PAP-818

Diversions From Alluvial Streams

January 1952

by

C.P. Lindner

cw Thomas PAP-818

VOLUME 78 SEPARATE No. 112

PROCEEDINGS

AMERICAN SOCIETY OF CIVIL ENGINEERS

JANUARY, 1952

AMERICAN SOCIETY OF CIVIL ENGINEERS FOUNDED 1852

DIVERSIONS FROM ALLUVIAL STREAMS

By C. P. Lindner, M. ASCE

WATERWAYS DIVISION

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

PRICE $0.50 PER COPY

GUIDEPOST FOR TECHNICAL READERS

"Proceedings-Separates" of value or significance to readers in various fields are here listed, for convenience, in terms of the Society's Technical Divisions. Where there seems to be an overlapping of interest between Divisions, the same Separate number may appear under more than one item.

Technical Division	*Proceedings-Separate Number*
Air Transport	42, 43, 48, 52, 60, 93, 94, 95, 100, 103, 104, 108 (Discussion: D-XXVIII, D-7, D-16, D-18, D-23, D-43)
City Planning	58, 60, 62, 64, 93, 94, 99, 101, 104, 105 (Discussion: D-16, D-23, D-43, D-60, D-62)
Construction	43, 50, 55, 71, 92, 94, 103, 108, 109, 113 (Discussion: D-3, D-8, D-17, D-23, D-36, D-40)
Engineering Economics	46, 47, 62, 64, 65, 68, 69, 95, 100, 104 (Discussion: D-2, D-19, D-27, D-30, D-36, D-57)
Engineering Mechanics	41, 49, 51, 54, 56, 59, 61, 88, 89, 96 (Discussion: D-5, D-XXIII, D-XXV, D-18, D-24, D-33, D-34 D-49, D-54, D-61)
Highway	43, 44, 48, 58, 70, 100, 105, 108, 113 (Discussion: D-XXVIII, D-7, D-13, D-16, D-23, D-60)
Hydraulics	50, 55, 56, 57, 70, 71, 78, 79, 80, 83, 86, 92, 96, 106, 107, 110, 111, 112, 113 (Discussion: D-XXVII, D-9, D-11, D-19, D-28, D-29)
Irrigation	46, 47, 48, 55, 56, 57, 67, 70, 71, 87, 88, 90, 91, 96, 97, 98, 99, 102, 106, 109, 110, 111, 112, 114 (Discussion: D-XXIII, D-3, D-7, D-11, D-17, D-19, D-25-K, D-29, D-30, D-38, D-40, D-44, D-47, D-57)
Power	48, 55, 56, 69, 71, 88, 96, 103, 106, 109, 110 (Discussion: D-XXIII, D-2, D-3, D-7, D-11, D-17, D-19, D-25-K, D-30, D-38, D-40, D-44)
Sanitary Engineering	55, 56, 87, 91, 96, 106, 111 (Discussion: D-10, D-29, D-37, D-60)
Soil Mechanics and Foundations	43, 44, 48, 94, 102, 103, 106, 108, 109 (Discussion: D-4, D-XXVIII, D-7, D-43, D-44)
Structural	42, 49, 51, 53, 54, 59, 61, 66, 89, 100, 103, 109, 113 (Discussion: D-3, D-5, D-8, D-13, D-16, D-17, D-21, D-23, D-24, D-25-K, D-32, D-33, D-34, D-37, D-39, D-42, D-49, D-51, D-54, D-61)
Surveying and Mapping	50, 52, 55, 60, 63, 65, 68 (Discussion: D-60)
Waterways	41, 44, 45, 50, 56, 57, 70, 71, 96, 107, 112, 113 (Discussion: D-8, D-9, D-19, D-27, D-28)

A constant effort is made to supply technical material to Society members, over the entire range of possible interest. Insofar as your specialty may be covered inadequately in the foregoing list, this fact is a gage of the need for your help toward improvement. Those who are planning papers for submission to "Proceedings-Separates" will expedite Division and Committee action measurably by first studying the ASCE "Guide for Development of Proceedings-Separates" as to style, content, and format. For a copy of this Manual, address the Manager, Technical Publications, ASCE, 33 W. 39th Street, New York 18, N. Y.

Published at Prince and Lemon Streets, Lancaster, Pa., by the American Society of Civil Engineers. Editorial and General Offices at 33 West Thirty-ninth Street, New York 18, N. Y. Reprints from this publication may be made on condition that the full title of paper, name of author, page reference, and date of publication by the Society are given.

