

RELATION OF SUSPENDED-SEDIMENT CONCENTRATION TO CHANNEL SCOUR AND FILL

By

LUNA B. LEOPOLD

U. S. Geological Survey, Washington, D. C.

THOMAS MADDOCK, JR.

U. S. Bureau of Reclamation, Washington, D. C.

INTRODUCTION

It is known that during the passage of a flood the channel of an alluvial stream scours and fills with considerable rapidity. Though such changes may be random, it seems more likely that there is a definite pattern of channel change directly related both to discharge and to the sediment load provided to the river by the drainage basin.

In a study by the authors [1] an analysis was made of concurrent values of suspended sediment load and width, mean depth, mean velocity, and discharge at a number of gaging stations. From the data analyzed it appeared that fairly definite relations exist between these variables. These relations are summarized in Fig. 1, to which the following definitions apply:

$$w = aQ^b, \quad d = cQ^f$$
$$v = kQ^m, \quad l = qQ^j$$

in which

w = width of water surface, in feet.

d = mean depth, in feet, cross-sectional area divided by width.

v = mean velocity, in feet per second, discharge divided by area.

l = suspended sediment load in the stream, in tons per day.

a, c, k, p, b, f, m, j = coefficients and exponents.

In Fig. 1 the ordinate is the ratio

$$\frac{m}{f} = \frac{\text{rate of increase of log of velocity with log of discharge}}{\text{rate of increase of log of depth with log of discharge}}$$

The figure shows that for a given relation of width to discharge (value of b), the slope of the suspended load rating curve j is a function of the ratio m/f .

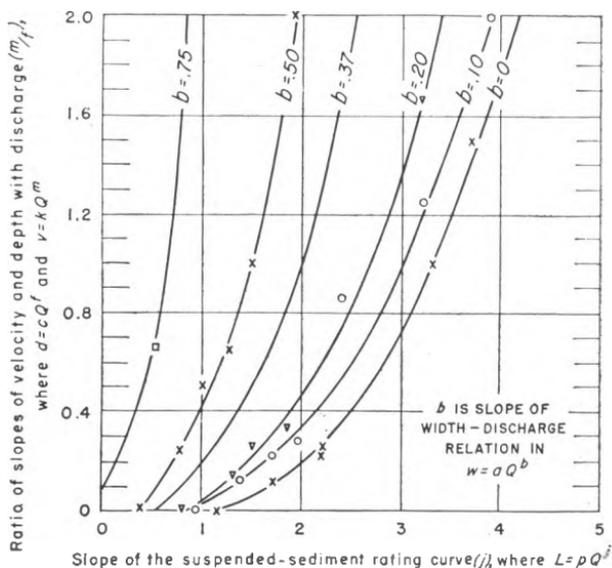


FIG. 1. RELATION OF RATES OF INCREASE WITH DISCHARGE OF WIDTH, DEPTH, VELOCITY, AND SUSPENDED LOAD.

Similar relations are derived for constant discharge and can be expressed as follows, comparing natural channels of various characteristics. For constant discharge and width, an increase in suspended load is accompanied by an increase in velocity at the expense of depth. For constant discharge and velocity, an increase in width at the expense of depth is accompanied by a decrease in suspended load. If these relationships exist between various natural river cross sections in alluvial streams, it is logical that they should also apply to the short-term changes of these same factors during scour and fill accompanying a flood passage.

This present discussion concerns the analysis of some particular flood passages during which an adequate number of essentially simultaneous measurements of suspended load and discharge were made. To be useful for this purpose the discharge measurements must be made by current meter in order that changes in width, mean depth and mean velocity can be determined.

OBSERVED HYDRAULIC CHANGES DURING BED SCOUR AND FILL

Consider first the gaging station on the San Juan River at Bluff, Utah. This river has a bed of sand, silt, and some gravel, which

characteristically shifts during a flood. At high stages the banks of the stream are fixed by rock walls, but some changes in width are possible at low stages. The control at the station is a reach of gravel and boulders just downstream from the gaging section, subject to shift under flood conditions. Discharge measurements are made from a cable.

Daily current-meter measurements and suspended-load samples are available for a few years. Figure 2 shows the changes that oc-

