The Effect of Bed Roughness on Depth-Discharge Relations in Alluvial Channels

By D. B. SIMONS *and* E. V. RICHARDSON

STUDIES OF FLOW IN ALLUVIAL CHANNELS

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A discussion of the variations in depth-discharge relations in alluvial channels and the factors that produce these variations

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By D. B. Simons and E. V. Richardson

ABSTRACT

Alluvial channel stage-discharge and depth-discharge relations were studied in a large sand-bed recirculating flume. From this study, it was found that the form of these relations are intimately related to:

1. Regime of flow
2. Form of bed roughness
    a. Characteristics of the bed material
    b. Concentration of fine sediment
    c. Temperature
3. Rate of change of discharge with time

In the range of shear where ripples and dunes develop on the bed, the stage-discharge curve for a rising stage is usually quite different from that for a falling stage. These curves are valid only for the conditions upon which they are based; no general solution is possible. In the range of shear—which develops plane bed, standing sand and standing water waves that are in phase, and antidunes—the rising- and falling-stage curves coincide and hold for all values of discharge associated with these forms of bed roughness.

When a shear stress in a channel forms dunes at small discharges and plane bed and perhaps standing waves and antidunes at larger discharges, there is a discontinuity in the stage-discharge or depth-discharge curves, particularly on the rising stage that occurs when the dunes wash out. This is caused by the great reduction in resistance to flow—which occurs when the bed form changes from ripples or dunes to plane bad, standing waves, or antidunes—and the resultant reduction in depth, even though discharge is increasing.

FORMS OF BED ROUGHNESS IN ALLUVIAL CHANNELS

In a rigid channel a well-defined depth-discharge or stage-discharge curve can be developed that shows only minor scatter and generally no discontinuities. When plotting stage-discharge curves for alluvial streams, this ideal condition is not usual even when scour or fill do not occur. Because of the extreme variation in the resistance to flow as discharge and form of bed roughness vary and because of the effect of rate of change of discharge with time on the rate of development of the various forms of bed roughness, the stage-discharge relation for alluvial channels is not well defined. In fact, several different curves are possible at a single station unless the shear stress on the bed is always large enough that ripple and dunes do not form. If the possible changes in the form

of bed roughness, which cause the shape of the stage-discharge curve to vary from time to time and flood to flood, are not known, it is impossible to explain the apparent haphazard scatter of points that results.

Two regimes of flow, the lower regime and the upper regime occur in alluvial channels. In the lower-flow regime the forms of bed roughness that can form are: plane bed (no sediment movement), ripples, dunes with ripples superposed, and dunes. In the upper-flow regime the forms of bed roughness that can form are: plane bed, standing sand waves, antidunes, and violent antidunes. The two regimes of flow are connected by a transition zone in which the dunes gradually vanish with increasing boundary shear.

These forms of bed roughness were observed in equilibrium experiments, in which a recirculating flume, 8 feet wide and 150 feet long, was used. Flume discharge could be varied from 2 to 22 cfs and slope from 0 to 1.5 percent. The term "equilibrium" is used to denote the conditions that exist after a run has been continued until the average slope of the water surface is parallel with the average slope of the bed, and the bed configuration is fully established for that particular discharge and slope.

In this study the plane bed with sediment moving in the upper-flow regime only occurred when the medium size of bed material was approximately 0.4 mm and smaller. Standing waves only occurred when the median size of bed material, d, was larger than approximately 0.4 mm. The major forms of bed roughness are illustrated in figure 1. The major variables that influence the form of bed roughness as discussed by Simons and Richardson (1960) are indicated in equations 1 and 2.

$$\text{Bed roughness} = \phi_1 (D, S, d, \sigma, \rho, g, \omega, S_f, f_s) \qquad (1)$$

in which

$$\omega \text{ or } d^1 = \phi_2(d, \rho_s, \rho, g, S_p, \mu) \qquad (2)$$

and

D is the depth
S is the slope of energy gradient
d is the median diameter of bed material
d^1 is the effective median fall diameter of the bed material
σ is a measure of the size distribution
ρ is the mass density of the water
g denotes the acceleration of gravity
ω is the fall velocity of the bed material
S_f is the shape factor of the cross section
f_s describes the seepage force
ρ_s is the mass density of the bed material
S_p is the shape factor of the particle
μ is the viscosity of the water sediment mixture

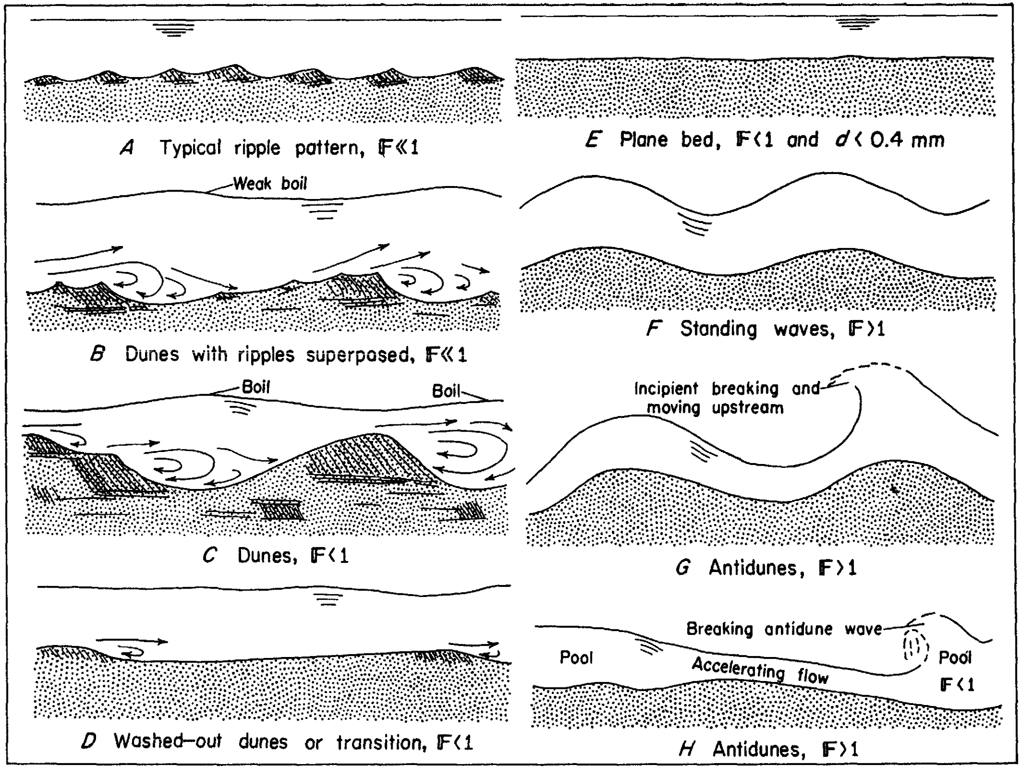

Figure 1.—Forms of bed roughness in alluvial channels.

In alluvial channels there is usually either inflow to or outflow from the channel through the bank and bed material that causes seepage forces. If there is inflow, the seepage force acts to reduce the effective size of the sand; and consequently, the stability of the bed material. If there is outflow from a channel, the seepage force acts in the direction of gravity and increases the effective size of the sand and stability of the bed material. In effect, the seepage force reduces or increases the effective size of the bed material by changing its effective weight. As a direct result, the seepage forces can influence the form of bed roughness and the resistance to flow for a given channel slope, channel shape, bed material, and discharge. For example, a bed material with median diameter of 0.5 mm will be molded into the following forms as shear is increased: ripples, dunes, transition, standing sand and water waves, and antidunes. If this same material was subjected to a seepage force that reduced its effective weight to a value consistent with that of fine sand, which has a median diameter, $d=0.3$ mm, the forms of bed roughness would be ripples, dunes, transition, plane bed, and antidunes for the same flow conditions. The reason for this difference in the forms of bed roughness is the reduction in effective weight of the bed material. With the 0.5 mm sand, a break in the rating curve normally occurs as bed roughness changes from dunes to standing waves. However, with the seepage force in effect, a break in the rating curve can occur when the dune condition changes to plane bed.