Planning the Diversion Entrance

Should there be a choice in locating the diversion entrance, many of the factors discussed above will affect that choice as well as the layout of the diversion. Four of the major considerations are:

(*a*) *Relation to the Point at Which Reduced Stage is Desired.*—If the purpose of the diversion is the reduction of flood stages, it appears preferable to locate the diversion above the stretch in which the stage reduction is desired, unless this location places a large storage area within the range of drawdown influence.

(*b*) *Increase in Velocity.*—The entrance to a diversion should be located upstream from the stretch in which an increase in velocity is undesirable, either from the standpoint of navigation or of acceleration of bank caving. If an upstream location of the diversion's entrance is not practicable, it should then be located as far downstream as possible.

(*c*) *The Angle of Diversion.*—The angles between the entrance to the diversion, the main stream, and the bed-load path will affect the amount of bed load withdrawn.

(*d*) *The Site at Which the Diversion Leaves the River Channel.*—The amount of bed load withdrawn will depend on the point at which the diversion is made from a river channel. A diversion entrance cut through a bar or located near the bed-load path will withdraw a large amount of material. One located far from the bed-load path will withdraw little material.

Conclusions

Each diversion contemplated from an alluvial stream must be given intensive study. Effects have been sufficiently discussed in this paper to permit an estimate of the results to be expected if all necessary factual data are obtained. Though a diversion from an alluvial stream cannot be designed to accomplish desired results with the exactness of other engineering design, thorough analysis will produce a design that will approach the ends desired and will remove many of the uncertainties. A qualitative analysis may be possible, but a quantitative analysis is apparently still beyond the capabilities of present scientific knowledge. Quantitative predictions involving the time factor can be approached only by statistical study of past occurrences and by model experimentation. The latter is costly and difficult. It is almost an impossible task to reproduce to scale all the conditions found in a natural stream. However, at the present time model experiments offer the most promising method of securing a quantitative approximation of results in which confidence can be reposed. Continued study by the engineering profession may yet bring forth a thoroughly scientific approach.

in the diversion unless the stage increase is prevented by enlargement of the main stream below the diversion. If the slope is increased in this manner and the bed load is reduced sufficiently to enable the discharge in the diversion to transport the bed load withdrawn from the main stream, a condition of quasi balance will eventually be created similar to the balance in an alluvial stream as previously discussed. Bends will form if the banks are erodible, and the diversion will act as a normal stream in an alluvial bed. However, the slope increase is limited by the stage in the main stream that existed before the diversion was made. In fact, if scour occurs in the main channel below the diversion, the limit of slope increase will be still lower. The attainment of this limit requires complete closure of the diversion. Thus, an explanation may be offered for the closure of natural outlets in the past. When sufficient slope cannot be attained to transport the material deposited at and carried into the the head of the diversion, its channel will fill, with a large amount of the material deposited near the head of the diversion in the form of a bar. At high water this bar may be elevated so that the succeeding low water will be below the crest of the bar, and no water will be diverted at that time. When the river stage again exceeds the crest elevation of the bar, a large amount of material will be carried over the bar for a brief period, widening it and further reducing the flow and transporting capacity across the bar and in the rest of the diversion channel. As a result the bar will continue to be elevated. Eventually its crest will be topped only by high stages. This is the probable action that takes place when a high bar forms across the entrance to the old bendway channel at the head of a cutoff.

For a diversion designed and located to withdraw a minimum of bed load, the action will be the same as discussed above for the river below the diversion with a disproportionate decrease in bed load. With easily erodible bed and banks scouring will occur in the diversion channel immediately below the entrance. This will increase the flow into the diversion which in turn will increase the rate of scour, unless the withdrawn bed load is increased in proportion to the increase in discharge. The scour will proceed in a downstream direction, enlarging the entire diversion. The diversion will continue to enlarge until: (1) Sufficient material is drawn from the main stream to inhibit further enlargement; or (2) a delta of sufficient length to reduce velocities below scouring magnitudes is built out from the outlet of the diversion; or (3) a portion of the diversion develops a braided channel to an extent capable of increasing stages and reducing velocities so that discharge increase is stopped and scouring velocities no longer exist.

A diversion constructed with a slope greater than that required to carry the bed load delivered to it will act in a manner similar to the diversion that extracts a relatively small amount of bed load from the main stream. It will scour its bed and banks, and, if compensating factors such as increase in bed load or delta building do not develop rapidly enough, the main stream may adopt the diversion for its ultimate course. This situation is illustrated by a cutoff across a narrow neck of a bendway that quickly becomes the main channel.