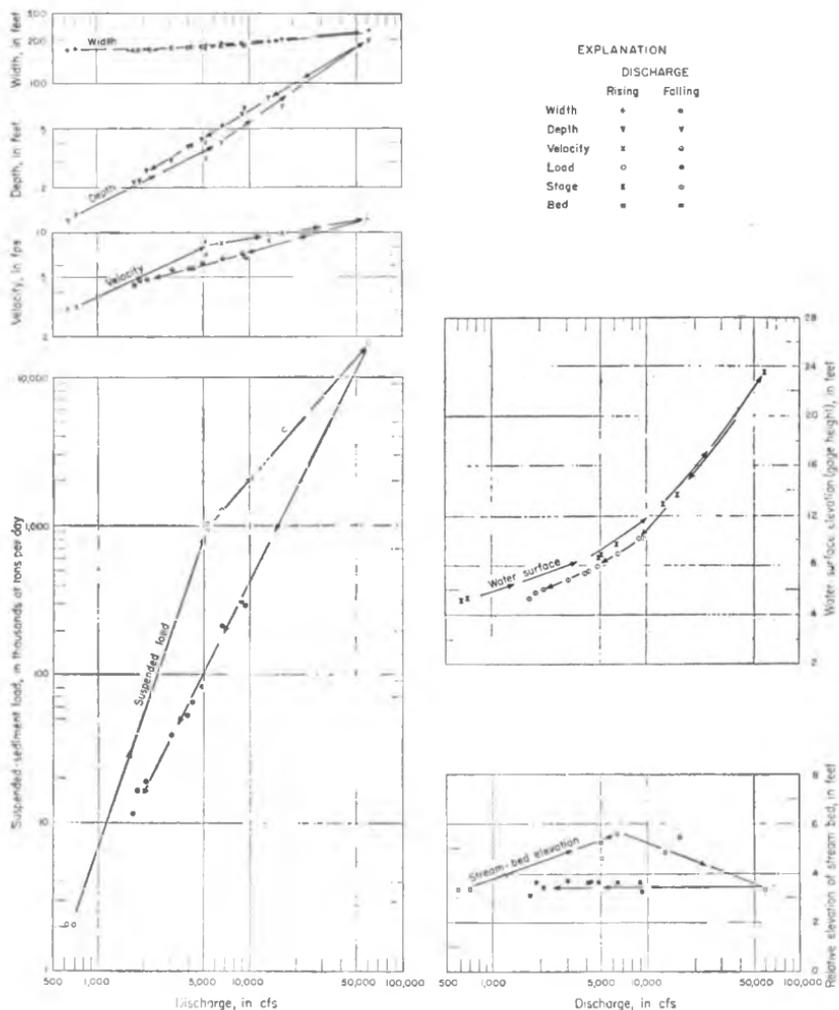


FIG. 2. CHANGES IN CHANNEL-SHAPE FACTORS, SAN JUAN RIVER NEAR BLUFF, UTAH, DURING FLOOD OF SEPT.-DEC. 1941.

curred during a river rise between September 9 and December 9, 1941. Each measurement is indicated by a point in each of the six graphs. For example, during the first day of the rising stage the discharge was 635 cfs., width 171 ft., depth 1.20 ft., velocity 3.08 fps., and suspended load 2,140 tons per day. To simplify the picture, an intermediate rise and fall in discharge between September 16 and 29 is omitted. The width-discharge relationships show that the rising discharge was accompanied by a slight increase in width up to the peak of 60,000 cfs. and the falling discharge retraced nearly the same path on the width curve.

Load, on the other hand, increased at a very rapid rate as the discharge rose from 600 to 5,000 cfs., then remained essentially constant while the discharge continued up to 60,000 cfs.

Depth increased uniformly with discharge up to about 5,000 cfs. Then the slope of the depth-discharge curve increased as the discharge rose from 5,000 to 60,000 cfs. During the falling stage, a new slope of the depth-discharge curve was established which was intermediate between the two values during the rising stage. Note that, at a discharge of 5,000 cfs., the depth was approximately 3.2 ft. during the rising stage and 4.4 ft. during the falling stage.

A corresponding adjustment in the velocity-discharge curve is apparent. At 5,000 cfs. during the rising stage the velocity was 8.6 fps.; at the same discharge during the falling stage it was about 6.0 fps.

The graph of stream-bed elevation versus discharge is also of interest. Bed elevation as plotted is a relative value which was derived by subtracting the mean depth from the gage height (water-surface elevation). This difference is a satisfactory estimate of bed elevation since width varied but little with discharge. Detailed river cross sections at various intervals during the flood have been plotted from current-meter measurements and are presented in Fig. 3.

The bed elevation rose during the first part of the flow increase. That material deposited on the stream bed at the measuring section during the initial part of the flood can be seen by comparing the cross sections in Fig. 3 for September 9 (635 cfs.) and September 15 (6,560 cfs.). Note that this deposition continued progressively as long as the slope of the sediment-discharge curve was great. At a discharge of about 5,000 cfs. the sediment-discharge curve became less steep and remained so as the discharge continued to

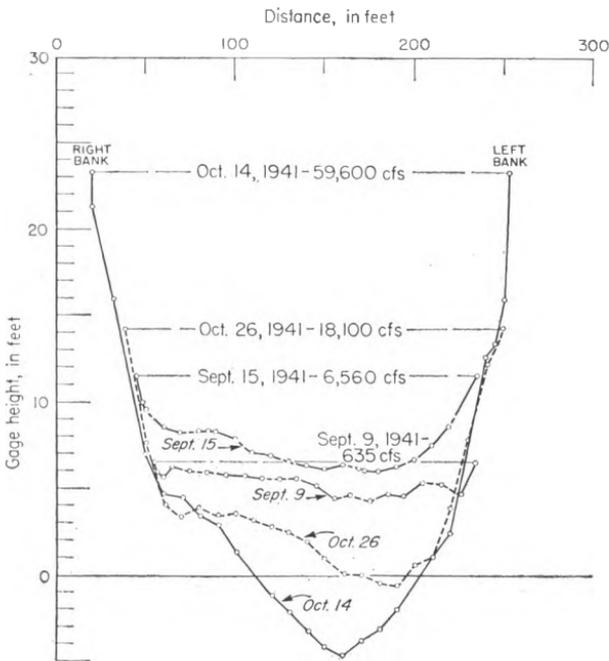


FIG. 3. CHANNEL CROSS SECTIONS DURING PROGRESS OF FLOOD, SEPT.-DEC. 1941, SAN JUAN RIVER NEAR BLUFF, UTAH.

rise to the peak flow of about 60,000 cfs. At discharges between about 5,000 and 60,000 cfs. the suspended-sediment concentration increased less rapidly per increment of discharge than in the range below 5,000 cfs. The smaller rate of increase of suspended-sediment concentration was associated with bed scour. After the peak flow, the falling discharge was accompanied by a stable bed elevation.