With the seepage force acting with gravity, the 0.5 mm material acts as if it were coarser and again there is some effect on form of bed roughness and the stage-discharge relation.

A rather common field condition involves outflow from the channel during the rising stage, which builds up bank storage and increases the stability of the bed and bank material. Then on the falling stage, the situation reverses. There is inflow to the channel because of the presence of bank storage, which reduces the effective weight and stability of the bed and bank material. This field situation can also influence the form of bed roughness and the stage-discharge relations.

Simons, Richardson and Haushild have shown (1960, written communication) that the presence of fine sediment in the water, such as clay, influences the resistance to flow. Using a bentonite clay, it has been determined in the laboratory that with concentrations of this type of fine sediment on the order of 40,000 ppm, resistance to flow in the dune range is reduced as much as 40 percent. The fine material may reduce resistance to flow to an even greater extent under field conditions by decreasing the bank roughness as well as the bed roughness, and as previously discussed, any factor that influences bed roughness and resistance to flow will likewise alter the form of the stage-discharge relation. Also, fine sediment in the flow may change a standing-wave condition into a breaking antidune, which will increase the resistance to flow. Thus, the stage-discharge relationships for a stream may be different for clear water than for flow heavily laden with sediment.

The principal reason for changes in resistance to flow is that the viscosity and specific weight of the water-sediment dispersion increases as the concentration of fine sediment increases. This reduces the fall velocity of the bed material and its effective size. Form of bed roughness and resistance to flow are related to fall velocity; with a plane bed, however, physical size also is important.

Changes in temperature can alter the form of bed roughness; and hence, the resistance to flow. Vanoni and Brooks (1957) report that with higher temperature, there is a decrease in resistance to flow; whereas, Hubbell (1956) reports that with higher temperature, there is an increase in the resistance to flow. These two apparently contradicting statements, which show the effect of temperature variation, are easily explained by considering the forms of bed roughness that existed in the alluvial channels in question, and the effect of temperature change on the fall velocity of the bed material. Lowering the temperature increases the viscosity of the water and decreases the fall velocity of the sand. Thus, a lowering of the temperature decreases the fall velocity of a given sand in the same manner that an increase in concentration of fine suspended sediment decreases its fall velocity. Consequently, if a sand bed is covered with small ripples and the temperature of the water is lowered, the mobility of the particles is increased because of the decrease in fall velocity of the sand, larger ripples form, and resistance to flow increases. On the other hand, if the form of bed roughness is near to or in transition and there is a reduction in the temperature of the water, the fall velocity of the bed material is reduced, the given shear causes the dunes to wash out to a greater extent or perhaps even causes the bed to become plane, which (in either event) is accompanied by a decrease in resistance to flow. Both of these phenomena are reversible.

RESISTANCE TO FLOW IN ALLUVIAL CHANNELS

The resistance to flow in alluvial channels, whether in equilibrium or otherwise, is largely dependent on the form of the bed roughness. This concept has been clearly stated by Leopold and Maddock (1953) and Rubey (1952). In general, the resistance to flow is relatively small with a plane bed prior to the beginning of transport of bed

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material and increases in magnitude with increasing shear stress, reaching a maximum value with ripples or dunes, depending on the characteristics of the bed material. Resistance to flow is relatively large throughout the range of fully developed ripples and dunes. With further increase in shear, the transition zone is reached. Within this zone, resistance to flow reduces rapidly with further increase in velocity—to as little as one-third of its maximum value. The resistance to flow is minimum for a given bed material throughout the plane bed and (or) standing wave range. Then as antidunes form, the resistance to flow increases with further increase in boundary shear.

A more quantitative concept of the relationship between form of bed roughness, resistance to flow, and size of bed material can be obtained by referring to figure 2. Note that with the finer sand, the maximum resistance to flow occurs in the ripple range. This condition, which is related to the effect of size of bed material on forms of ripples and dunes, is discussed in a paper on forms of bed roughness by Simons and Richardson (1960, 1961).

On the basis of a preceding concept of the regimes of flow, the forms of bed roughness and resistance to flow in alluvial channels, a realistic interpretation of flume depth-discharge curves, and the peculiar variations that occur in them can be presented. These interpretations are also generally valid for stage-discharge relations in the field although the effect of scour and fill is not accounted for.

In the field, the conditions are such that the variation of discharge with time is large, but the corresponding variation of slope is relatively small. Conversely, for laboratory conditions the variation in discharge is small (limited by the capacity of the pumping plant) and slope can be varied over a large range at will.

EFFECT OF FORM OF BED ROUGHNESS ON DEPTH-DISCHARGE RELATIONS

To illustrate the effect of regime of flow and form of bed roughness on depth-discharge relations, a series of runs simulating runoff events in which discharge and slope were varied were routed through a recirculating flume with a sand bed. The resultant depth-discharge curves resemble the field depth and stage-discharge relations reported by Leopold and Maddock (1953), Colby (1960), and Dawdy (1961).

In each run the discharge rate was changed in steps of 3–4 cfs every 30–45 minutes from a minimum of 5 cfs to a maximum of 21.5 cfs as indicated in figure 3. The duration of each run was approximately 8 hours. For each discharge on both the rise and the recession, the stage, depth, velocity, slope of water surface, total-sediment load, and

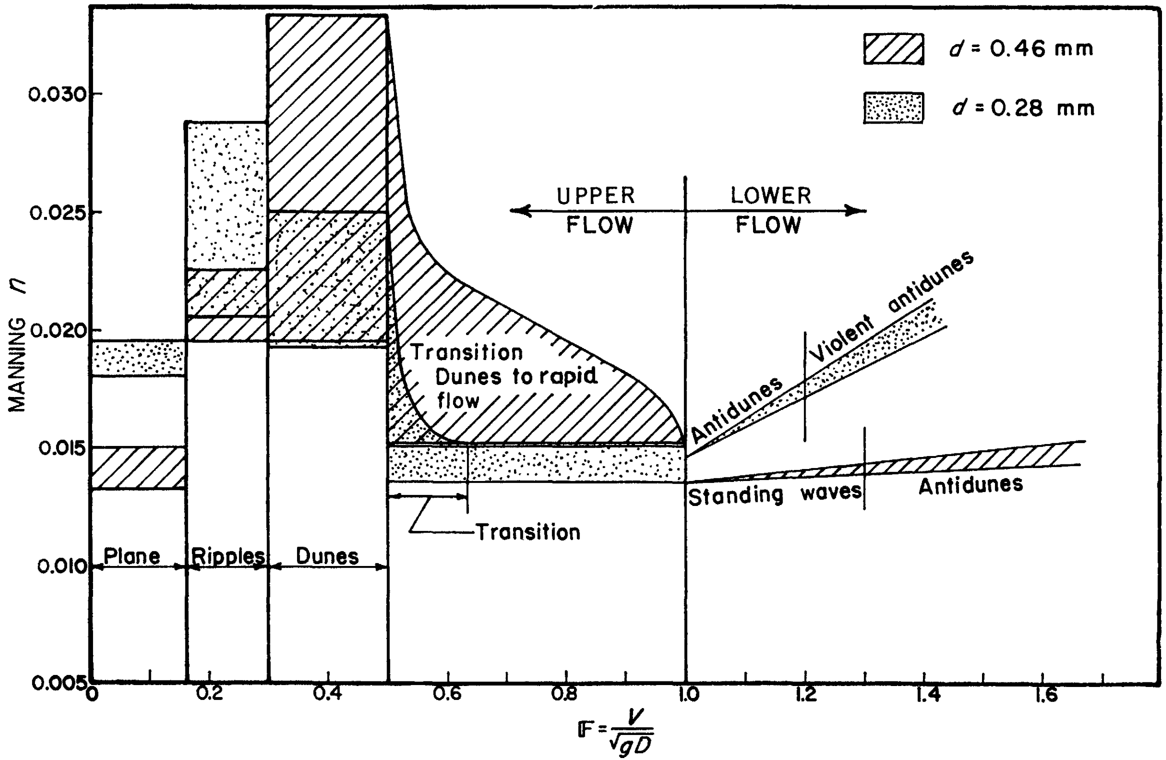

Figure 2.—Effect of size of bed material on form of bed roughness and Manning *n*.

