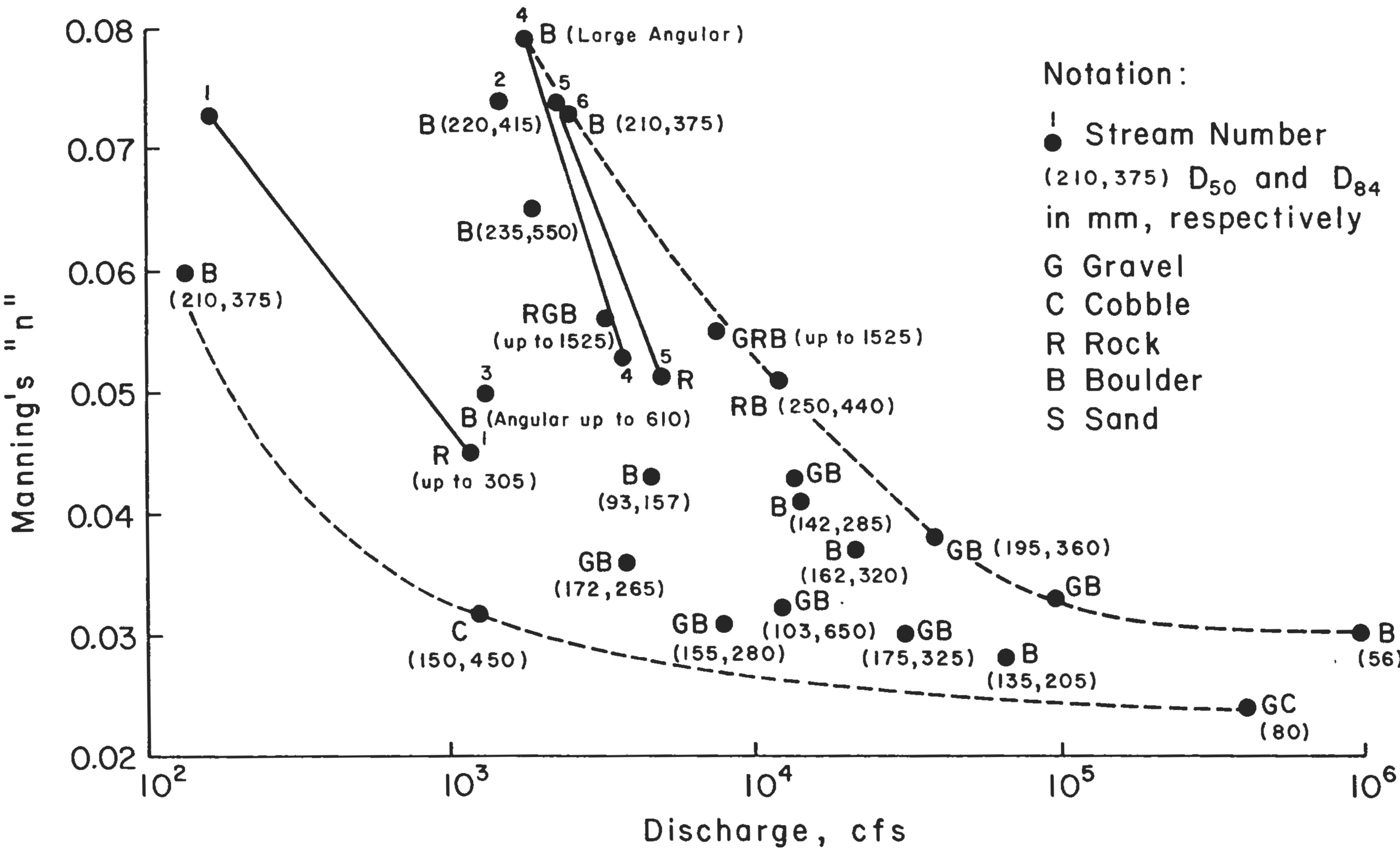

FIG. 11.- Variation of Manning's Coefficient with Discharge in Natural Streams [After Barnes (1)].

Based upon the proceeding discussion and results, it is possible now to schematically illustrate the temporal variation of the resistance to flow in a rock channel. As a result of extreme hydrological events large quantities of sand and gravel size sediments are released from the watershed or caving banks of such channel. For this event the relation between the Manning coefficient and the sediment discharge, Q_s , is given in Fig. 12a. Fig. 12b illustrates the corresponding temporal variation of the ratio between the actual (measured) Q_a , and the estimated (calculated) Q_e , channel discharges. The estimated channel discharge is determined either by calculating a resistance coefficient (based upon the characteristics of the channel bed material at low or intermediate flows) or estimated from a stage-discharge relation.