This flood was one in which the slope of the width-discharge curve was about the same throughout its passage; consequently, the mutual adjustment between suspended load, velocity, and depth is quite evident. At 5,000 cfs. during the rising stage the suspended load was approximately 1,000,000 tons per day. At the same discharge and width, during falling stage the suspended load was only 100,000 tons per day. The lower suspended load was accompanied by a smaller velocity and a correspondingly greater depth. This is in accord with the relation already noted; that is, at constant discharge and width, decrease in suspended-sediment load is accompanied by a decrease in velocity and an increase in depth.

The observed relations during this flood are also in accord with the concepts explained in connection with Fig. 1. For the same value of b (slope of the width-discharge line), a decrease in the

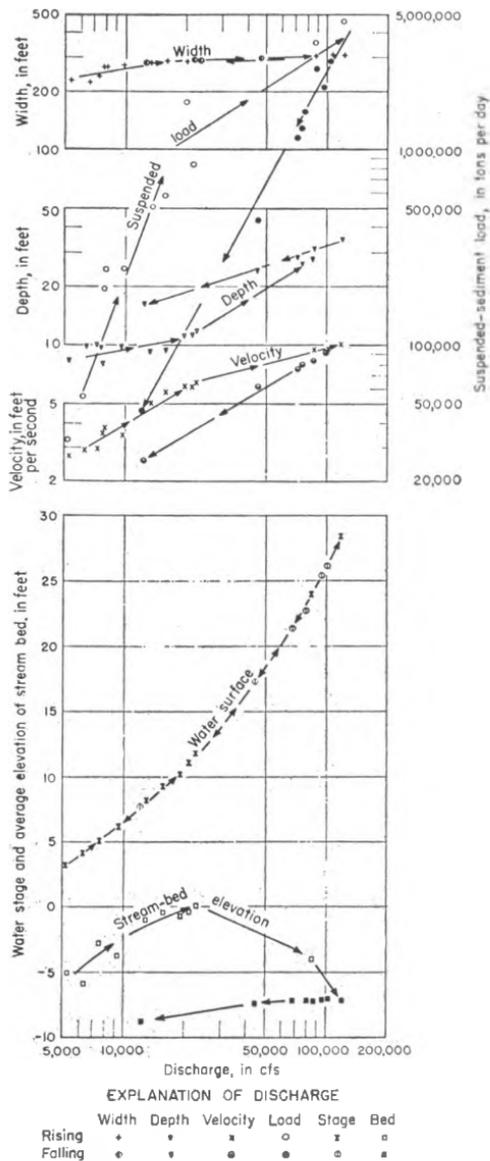


FIG. 4. CHANGES IN CHANNEL-SHAPE FACTORS, COLORADO RIVER NEAR GRAND CANYON, ARIZ., DURING FLOOD OF DEC. 1940-JUNE 1941.

value of j (slope of the suspended load-discharge line) is associated with a decrease in the m/f ratio; that is, the slope of the velocity-discharge line m decreased while the slope of the depth-discharge line f increased.

As a second example of the day-to-day adjustments of channel shape and suspended load, the spring rise of 1941 on the Colorado River at Grand Canyon is used (Fig. 4). During this flood passage, at a discharge of 20,000 cfs. there is a break in the width-discharge curve, as well as in the relations of load, velocity, and depth to discharge. At 20,000 cfs., during the rising stage the load was about 1,000,000 tons per day, whereas during the falling stage the daily load was about 120,000 tons. This smaller load was accompanied by a definite increase in depth and decrease in velocity, whereas the width remained the same.

It is to be noted that the bed elevation rose during the first portion of the flood, fell as the discharge continued to increase toward the peak flow, and continued to fall during the falling stage. At 20,000 cfs. the bed elevation was $8\frac{1}{2}$ ft. lower on the falling than on the rising stage. The gage height, plotted against discharge, showed

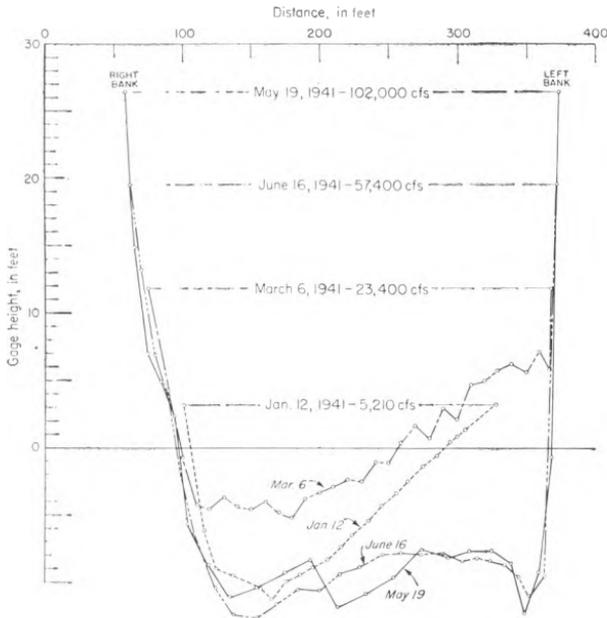


FIG. 5. CHANNEL CROSS SECTIONS DURING PROGRESS OF FLOOD, DEC. 1940-JUNE 1941, COLORADO RIVER NEAR GRAND CANYON, ARIZ.

that the water surface was the same in both rising and falling stages at each discharge. At the measuring section, therefore, the difference in channel shape was taken care of by changes in bed, but the control downstream, a bar of heavy gravel, did not shift.