water temperature were continuously measured. The form of bed roughness and its variation with discharge and time was carefully observed, described, and photographed. The characteristics of the bed material used in each run were determined beforehand. The methods used to measure the variables are described in detail by Simons, Richardson, and Albertson (1961). To observe the variation of the measured variables with time as discharge was changed, refer to figure 3. The accuracy of the discharge measurements were excellent. The accuracy with which the other variables such as slope, total load, velocity, stage, and depth were measured was limited because of the nonequilibrium condition of the flow, the relatively small number of measurements upon which the magnitude of a variable was based, and the natural variation of these variables with time and distance. For example, it has been verified by the writers that it is necessary to sample total-sediment load almost continuously over a 1- to 2-hour period in order to determine accurately total-sediment transportation. In the nonequilibrium runs, sampling could only be done over a 15- to 30-minute interval; and in addition, sediment load varied more radically with time than normally because once the run was started, there was never time for the channel to become completely stable before the discharge was changed.

In spite of the limited accuracy with which some of the variables were measured, data for depth, discharge, and form of bed roughness can be utilized to illustrate the importance of form of bed roughness on rating curves for depth and discharge. Depth-discharge relationships were used because they eliminate changes that would occur in stage-discharge relationships resulting from scour and fill. The importance of form of bed roughness on the depth-discharge relations is obviously equally valid for stage-discharge relations. Einstein and Chein (1958) predicted some of the forms of depth-discharge curves presented in the following sections. However, contrary to present evidence, they did not believe they were of practical importance.

LOWER-FLOW-REGIME RUN WITH CONSTANT CHANNEL SLOPE

The run upon which figure 4 is based was in the lower-flow regime. The sand bed had a median fall diameter of 0.45 mm. Flume conditions were such that the slope was held nearly constant throughout the duration of the run. The initial discharge of 5.04 cfs was set up 12 hours prior to the beginning of the run in order to start with stable channel conditions. The initial form of bed roughness, at minimum discharge, was small dunes with ripples superposed. As the discharge was increased, the ripples were gradually eliminated and larger and

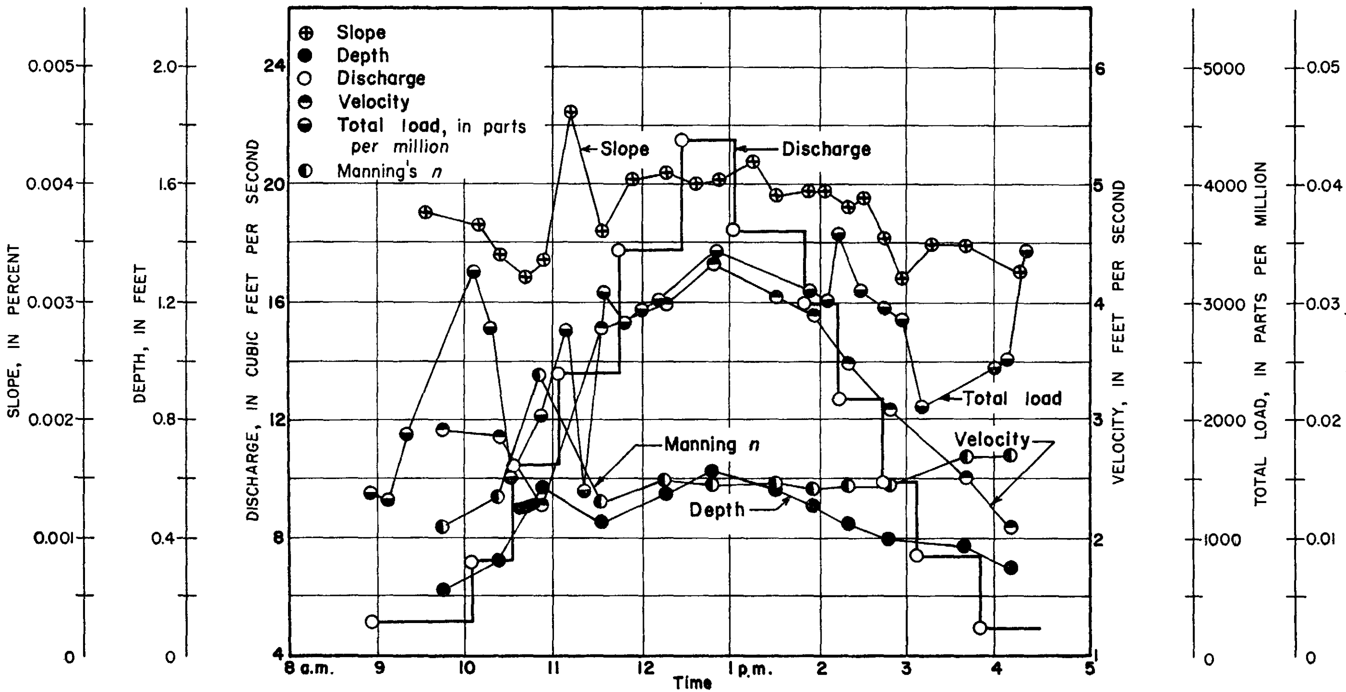

FIGURE 3.—Variation of hydraulic variables with ti me for a lower- and upper-regime-flow hydrograph.