SUMMARY CONCLUSIONS AND IMPACTS

When the watershed of a channel with a bed formed of rock and cobbles is subjected to a major storm a large inflow of sand and gravel size sediments to the channel can result. This is particularly true for semi-arid and arid areas. The sand and gravel size sediments gradually fill the spaces between the large roughness elements and may submerge them completely allowing the channel to eventually behave as a sand bed channel. As a result, the resistance to flow can be greatly reduced. The experimental work conducted in a small flume simulating this phenomenon showed that resistance to flow in rock and cobble bed channels can be decreased from one-half to one-third its original value when sand and gravel size sediment is fed to the system from caving banks and from the watershed. The depth of flow can decrease to half its original value and the velocity of flow doubled.

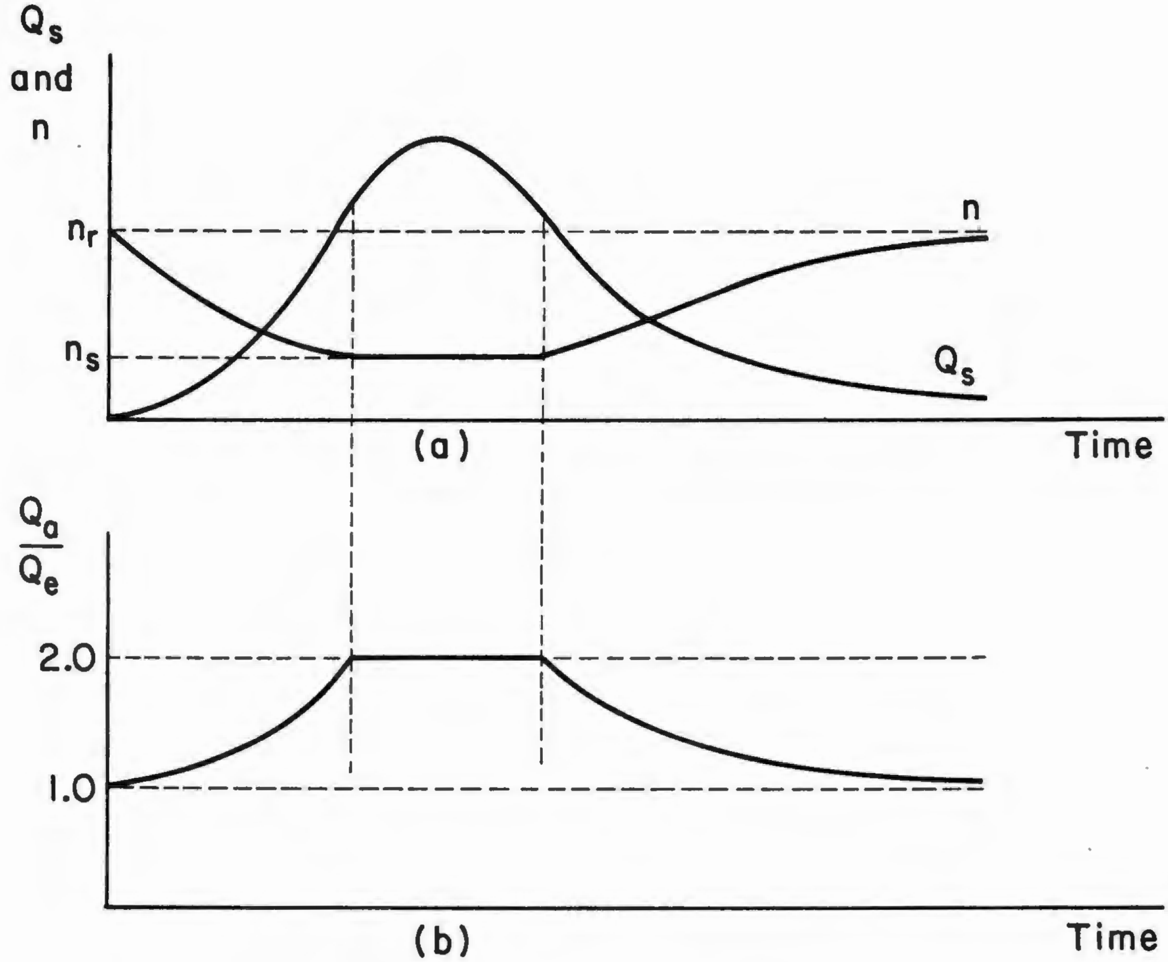

FIG. 12.- Temporal Variation of Sand and Gravel Sediment Discharge, the Manning Coefficient and the Ratio Between the Actual and Estimated Discharges in a Rock Bed Channel.