Deposition on the bed during the initial part of the flood rise can be observed in the successive cross sections in Fig. 5. The river bed

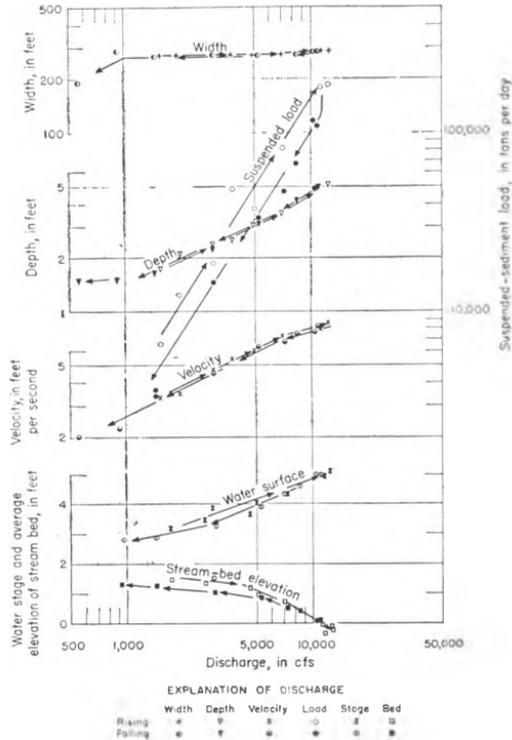


FIG. 6. CHANGES IN CHANNEL-SHAPE FACTORS, RIO GRANDE NEAR BERNALILLO, N. M., DURING FLOOD OF MAY-JUNE, 1948.

was lower on January 12 (5,210 cfs.) than on March 6 (23,400 cfs.). These cross sections demonstrate that the bed filled during the first part of the flood and then scoured as the discharge increased above 20,000 cfs.

A further example, which illustrates another type of adjustment to changing suspended load, is provided by the spring rise of 1948 on the Rio Grande at Bernalillo, N. Mex., presented in Fig. 6. There was some decrease in suspended load at the peak discharge of 11,000 cfs. The lesser load during the falling stage was accompanied by a

shift to smaller velocities and larger depths with practically no change in width. The relation of bed elevation to discharge, however, shows that the river bed scoured during the rising stage when the sediment concentration was high and filled during the falling stage when the concentration was low. The San Juan at Bluff and the Colorado at Grand Canyon, on the other hand, deposited during a part of the rising stage, then scoured during the remainder of the rise and continued to scour during the falling stage.

Figure 7 presents three cross sections of the Rio Grande channel at the gaging station during the passage of the 1948 spring freshet.

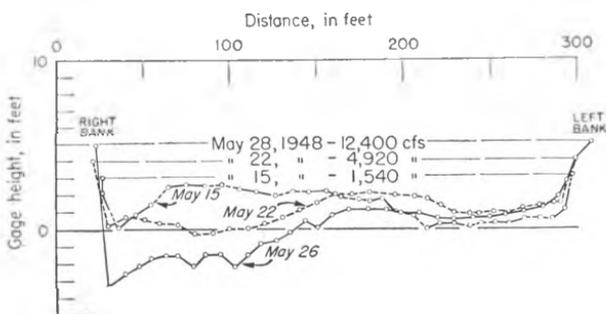


FIG. 7. CHANNEL CROSS SECTIONS DURING PROGRESS OF FLOOD, MAY-JUNE 1948, RIO GRANDE NEAR BERNALILLO, N. M.

The scour of the bed was irregularly distributed across the section but on the whole scour occurred progressively up to the peak discharge, followed by deposition during the falling stage.

The foregoing analyses of scour and fill of a river bed during flood demonstrate that the changes in the bed occur simultaneously with variations in the rate of change of suspended-sediment concentration. It is postulated that the observed changes in the stream bed resulted from changes in the sediment load brought into the reach from upstream, and that the hydrodynamic factors involved tend to promote a mutual adjustment between channel shape and the sediment load carried into the reach. The changes in sediment load which result in a change of channel shape involve both bed load and suspended load. However, because only the suspended load is measured, it is necessary to use the data on the suspended fraction of the load as an index to the total sediment movement.

That the suspended fraction is a meaningful index is demonstrated by the fact that the relations between the channel shape fac-

tors and suspended load, derived from measurements of a number of different rivers, appear to apply in principle to channel changes at a given station during an individual flood. Specifically, with no change of width a decrease of suspended load at a given discharge was accompanied by an increase in depth and by bed scour resulting in a decrease in velocity. This is the type of change indicated by Fig. 1. The decrease in velocity provides the necessary adjustment of capacity to carry the load of the particular size distribution supplied. In response to a decrease in load, the channel shape becomes adjusted through scour to the lower capacity required for equilibrium.