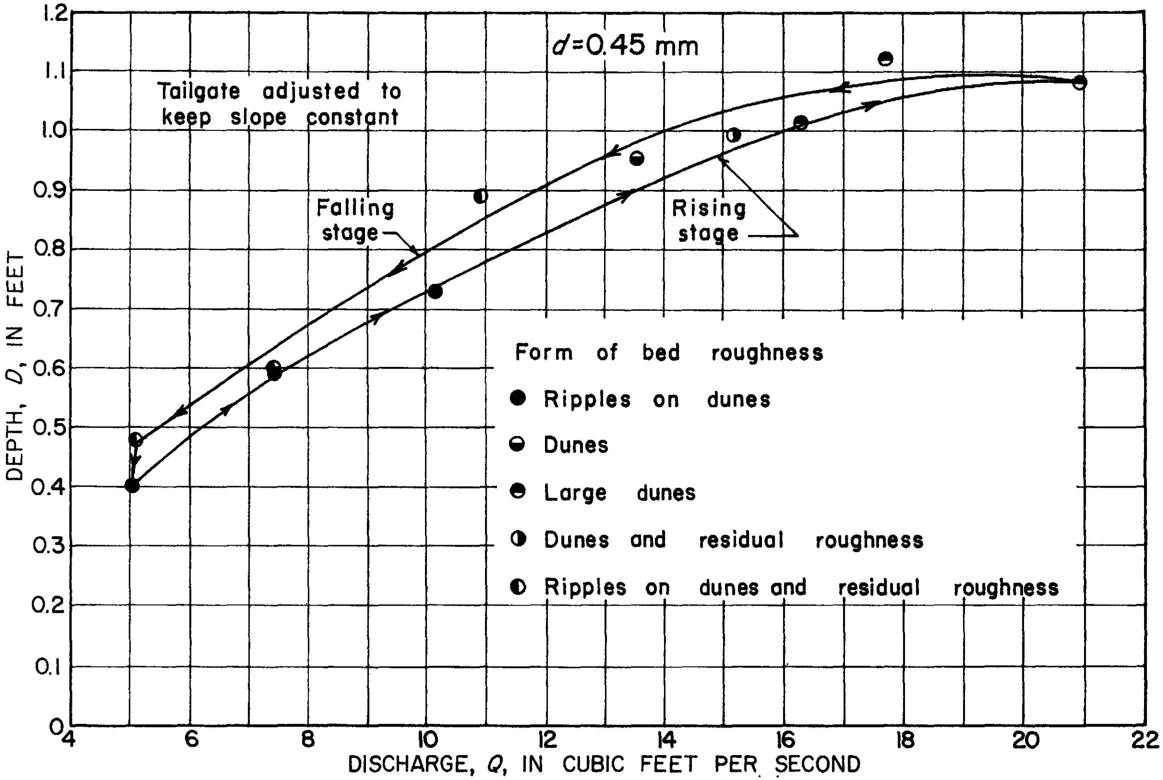

FIGURE 4.—Relation of depth to discharge for lower flow regime when channel slope is constant.

larger dunes were developed by the flow. At the peak discharge of 20.96 cfs, the form of bed roughness was large dunes. After reaching maximum discharge, the flow was reduced in steps to produce a nearly symmetrical variation of discharge with time as illustrated in figure 3. The depth-discharge curve for increasing discharge is lower than the depth-discharge curve for decreasing discharge. This situation can be explained in terms of the bed roughness and its changes with discharge and time. With increasing flow, the development of maximum roughness lagged behind the increase in discharge. That is, the type of bed configuration consistent with a particular discharge did not have time to develop fully before discharge was increased again. The net result was that the resistance to flow lagged behind the increase in discharge, and depth was less for a given discharge than it would have been if equilibrium had been established.

The opposite condition prevails for this run during recession. That is, when discharge was decreased, the flow could not fully alter the large dunes to smaller ones required for equilibrium in the limited time available. The net result was that the channel was rougher and deeper than it should have been for a given discharge, and the recession curve of the depth-discharge relation was above the rising curve of the same relation. The depth at the conclusion of the run was larger than the initial depth even though the discharge was the same. However, continuing the run for a few hours with the final discharge, the depth did return to its original value.

The magnitude of the spread between the two branches of the depth-discharge relations is dependent primarily on variation of roughness, which is influenced by rate of change of discharge with time, the characteristics of the bed material, and to a limited extent on concentration and type of fine sediment and other variables that are discussed later. If the rate of change of discharge with time is large, the spread between the two branches of the depth-discharge curve may be large or relatively small. If the rate of change of discharge with time is very small, the spread between the two branches will be small. At some intermediate rate of change of discharge with respect to time, the spread between the two curves will be maximum.

The size of the bed material is an important variable. With fine sand, the rate of change of bed configuration with time is faster than for a coarse sand, and the change from a dune bed to a plane-bed configuration occurs at smaller shear because of the increased mobility of the bed material. Hence, the spread between the rising and falling curves of a depth-discharge relation for a fine sand can be larger or smaller, and a break in the rating curve develops at a smaller depth for a particular runoff event than that for a coarse sand.

LOWER- AND UPPER-FLOW-REGIME RUNS

SMALL CHANNEL SLOPE VARYING WITH DISCHARGE

Another depth-discharge relation for the type of runoff event illustrated in figure 3 is presented in figure 5. There was no tailgate control at the end of the flume, the slope-of-energy gradient varied directly with discharge, and the median diameter of bed material was 0.28 mm. As in figure 4 for increasing discharge, the development of resistance to flow lagged behind the increase in discharge until $Q \geqq 19$ cfs. A common curve described the depth-discharge relation for both increasing and decreasing discharge when $Q \geqq 19$ cfs, and the recession curve was above the rising depth-discharge curve when $Q < 19$ cfs. This latter condition indicates an excessive resistance to flow caused by residual-bed roughness. That such was probably the case, can be verified by considering variation of form of bed roughness with discharge. As indicated in figure 5 at minimum discharge, the initial bed roughnes was ripples. As discharge was increased, the bed form changed to ripples superposed on dunes, then to large dunes and finally the transition zone developed that was followed by a plane bed. With decreasing discharge, the bed roughness was first modified from the plane bed to transition condition and then back to large dunes. With further reduction in discharge, the resistance to flow was greater than normal because of the residual dunes. At minimum discharge, the bed roughness was ripples superposed on small dunes and residual dunes. The minimum flow was maintained for a period of 12 hours beyond completion of the 8-hour run. At the end of this time, the residual dunes had disappeared and the rising and falling depth-discharge curves coincided giving the closed-loop relationship presented in figure 5. It is important to note near the maximum discharge, that after the change from lower to upper flow regime the depth-discharge curve was the same for both increasing and decreasing discharges.

MODERATE CHANNEL SLOPE VARYING WITH DISCHARGE

The physical conditions associated with this upper- and lower-flow-regime run with slope varying with discharge were the same as those described for figure 5 except that channel slope was steeper. Referring to figure 6, the initial bed roughness at the beginning of the run (stable flow) was dunes with ripples superposed. As the discharge was increased, ripples were eliminated and larger dunes developed. With further increase in discharge the form of bed roughness gradually changed from dunes to a plane bed. The curve connecting the points for the plane-bed condition was displaced to the