In estimating flood peaks and in designing safety areas it is, therefore, not sufficient to find a friction factor based upon the characteristics of bed material observed in the channel at low and intermediate discharges. Nor is it possible to rely entirely on a well established stage-discharge relation which was derived under different sand and gravel sediment discharge conditions. Rather, an estimate of the sediment yield from eroding banks and the watershed is necessary. Underestimation of the friction factor can be significant impacts on a variety of engineering works related to the river and to river control and development. Some of these impacts are:

1. An overestimation of resistance to flow can result in an underestimation of the actual flood discharge by a factor of two. This leads to an underestimation of the actual quantity of water that can be utilized downstream for irrigation and other purposes.
2. An underestimation of the velocity of flow by a factor of two can influence bank stability and bank protection works. The selection of the size of riprap or the selection of other suitable protection material is greatly influenced by the magnitude of the velocity of the flow.
3. Sediment transport in the river is a function of the velocity of flow raised to an exponent ranging between 3 and 6. An underestimation of the magnitude of the velocity by a factor of two can lead to an underestimation of the transported sediment by a factor ranging between 8 and 64. Since reservoir life is directly related to the amount of sediment transported by a river, a shortening of reservoir life by a factor ranging from 1/64 to 1/8 can result.

4. Among other factors, discharges of both water and sediment and velocity of flow influence the calculation of safe scour depth for bridge piers. An underestimation of these quantities can lead to unsafe hydraulic design of bridges and other hydraulic structures.
5. Channel alignment is related to water and sediment discharges. Therefore, highways located along a stream should not encroach upon places of possible realignment of the stream when subjected to flood conditions. An underestimation of the actual discharges can lead to an improper design of the road location and to its eventual destruction.

APPENDIX I.--REFERENCES

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APPENDIX II.--NOTATIONS

The following symbols are used in this paper:

a = constant;

A_{bed} = area of the channel bed;

A_F = frontal cross-sectional area of roughness elements;

C = Chezy's coefficient;

$D_{84}, D_{90}, D_{x\%}$ = the diameter which is equal to or larger than 84, 90 and x percent of the bed particles, respectively;

d = average depth of flow;

d_r = average depth of flow in the rock channel bed corresponding to discharge Q;

d_s = average depth of flow in the sand channel bed corresponding to discharge Q;

Δd = change in the depth of flow corresponding to change from smooth to rough boundaries;

F_r = $U/\sqrt{gR}$ is the Froude number;

f = Darcy-Weisbach resistance coefficient;

fn = function of;

log = logarithm to the base ten;

g = gravitational acceleration;

m = constant;

n = Manning's coefficient;

n_r, n_s = Manning's coefficient for rock and sand beds, respectively;

Q = channel discharge;

Q_o = subflow discharge;

Q_1 = $Q-Q_o$;

Q_a = actual (measured) channel discharge;

Q_e = estimated channel discharge (based upon characteristics of bed material or stage-discharge relations);

Q_s	= sand and gravel sediment discharge;
R	= hydraulic radius;
R_*	= $\frac{U_* d}{\nu}$ is the shear velocity Reynolds number;
S	= channel bed slope;
U	= average velocity of the flow;
U_r, U_s	= point velocity of flow in rock and sand bed channels, respectively;
U_*	= $\sqrt{RS}$ is the shear velocity;
W	= surface width of the flow;
λ	= $\sum_1^n A_F/A_{bed}$ is the roughness spacing coefficient;
ν	= kinematic viscosity of water;
τ	= shear stress;
τ_c	= critical shear stress.

KEY WORDS: Channel stabilization; Canals, Flood control; Floods; Hydraulics; Resistance to flow; Rivers; Sediments; Streams

ABSTRACT: Field and experimental evidence are presented to demonstrate the importance of the inflow of sand and gravel size sediments, released under extreme floods from watersheds and banks of streams, on resistance to flow in channels whose beds are formed of large size roughness elements such as cobbles, rocks and boulders. The released sediments fill the spacings between the large size roughness elements, and may inundate them completely, forcing the channel to behave as a sand bed channel at a much reduced resistance to flow coefficient. Under extreme conditions resistance to flow in these channels decrease to more than one-third its original value resulting in an underestimations of the following quantities: water discharge by a factor of two, sediment discharge by a factor ranging between 8 and 64, velocity of flow by a factor of two. Furthermore, an overestimation of flow depth by a factor of two can result. Impacts of failure to estimate the previous quantities with a reasonable degree of accuracy are: underestimation of the actual quantity of available water, improper selection of bank protection material, overestimation of reservoir life, unsafe design of scour depths at hydraulic structures, improper design of highway location as well as others relating to river control and development.