In the foregoing hypothesis it was postulated that the changes in channel shape occurred in response to a change in sediment load brought into the reach. This requires proof that the observed change in suspended sediment is not the result of the observed change of velocity in the reach rather than the cause.

If the high suspended-sediment concentrations resulted from the scouring action of high velocities, it would be implied that high velocity in a given reach scours the channel in that reach. The increase in sediment in transport resulting from the local bed scour should then account for the observed increase in sediment concentration. Under such an assumption increasing velocity should be associated with bed scour and decreasing velocity with deposition on the bed.

For rising stages the San Juan River at Bluff (Fig. 2) and the Colorado River at Grand Canyon (Fig. 4) the beds aggraded during a period of rapidly increasing velocity concomitant with a rapidly increasing suspended-sediment load. The sediment necessary for deposition obviously came from upstream.

With respect to the seasonal sequences of scour and fill, the three rivers discussed are typical of a number of streams in the western United States. The spring floods are derived primarily from snow-melt in the mountains. Considerable sediment is carried into the main stem channels by this melt water, and this load is augmented by the transport of readily available material deposited in the channel system during the local summer floods. Passing of the spring flood leaves the river bed at a lower elevation than that preceding the spring snowmelt. This succession of events is approximately the same each year.

To summarize, the scour and fill of the bed of an alluvial river during flood appears to be an adjustment of channel shape in re-

sponse to a varying sediment load. This adjustment takes place rapidly, but should not be interpreted as implying a complete absence of a time lag. In the long-continued flood passages derived from spring snowmelt, the progressive adjustment of channel to load is easily observed, as has been demonstrated. However, similar graphs for small irregular changes in discharge, even for the same stations, show that the adjustment is not complete. A time lag of days or perhaps weeks is required for adjustments to take place, as might be expected.

THE ROLE OF CHANNEL ROUGHNESS AND SLOPE IN THE ADJUSTMENT OF CHANNEL SHAPE TO SUSPENDED LOAD

It has been stated earlier that at constant discharge the suspended-sediment load appears to be related to the quantities — width, velocity, and depth. It was noted that at constant width and discharge, increased suspended-sediment load would be associated with increased velocity. But because Q and w are constant, the product Vd must be constant. Any increase in velocity, therefore, must require a decrease of depth.

Consider the Manning formula :

$$V = \frac{1.49}{n} d^{2/3} S^{1/2}$$

in which V = velocity

d = depth = hydraulic radius

S = slope of the energy grade line

n = roughness parameter

It is clear that an increase in velocity and a decrease in depth requires an increase in the factor $\frac{S^{1/2}}{n}$; or, in other terms, increased velocity and decreased depth would require an increase in channel slope or a decrease in roughness or both.

Because of the apparent importance of the suspended-sediment load of streams in channel configurations, it is necessary to consider the general effect of sediment load on channel roughness. Vanoni [2] showed that an increase in suspended load tends to decrease channel resistance and thus causes an increase in velocity. He explains this effect as a result of decreased turbulence. The same effect was noted by Buckley [3] in measurements of the Nile River and by Thomas [4].

The effect of suspended-sediment concentration on channel rough-

ness was discussed by Thomas, who also concluded that increased concentration was associated with decreased values of Manning roughness factor n .

It should be expected, then, that when a given river cross section is considered, the large changes in suspended-sediment concentration which occur with changes in discharge should be reflected in important changes in channel roughness. In a given cross section, an adjustment of slope probably cannot take place rapidly enough to account for the observed variations in the velocity-depth relations. The velocity-depth changes and their relation to suspended load observed at a single cross section, as on the Colorado River, the Rio Grande, and the San Juan River, are typical of all the cross sections studied for which adequate data are available. This appears to support the concept that such changes are typical of fairly long reaches of channel, measured in tens of miles rather than in tens of yards. If this is true it is impossible to believe that changes in slope provide the primary mechanism which accounts for the observed changes in velocity-depth relations. In long reaches of river a continuity of slope must be maintained, at least during periods of some months. In other words, the changes in velocity-depth relations typified by the individual floods measured at Grand Canyon, Bluff, and Bernalillo must primarily represent changes in roughness rather than in slope.

No attempt has been made in this preliminary analysis of the problem to explain the hydrodynamics of the empirical relations observed. Certainly bed load is important in helping to determine roughness, but the available data on suspended load must, perforce, be used as a rough index to the load conditions. Further work of a theoretical nature as well as additional analysis is required to explain more fully the observed general relations.

DISCUSSION

Mr. Coldwell stated that even though Mr. Leopold has presented so much worthwhile material, he wished to introduce a new aspect of the problem. The Washita River arm of Denison Reservoir, on the Red River between Oklahoma and Texas, (Fig. 8) offers an opportunity to observe conditions of bed scour and fill of quite pronounced magnitude. The differences between the locations mentioned by Mr. Leopold and this one are that the measuring section for the latter is affected by backwater from Denison Reservoir, and

that rises on the Washita River are almost always short in duration and are not caused by melting snow. During flood periods the water-surface slope is about 1.5 feet per mile, then as the reservoir approaches its normal pool elevation the slope becomes negligible. At the nearest gaging station upstream not affected by backwater some