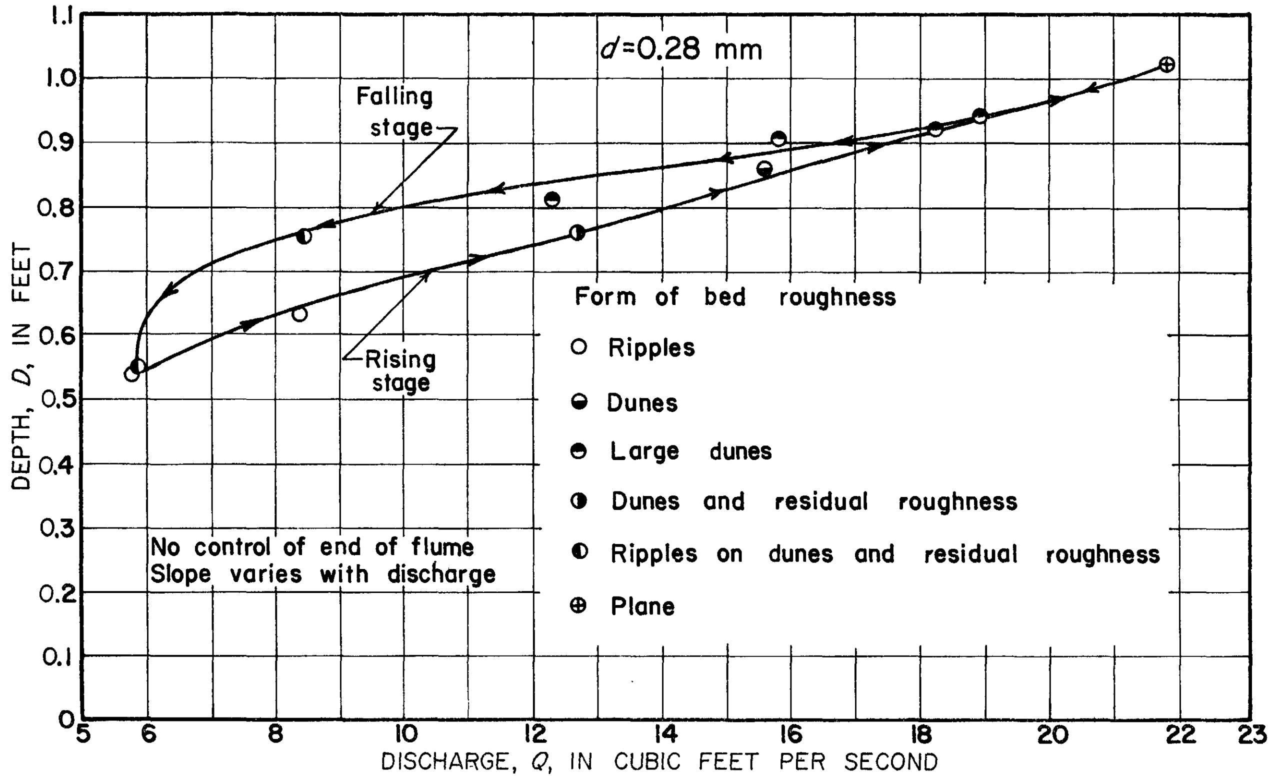

FIGURE 5.—Relations of depth to discharge for lower- and upper-regime flow when the variation of slope with discharge is small.

right appreciably from the increasing discharge curve for ripples superposed on dunes and dunes. That is, the change in resistance to flow, which occurred as the form of bed roughness, changed from dunes to plane bed caused a significant break in the rating curve. This break in the depth-discharge curve is typical of the breaks in the stage-discharge curves of most alluvial channels in which the form of bed roughness changes from ripples and (or) dunes to plane bed, standing waves, or antidunes (Colby, 1960, and Dawdy, 1961).

The curve representing the decreasing depth and discharge condition shows that there is a common curve for increasing and decreasing discharge with upper-regime flow. However, the change from dunes to plane bed takes place at a larger discharge as discharge is increasing than the change from plane bed to dunes when discharge is decreasing. In fact, in this run it was difficult for the bed to change from a plane bed to dunes in the time allowed between changes in discharge. That is, dune and ripples never developed with decreasing discharge to the extent that they did with increasing discharge. Hence, resistance to flow and depths were smaller for small discharges as depth was decreasing than they were for the corresponding discharge when depth was increasing with time. Note that the reverse condition was true in figure 4 and figure 5. However, the foregoing condition could be reversed by using a longer time period between changes in discharge—that is, if rate of change of discharge with respect to time was decreased. Under this condition, dunes would have time to develop and the increasing- and decreasing-depth curves in the ripple and dune range of bed roughness would be closer together. In fact, if the rate of change of discharge was much slower with decreasing depth than with increasing depth, the curve that represents decreasing discharge and depth would probably cross and be above the increasing-discharge curve. Thus, rate of change of discharge with respect to time is extremely important in defining shape of the depth-discharge relation. At minimum discharge, at the end of the run, the point on the decreasing-depth curve was considerably below the corresponding point for equilibrium conditions on the increasing-depth curve. Holding discharge constant, this point moved vertically upward with time (depth increased) until, when equilibrium conditions were again reached, the two points coincided.

LARGE CHANNEL SLOPE VARYING WITH DISCHARGE

The conditions for the run shown in figure 7 were similar to those that yielded figure 6, except that the size of the bed material was 0.45 mm instead of 0.28 mm. There was no control at the tailgate,

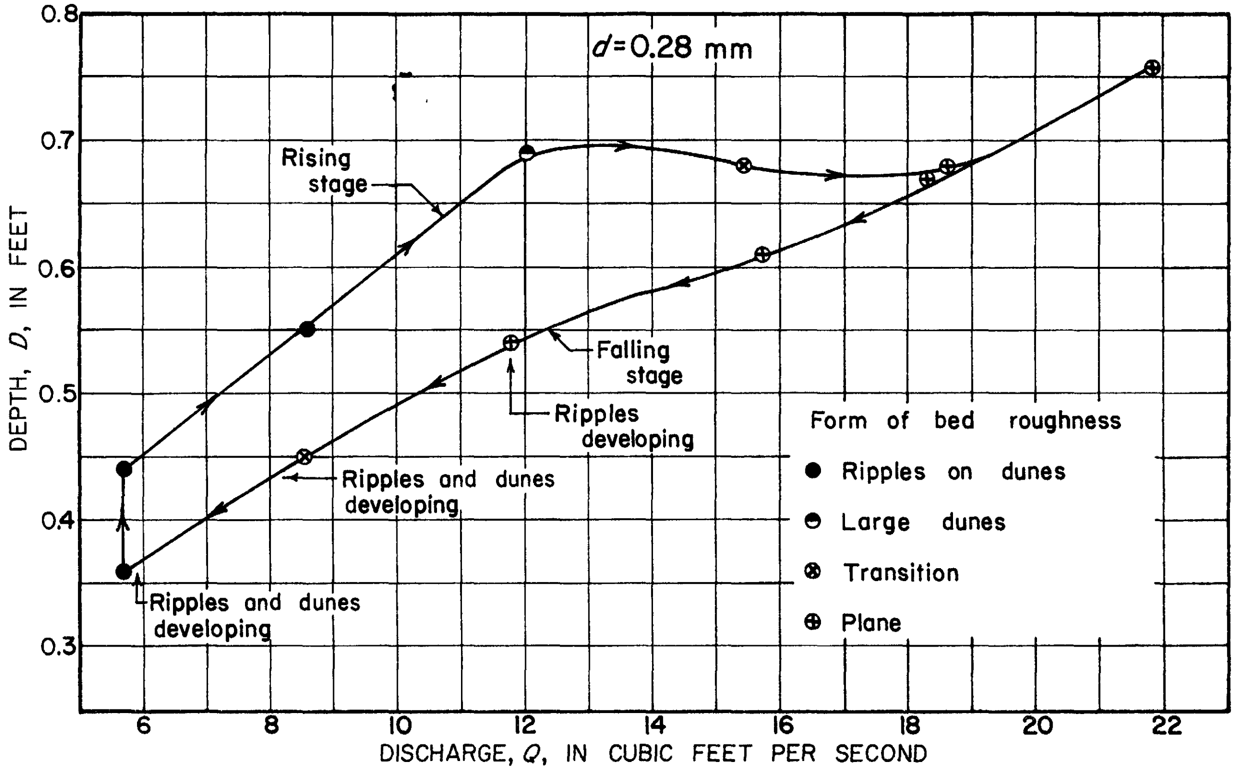

FIGURE 6.—Relation of depth to discharge for lower- and upper-regime flow when the variation of slope with discharge is moderate.

and the variation of discharge with time was almost symmetrical as illustrated in figure 3. In figure 7 at the beginning of the run, the bed configuration was regular dunes of medium amplitude. As the discharge was increased, large dunes, transition, and finally standing waves developed. As the form of bed roughness changed from dunes to standing waves, there was a significant break in the depth-discharge curve. To the right of the break in the upper flow regime, the increasing and decreasing discharge relation can be represented by a single curve. This part is similar to the depth-discharge relation illustrated in figure 9, and the part of figure 6 to the right of the loop. With decreasing discharge in the vicinity of and immediately to the left of the break in the rating curve, dunes were reforming; but the size of the dunes and, hence, the magnitude of resistance to flow was less than for comparable discharge with increasing depth. With further reduction of discharge, dunes developed to the point where at a still smaller discharge, a residual-dune effect was apparent, that is, dunes remained that were larger than they were for comparable discharge on the increasing depth curve; hence, the decreasing depth-discharge relation crosses the increasing depth-discharge relation and remains above it because of the extra resistance contributed by the residual dunes. At the termination of the run, the point on the decreasing depth curve continued to drop with time until it matched the initial point on the increasing depth curve completing the loop as shown. The return to the original depth with continued minimum flow, after completion of the runs (figs. 5, 6, and 7), indicates the accuracy of the data and the ability to accurately repeat an equilibrium run.