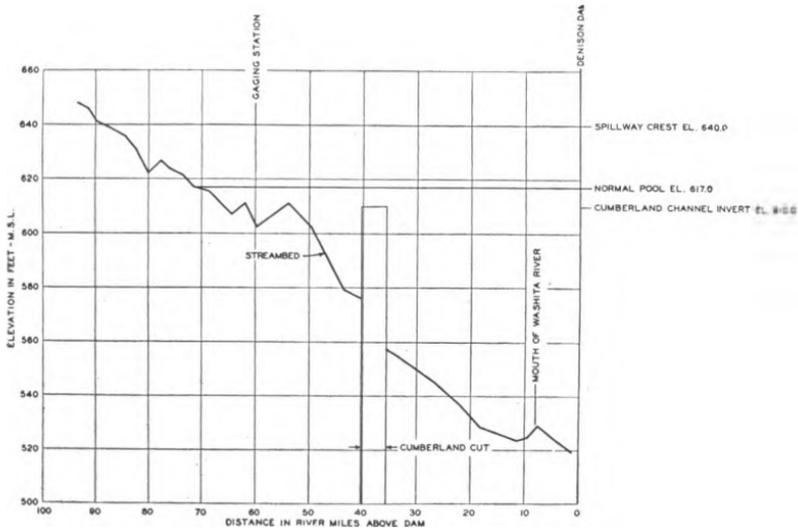


FIG. 8

change in the bed occurs during each flood, but, as soon as the flood is over, the bed is in approximately its original condition. At the location being discussed, changes are more gradual.

The stream section on Feb. 15, 1949, is shown in Fig. 9. In May 1950 a flood of near record discharge, but not great volume, occurred, resulting in the stream section shown for May 13, 1950. The duration of flow greater than base flow was only about 3 days. On May 19, only 6 days after the crest of the flood, another measurement was requested at this station. Contrary to expectations, there had been no significant change in the bed during the 6-day period. Now, it is realized that backwater from the reservoir had decreased the supply of suspended sediment. On December 28, 1950, the section was as shown. During this 7-month interval there had been a few short periods of about 10,000 c.f.s. inflow during the summer, but very low flows during the fall months. Observations since that time show that the stream is always tending to return to the condition of December 28, 1950. Incidentally, the width of the pro-

nounced channel almost exactly fulfills Gerald Lacey's equation for wetted perimeter, $p = 2.67 \sqrt{Q}$. During rises, the width is always less than that indicated by Lacey but probably this is because the rise is not of sufficient duration. Apparently the stream is always trying to stabilize at some width comparable to that given by the equation.

Mr. Leopold has effectively shown that the bed elevation rises during the early part of the rise on the Colorado River, but the same thing does not seem to happen on the Rio Grande. Could it be that, on the Colorado River, in trying to adjust to its desired width the river had too much depth during the early part of the rise? There

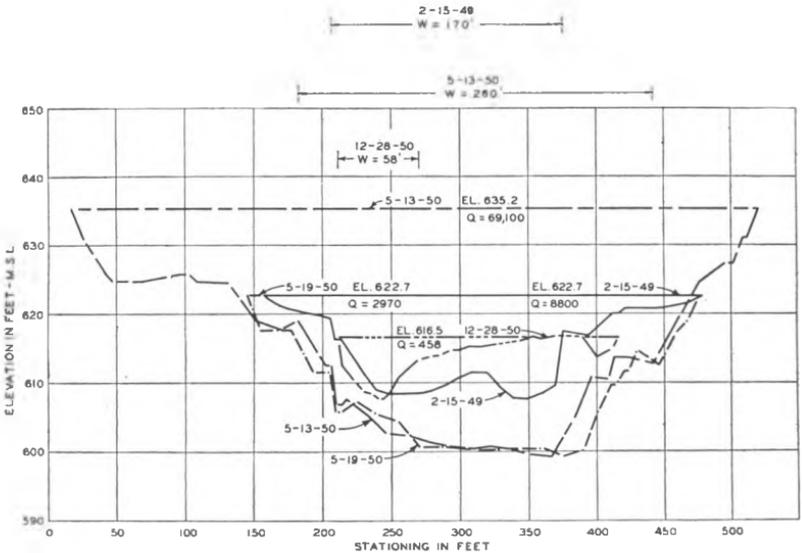


FIG. 9

is evidence on all the low-flow cross sections presented that the portion of the channel where concentrated scour is taking place is only a fraction of the width covered by water.

Mr. Mitchell praised Mr. Leopold's attempt to provide a functional relationship between the movement of suspended sediment and the so-called "hydraulic geometry" of the stream channel through which this movement occurs. A relationship of this nature would be a great boon to the engineer concerned with sediment problems in a river, as well as to the geologist, for whom Mr. Leopold's investigations seem primarily to have been made. It is questionable, however, that the profession can benefit appreciably from the work

done by Mr. Leopold so far, since his approach inherently obscures the variations in the hydraulic geometry — sediment movement relationships which are important to the hydraulic engineer. The needs of the geologist and the hydraulic engineer are antithetical in this case — the former works with averages for decades and centuries, while the latter is concerned mostly with averages for days, months and years.

Mr. Leopold has established his relationship between width, depth and velocity of flow from records of discharge measurements made at regular river-measuring stations over a period of years. These stations are intentionally located at points where the change in the width-depth-velocity relationship with discharge is as nearly regular as possible, since this reduces the cost of station operation. The width is usually well fixed and careful consideration is given to the degree of "control" which exists to regularize the change of depth with discharge. Under such conditions it is not surprising that average values of the exponents of Q in the relationships $w = aQ^b$, $d = cQ^f$, and $v = kQ^m$ should be well defined by a large number of measurements. It is probable that Mr. Leopold has selected, of necessity, the most simple case (at constricted sections) to develop his thesis and that there are few other locations in rivers where this average relationship is applicable.

The selection of total suspended sediment load as a variable dependent upon discharge in the effort to relate sediment behavior to channel shape and flow velocity may have been the unfortunate result of having too little data on sands alone with which to work. His assumption

$$L = pQ^j$$

implies that the flow is responsible for the total suspended load of the stream and is derived from the "sediment rating curve" idea. This assumption has been shown to be fallacious for short-term conditions in many watersheds. When drastic variations in climatic conditions (drought, etc.) are considered, it is probable that a sediment rating curve would not be correct except when based on records covering scores of years and should not be applied except as an average for a similarly long period. His method of relating suspended sediment movement to hydraulic geometry

$$j = \varphi(m/f) \text{ for various values of } b$$

is ingenious but highly empirical. The use of such a relationship requires that the many variations be explained by either change of

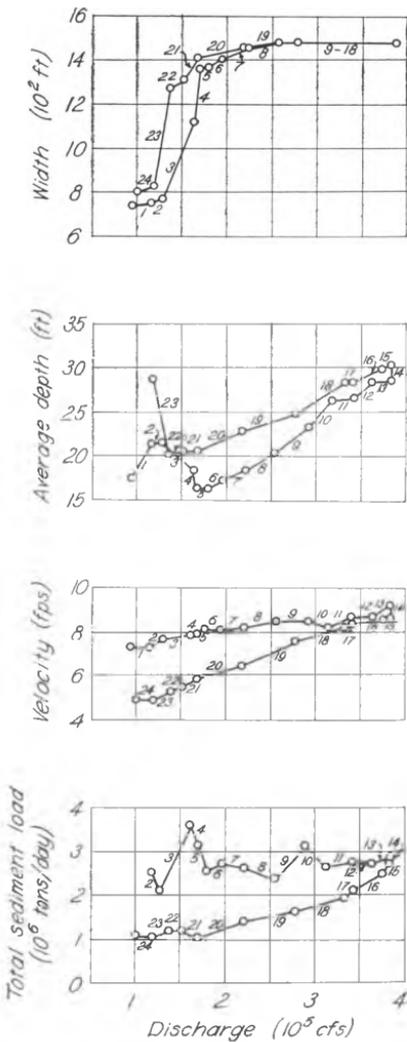


FIG. 10

River at Omaha throughout the flood are shown in Fig. 10. In order to have as many points as possible on the plot of m/f vs j , the slopes were obtained mathematically for each interval between measurements. The requirement that the sum of the exponents b , f , and m equal 1.0 for each interval was easily met within the limits of computation, since all are derived from the basic measured values of

slope or of roughness. No data are available to show how either of these important parameters may be related to such variations, and without such consideration, the validity of the above assumption is highly questionable. It is probable that some variation in hydraulic geometry occurs with variation in movement of sands, but the degree of lag in adjustment may be also a variable. The role of wash load in influencing the flow pattern in natural rivers is therefore quite obscure, in spite of the implications of the work in this field by Mr. Vanoni and others.

The Corps of Engineers has attempted to apply Mr. Leopold's approach to the Missouri River flood of April 1952 at the regular discharge measuring and sediment sampling station at Omaha. Mr. Leopold's requirements for simultaneity in measuring discharge and sampling suspended sediment were well fulfilled for this period.

The plots of these four relationships for the simultaneous measurements of the Missouri

mean velocity v' for each fractional area $w'd'$, which are then multiplied to give the fractional discharge q . These derivations are simply

$$Q = q \quad , \quad A = w'd'$$

$$w = w' \quad , \quad d = a/w \quad , \quad v = Q/a$$

However, it was found that the values of f , m , and j were negative at times and that absolutely no correlation could be obtained between m/f and j with various values of b . An attempt was made to reduce the scatter in the latter plot by averaging the slope, but negative values were yet obtained at times and no trend with b became apparent. Some water-slope data taken during a 5-day period at the peak of the flood were analyzed to see if any correlation between the roughness factor n in the Manning formula and the values of j could be found. This effort was unsuccessful.

The principal results of this attempt to apply Mr. Leopold's approach were the demonstrations that negative values of the exponents are to be expected in practice and that no relationship with the exponent b can be found. The conclusion which must be drawn is that Mr. Leopold has much more work to do on his theory before it can be used to advantage by the hydraulic engineer.

Mr. Sullivan remarked that during the flood of April 1952 on the Missouri River, measurements at Sioux City indicated that a shift in the bed and stage-discharge relation occurred at a stage of about 10 feet, as compared to a peak stage of 24 feet. It was not until the stage returned to about 12 feet that another shift, which apparently occurred about the first of May, was noted. Similar conditions were not noted at other Missouri River stations downstream. The explanation of the Sioux City shift is not clear.

Mr. Izzard asked if Mr. Leopold had any data of bed movements in the Minnesota River. He understood that at several bridges the bed had lowered from 10 to 15 feet.

Mr. Craven commented that from observations of sediment movement in water in pipes, as the sediment concentration increased a bed appeared in the form of scattered dunes, which became progressively larger and flatter as the concentration increased, accounting for the increase in roughness with increasing concentration, to which Mr. Leopold referred.