This depth-discharge curve also indicates that size of bed material and rates of change of discharge with time are closely related to the shape of the depth-discharge relation in the ripple and dune range of bed roughness. Thus, an infinite number of possibilities exist in the ripple-dune range. If the rate of change of discharge with time was faster, the decreasing discharge curve might not cross the increasing discharge curve at all; or if the rate of change of discharge was very slow, the decreasing discharge curve would cross the increasing discharge curve at a larger discharge. Similarly, if the rate of change of discharge with increasing depth was different, the position of this curve would be changed; and for a different size of bed material, the break in the rating curve would occur at a different discharge.

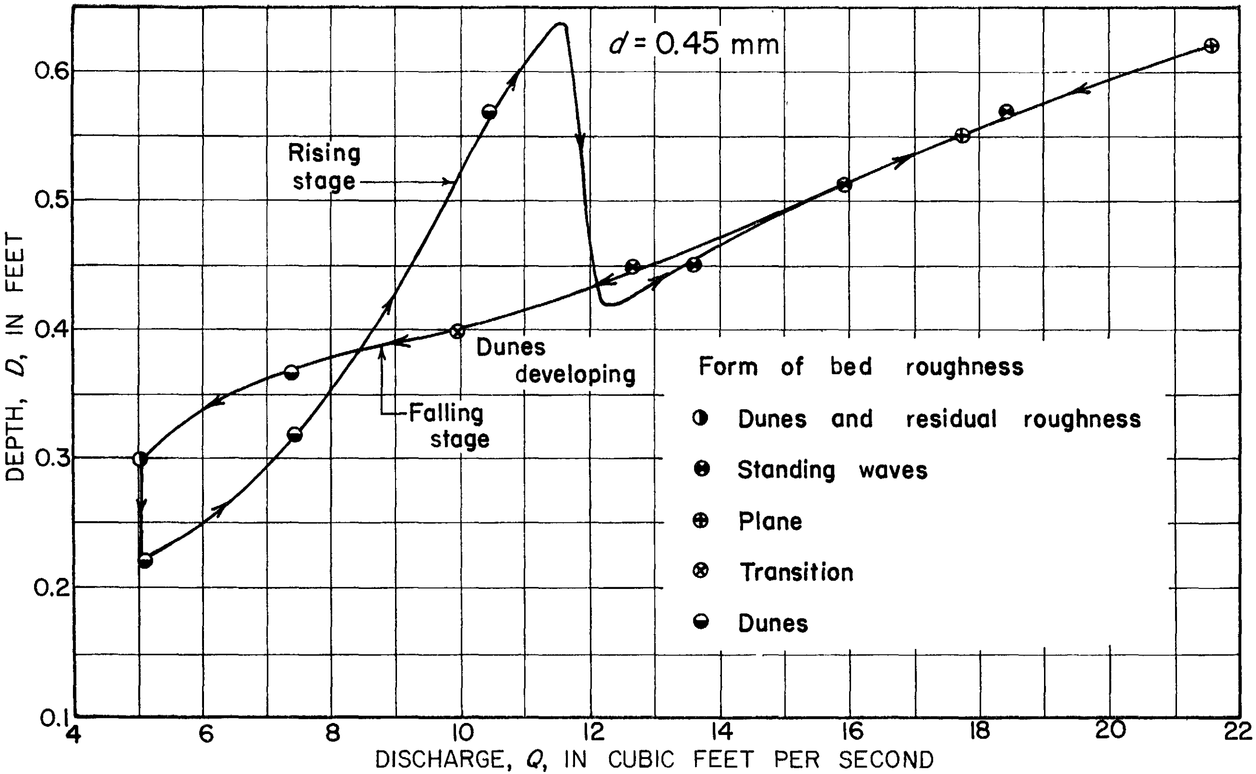

FIGURE 7.—Relation of depth to discharge for lower- and upper-regime flow when the variation of slope with discharge is large.

UPPER- AND LOWER-FLOW-REGIME RUN WITH CHANNEL SLOPE VARYING INVERSELY WITH DISCHARGE

To further illustrate the numerous types of depth- and stage-discharge relations that are possible in alluvial channels, consider the situation where there was a channel constriction at the end of the flume. The channel slope and size of constriction were of such a nature that at small discharges flow was rapid; and as discharge was increased, the constriction caused tranquil-flow conditions to develop. This condition could exist in the field upstream from a bridge, culvert, or natural constriction. The depth-discharge relation for this condition is illustrated in figure 8. At the beginning of the run, flow was rapid. There were small in-phase standing sand and standing water waves as well as antidunes. As discharge was increased, the magnitude of the Froude number soon began to decrease because of the backwater effect of the constriction and dunes began to form. With still further increase in discharge, the dunes increased in size and the largest dunes occured at maximum discharge. As magnitude of discharge decreased, large residual dunes persisted, causing a greater resistance to flow with decreasing discharge than that which existed at the same discharge with increasing depth. With further reduction in discharge, the effect of the backwater curve lessened and the Froude number increased until the transition condition (washed-out dunes) developed. With still further reduction in discharge, upper-flow regime conditions developed with standing sand and standing water waves and some antidune activity.

The depth-discharge relation of figure 8 is practically the reverse of the ones illustrated in figures 5 and 6.

As with the other depth-discharge relations presented herein, the form of the curve or curves is intimately related to the rate of change of discharge with time and the size and gradation of the bed material. Except for plane bed, standing wave, and antidune conditions (upper-flow regime) the depth-discharge relations can only be identical for runs and physical conditions that are identical.

UPPER-FLOW-REGIME RUN

The most simple form of depth-discharge curve in alluvial channels exists when only plane bed, standing waves, and antidunes develop (no ripples, dunes or transition). This condition was investigated in the laboratory using a bed of sand of a median diameter of 0.45 mm. The resultant depth-discharge curve is presented in figure 9. At minimum flow on the increasing discharge curve, the bed roughness consisted of plane bed, standing waves, and very limited antidune activity. As discharge was increased, the antidune activity increased