Mr. Laursen asked if Mr. Leopold had any information on the particle size of the suspended load as compared to the bed material.

Mr. Rand inquired if the slope which was referred to was that

of the river bottom, the flow surface, or the energy grade line, and if the free surface and the bottom could be considered parallel.

Mr. Harrison contributed a discussion of two points. The premise that changes in a suspended-load concentration can be correlated directly to scour and fill at a cross section is not necessarily valid. Whether or not a reach of river aggrades, degrades, or remains in equilibrium depends on the balance between the bed-material load transported into the reach and that transported out of the reach. An increase in discharge can bring about an increase in the bed-material load supplied to the reach, but, at the same time, it also increases the transporting capacity of the reach itself. If the increase in capacity equals the increase in supply, no net change in the bed elevation will result even though sediment concentration increases. For this reason, scour and fill more properly should be related to the difference in the rates of bed-material transport at the upstream and downstream ends of a short reach rather than to the change in the concentration at a single cross section.

His second point for discussion was the use of total load concentration in this study. As pointed out above, only changes in the concentration of those sediment sizes which are also found in the bed should be significant in a study of bed changes. Since an alluvial river bed contains mostly sand and very little silt or clay, the analysis would have been more significant if it were based only upon the sand portion of the total sediment load.

After expressing appreciation for the discussers' contributions, the authors called to the attention of Mr. Coldwell the fact that the Lacey equation relating wetted perimeter to the square root of discharge is not strictly applicable to changes at a given stream cross section. It should be restricted to the comparison of widths of various cross sections distributed along the length of a river in which discharge increases with increasing drainage area.

In answer to Mr. Coldwell's question concerning the comparison of the Rio Grande and the Colorado River, the authors reiterated their belief that scour or deposition on the bed depends to a great extent on the sediment load brought into the reach. The sequence in the Colorado-River example of fill and scour during the rising stage was concurrent with a sequence of rapid increase of suspended-sediment concentration followed by a less rapid increase. Mr. Coldwell's explanatory statement is considered essentially correct but the authors would change the wording slightly. The Colorado, under

the condition of width existing, did not have sufficient velocity to carry the supplied load. The increased velocity necessary for quasi-equilibrium was attained by deposition on the bed.

The authors stated that this principle is shown clearly by the data presented by Mr. Mitchell in his discussion. They felt that, far from demonstrating the inapplicability of the generalization presented by them as Mr. Mitchell suggested, these data supported it. They make the following interpretation of Mr. Mitchell's plot (Fig. 10), but the explanation must remain incomplete because Fig. 10, in contrast with the author's examples, does not include graphs of bed elevation, water surface, and channel cross sections.

That part of the rising stage between points 6 and 15 during which width was nearly constant was characterized by a nearly constant load, or in other words a decreasing sediment concentration with increasing discharge. In contrast, on the falling stage, between points 15 to 22, load changed rapidly with discharge or concentration was nearly constant.

According to the principles outlined in the paper, the authors would expect the rising stage to show a less rapid change of velocity with discharge than the falling stage. The velocity-discharge graph shows this admirably. Similarly, between points 6 and 15, the depth-discharge curve should be steeper than between points 15 to 22, and the graph shows this clearly.

Using the reasoning at constant discharge, the authors called attention to the comparison of point 5 with point 21 in Fig. 10. These two points fall at about equal discharge on rising and falling stage respectively. Widths were also about equal. They postulated that at constant discharge and width, a decrease of sediment load requires for quasi-equilibrium a decrease of velocity at the expense of depth. The comparison for Fig. 10 is as follows for $Q = 170,000$ cfs. and $w = 1800$ ft.:

	d	v	load
Rising stage (point 5)	16	7.8	3,100,000 tons/day
Falling stage (point 21)	21	5.8	1,100,000 tons/day

Thus the data bear out the postulate.

The authors warned specifically against the computation of values of b , m , f , and j between each daily discharge measurement or during very short periods as Mr. Mitchell attempted. They call attention to their statement ". . . similar graphs for small irregular changes in discharge even for the same stations show that the

adjustment is not as complete. A time lag measured in days and perhaps weeks is required for adjustments to take place."

The relations between m/f , b , and j shown by the authors' Fig. 1 are considered tentative and modifications will be required as new data become available. The importance of the figure lies in the general relationship of the variables rather than in the particular numerical values.

The authors agreed with Mr. Mitchell in the present inadequacy of the theory discussed for the prediction of events necessary in engineering design. They maintained, however, that ideas which improve understanding of scour and fill hold a promise of future practical results.

They held that Mr. Mitchell's example in Fig. 10, if inspected in terms of the overall slopes of the various graphs as was done in the examples presented by them, demonstrates the postulated relations.

REFERENCES

1. "The Hydraulic Geometry of Stream Channels and Some Physiographic Implications," *U. S. G. S. Prof. Paper*. In press.
2. Vanoni, V. A., "Transportation of Suspended Sediment by Water," *Trans. A. S. C. E.*, Vol. 111, 1946, pp. 67-133.
3. Buckley, A. B., "The Influence of Silt on the Velocity of Flowing Water in Open Channels," *Proc. Inst. of Civil Engrs.*, Vol. 216, 1922-23, pp. 183-211.
4. Thomas, A. R., "Analysis of Hydraulic Data of some Boulder Rivers," *Cent. Board of Irrigation, India*, Vol. 6, no. 1, 1949, pp. 67-71.