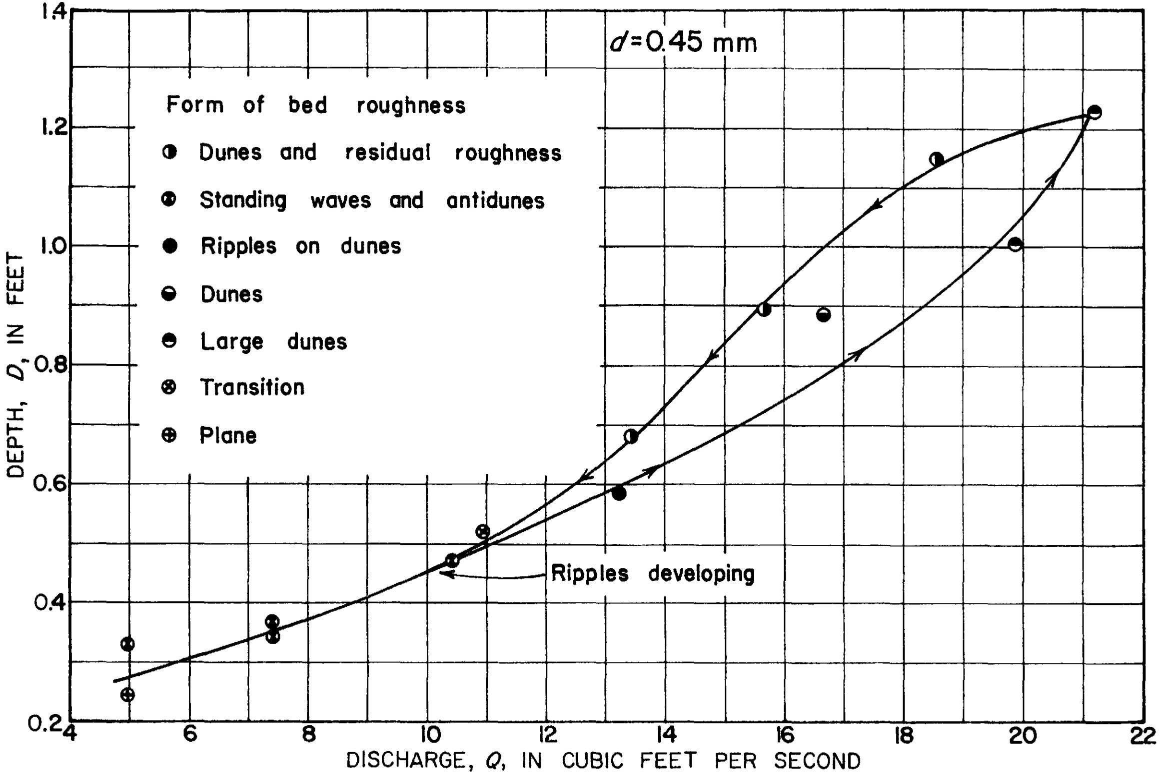

Figure 8.—Relation of depth to discharge for upper- and lower-regime flow when slope varies inversely with discharge.

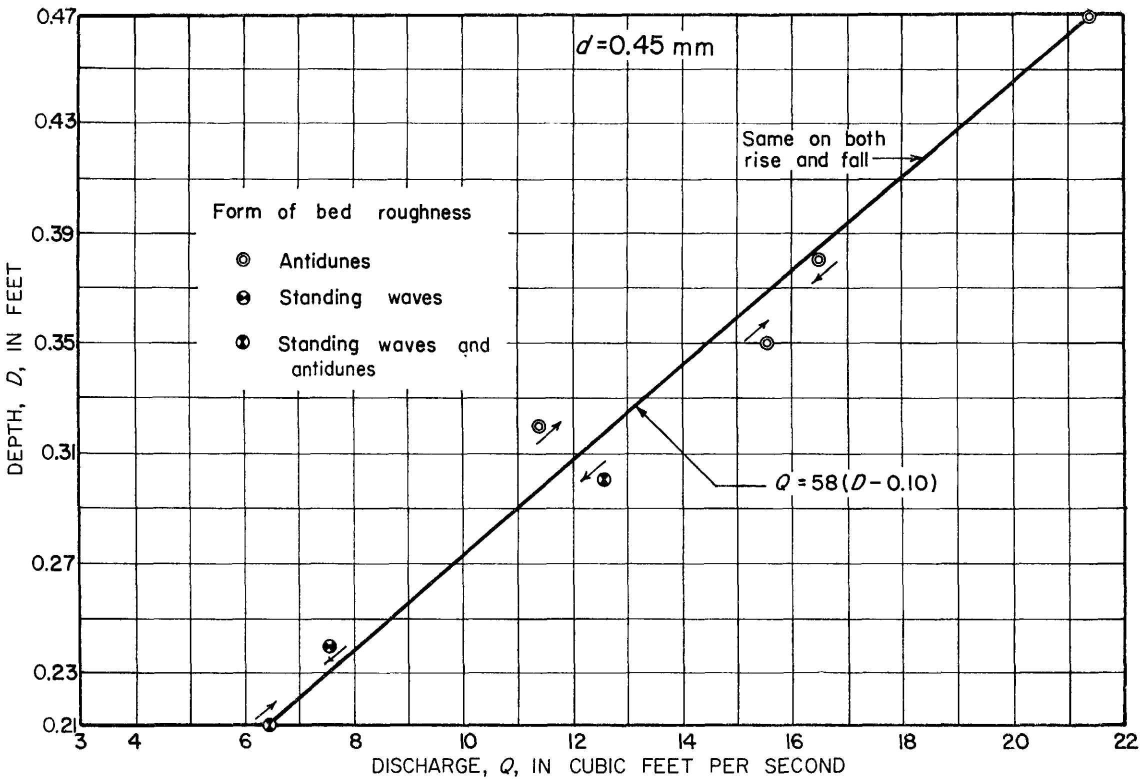

FIGURE 9.—Relation of depth to discharge for upper-regime flow.

until at peak discharge, there was very strong antidune activity. With decreasing discharge, the process reversed itself. That is, antidune activity diminished to the original plane-bed, standing-wave, and mild antidune condition. There is no break in this rating curve. The depth-discharge data plot on a common curve, excluding error in measurement of depth. This indicates that depth-discharge curves for field conditions should be reasonably accurate when the plane bed, standing waves, and antidunes are the only forms of bed roughness. The accuracy of this type of depth-discharge relationship is also illustrated in figure 7 in that part of the relation to the right of the break. With finer sand ($d \leq 0.3$ mm) there was a relatively rapid increase in resistance to flow with increasing Froude number for antidunes. This may increase the scatter in depth-discharge relations for flumes and streams with beds of fine sand.

OTHER FACTORS THAT INFLUENCE DEPTH- AND STAGE-DISCHARGE RELATIONS

Thus far, the importance of the physical conditions existing in a channel including the rate of change of discharge with time and the characteristics of the bed material on depth-discharge and stage-discharge relations have been emphasized. There are other factors that can be of at least minor importance, such as, bank vegetation, scour and (or) fill, the bulking or consolidation of the sand bed as changes occur in the form of bed roughness, multiple roughness, and wind action. These additional factors will be discussed qualitatively.

Bank vegetation which trails in the water cross section and (or) aquatic plants can appreciably increase resistance to flow in natural channels. Thus the presence of vegetation in an alluvial channel can delay or even eliminate the break in a rating curve. Vegetation can also change the spread between rising-stage and falling-stage curves within the lower-flow regime. For example, the channel vegetation presents a large resistance to flow on the rising stage, increasing depth until the vegetation is plastered down by the action of the water-sediment complex. Then on the falling stage, after the plastering down and the possible removal of some vegetation, the resistance to flow is relatively smaller. Considering the superpositioning of a vegetation effect on the depth-discharge relation of figure 5, it is conceivable that the spread between the two curves would be reduced or at least slightly changed, depending on the characteristics and behavior of the vegetation.

Under certain physical conditions, the reach for which a stage-discharge relation is being developed may tend to scour or aggrade during a flood. This change in bed elevation naturally effects the stage-discharge relationship. Also, the resultant change in bed elevation can influence bed roughness and the depth-discharge relation for the reach. Consider, for example, figure 8. The stream has a relatively large capacity to transport sediment per unit of flow at small discharges. As discharge increases, the backwater effect develops and reduces the transport capacity in the backwater area. A large sediment load is thus carried into a reach of reduced slope and velocity, and as a result, the bed of the channel begins to aggrade seeking a new equilibrium level. With increasing depth, the bed level increases with time, and on the falling stage, it continues to rise with time at a diminishing rate until the backwater effect is eliminated. Then, because of the aggraded bed, a steeper than normal channel slope can exist in the reach causing a larger Froude number and increased transport of sediment in the aggraded reach until the original equilibrium is restored.

The bed material of an alluvial channel is fairly loose and soft when ripples exists. It becomes even softer and bulks to an even greater extent as dunes form. When the transition zone is reached (washed-out dunes), the bed becomes firmer and its weight per unit volume increases. With further increase in shear stress the bed continues to become firmer until with plane bed and (or) standing sand and standing water waves, the bed has a maximum density. With still further increase in shear, antidunes develop. As larger and more violent antidune action occurs, the bed density may decrease slightly. This variation in density with bed congfiuration causes minor changes in bed elevation which can, at least slightly, affect stage-discharge relations. This concept is applicable to all breaking stage-discharge relations but can have only a very minor effect when limited to ripple and dune type configurations in the lower-flow regime. By working with depth instead of stage, this effect is automatically eliminated. Generally it is quite difficult to measure and record depth, but this problem may be eliminated eventually by using a sonic depth sounder to record bed elevations. A sonic depth sounder developed by Richardson, Simons, and Posakony (1961) does an excellent job of recording bed elevation under laboratory conditions and it should be possible to redesign this instrument so that it will measure and record depth of flow in the field.

The forms of bed roughness that were observed on the bed of the laboratory flume were consistent across the full width of the flume. In the field this may not be true. A multiple roughness pattern may exist. At the middle of the stream, the bed may be plane or have antidunes; whereas at the sides, there may be dunes. With these multiple roughnesses, the bed would be firm in the middle and soft at the sides of the channel. Another possible combination of roughness elements is antidunes and (or) plane bed on one side of the stream with dunes on the other and this situation may reverse with time at the same site. As changes occur in the magnitude and areal extent of the various forms of bed roughness in a stream, the depth-discharge, and consequently, the stage-discharge relation will also change during a runoff event.

Depending on the way in which the wind is oriented with respect to the reach of the channel in question, the resistance to flow may be increased or decreased, and in every instance channel stability is decreased. Wind in the opposite direction to flow can increase resistance to flow an appreciable amount. Wind in the direction of flow slightly decreases resistance to flow. Wind in either direction causes instability of banks because of the wave action it generates and reduces the stability of bed material by causing seepage forces. The problem of flow in a homogeneous alluvial bed, as a result of wave action above the bed has been analyzed by Putnam (1949). Using Putnam's results Simons has qualitatively verified that water surface waves generated by wind can reduce the effective weight of bed material by as much as 20 percent as a result of the additional tractive force exerted on the bed material because of the water waves and seepage forces set up in the bed because of difference in elevation between wave crests and troughs.

Because the wind action can affect the stability of the bed material and change the resistance to flow, it probably can also affect the stage-discharge relations.

The influence of changes in bed configuration, resistance to flow, and rate of change of discharge on depth-discharge relations for alluvial channels has been emphasized. All loops in the curves discussed were obviously the result of changes in bed roughness. However, there are also loop-rating curves, under certain circumstances, in rigid boundary streams. The magnitude of the spread between the two curves forming the loop depends on the slope of water surface, magnitude and velocity of the flood wave, rate of change of discharge with time, channel storage, and overbank storage (Corbett and others, 1945). These factors will also affect the stage-discharge relationship for alluvial channels in the same manner as in rigid channels, but in addition, they may play a more complex role since they may also change the bed roughness and the resistance to flow.

CONCLUSIONS

The resistance to flow in an alluvial channel under all conditions of flow is intimately related to the form of bed roughness. In turn, the form of bed roughness varies with such factors as the magnitude of the shear stress exerted by the water on the bed, the characteristics of the bed material, the fine sediment load, seepage forces caused by flow through the bed and bank material, and temperature.

As the form of bed roughness changes, the magnitude of the resistance to flow can change as much as 300 percent. For example, considering flume conditions and a plane or standing wave bed configuration the Manning *n* can be as small as 0.012; but by slightly decreasing the shear stress the plane bed or standing waves vanish and a dune-bed condition results that can have a Manning *n* as large as 0.036.

The large changes in resistance to flow, which occur as a result of changing the form of bed roughness, influences the form of the stage-discharge or depth-discharge curves for alluvial channels.

There are, in general, three types of stage- or depth-discharge relationships for alluvial channels. If the bed form always consists of some combination of ripples, dunes, or washed-out dunes regardless of variation in discharge, then consecutive measurements of depth and discharge made during one flood, when plotted, may loop or even cross forming two loops. That is, the depth for a given discharge on the increasing discharge curve will usually be larger or smaller than the depth at the corresponding discharge with decreasing discharge conditions. These loop-rating curves for increasing and decreasing discharge conditions are infinite in number for a given reach of channel. Each new runoff event yields a new set of curves unless the flows and channel conditions are identical. Hence, stable depth-discharge relationships do not exist under these conditions.

The reason for the loop or multiple loop depth-discharge curves is that the formation and alteration of roughness elements for each change in shear stress, with the increase or decrease in depth, will lag behind the change in depth. For instance, with increasing discharge, the dunes do not increase in size at a rate corresponding to the rate at which the discharge and shear stress are increasing. Consequently, the resistance to flow will be less than under equilibrium flow conditions. Whereas, with decreasing discharge the rate of decrease of the large roughness elements formed at the greater depth (residual roughness is lagging) lags behind the decrease in discharge and the resistance to flow is greater than it would be for equilibrium conditions. Thus, the curve for increasing depth is below the curve for decreasing depth in this instance.

The reverse situation, where the increasing-discharge curve is above the decreasing-discharge curve, can also be explained in a similar manner by the lag in the change of resistance to flow with respect to change in discharge. However, in this situation the resistance to flow is greater with increasing depth than with decreasing depth.

The shape of the loop curves depends on the form of bed roughness that forms under equilibrium conditions for a given depth, the amount of time it takes for the bed roughness consistent with equilibrium conditions to form, and the amount of time available for the bed to adjust before the depth changes as a result of additional change in discharge. The above three factors are determined primarily by the energy gradient, fall velocity of the bed material, and the rate of change of discharge with time.

The second type of depth-discharge curve occurs when the bed form is always plane, standing waves, or antidunes regardless of the discharge. In this type of curve, the slope of the energy grade line is steep enough and the shear stress is great enough, for the effective size of the bed material involved, so that only these forms of bed roughness can develop. For these conditions, the depth-discharge curve is the same for both increasing and decreasing discharge and is stable and reliable.

The third general relationship results when the shear varies over such a wide range that ripples and (or) dunes form at small discharges, and plane bed, standing waves, or antidunes form at large discharges. With these conditions, the lower part of the depth-discharge relationship will be the same as the first type of general curve including all of its variability. Then, there will be a break in the relationship at some intermediate discharge, which leads to the second type of curve. This break will be downward and to the right on a plot of depth versus discharge with increasing depth, because of the decrease in resistance to flow as the bed roughness changes, and it will be upward and to the left on the recession curve because of the increase in resistance to flow. In accordance with the description of the type two curve, there is little variation in the depth-discharge relationship to the right of the break. However, the break in the depth-discharge curve will not occur at the same discharge on the recession as it did on the rise, or at the same discharge from one runoff event to another. Where the break occurs in the relationship depends on the discharge, rate of change of discharge with time, and the characteristics of the bed material; its position may vary from rise to rise.

Stage-discharge relationships are influenced by all the variations that occur in depth-discharge relationships in addition to those resulting from local scour and fill as well as bulking or consolidation of the bed material. Thus stage-discharge curves can be similar to the depth-discharge curves presented or quite different depending on the amount of scour and fill; the porosity of the bed, which is related to form of bed roughness; and the time element involved.

The form of the stage or depth-discharge curves can be changed slightly, particularly the position of the point of discontinuity by the presence of seepage forces, large concentrations of fine sediment in the stream, wind action, vegetation, temperature change, rate of change of stage with time, multiple roughness, and unsteady flow.

With an understanding of the basic principles that cause the observed variation in depth-discharge and stage-discharge relations, a more effective use of these relationships is possible.

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