Proceedings—Vol. 78 January, 1952 Separate No. 112

AMERICAN SOCIETY OF CIVIL ENGINEERS

Founded November 5, 1852

PAPERS

DIVERSIONS FROM ALLUVIAL STREAMS

By C. P. Lindner,[1] M. ASCE

Synopsis

The hydraulic effects of diversions and their withdrawal of sediment from alluvial streams are discussed in this paper. In order that a clear understanding of the influence of diversion may be had, characteristics of the flood hydrograph and of the stage-discharge relation are described. Factors influencing the diversion of bed load and the variation in the quantity of diversion with the angle of diversion are developed and supported by analysis of model experiments. A conception of the balanced stream is presented to explain the effect of diversion on the river and diversion channels, and items to be considered in planning the diversion entrance are given. The use of the principles and factors of this paper will aid in arriving at a reasonable appraisal of the results to be expected from diversion, but model experimentation is the best medium for securing results upon which a high degree of dependence can be placed.

Hydraulics of Diversions

Effect on Discharge with Storage Area Above the Diversion.—When a diversion is located a short distance below an extensive valley storage area, the rate at which water is withdrawn from the main stream is not the net reduction in river discharge immediately below the diversion, for an increase in peak discharge is likely to result from operation. To demonstrate this effect synthetic discharge-storage relationships were prepared in which the increments of storage per unit change in discharge were quite large. These relationships were used with appropriate rating curves to route a hypothetical flood past a diversion floodway. The results of the routing are shown in Fig. 1. For the hypothetical flood the inflow to the stream reach attained a maximum rate of 1,800,000 cu ft per sec. Thus the natural storage, with the floodway not operating, reduced the peak inflow by about 450,000 cu ft per sec. With the floodway operating,

Note.—Written comments are invited for publication; the last discussion should be submitted by July 1, 1952.

[1] Chf. Engr., So. Atlantic Div., Corps of Engrs., U. S. Army, Atlanta, Ga.

valley storage reduced the same peak inflow by about 360,000 cu ft per sec. Approximately 90,000 cu ft per sec, then, was the lost storage effect or the increase in discharge caused by operation of the floodway. This is emphasized further in Fig. 1, which shows the discharge in the floodway to be slightly under 230,000 cu ft per sec and the net reduction in river discharge to be about 140,000

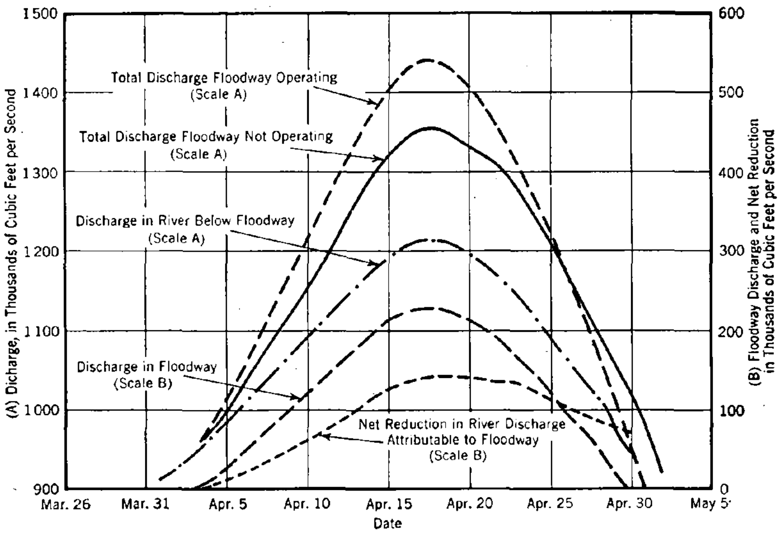


Fig. 1.—Operation of Floodway Downstream From Large Storage Area

cu ft per sec. About 39% of the water withdrawn by the floodway was required to compensate for the lessened natural storage effect caused by floodway operation.

Care must be exercised in the operation of a diversion with a controlled inlet. If the control works are opened abruptly, the total discharge rates will be increased by virtue of withdrawal from valley storage until sufficient time has elapsed to permit the attainment of channel slopes that are normal with the diversion operating. For many years it was thought that a cutoff (which may be considered a re-entrant diversion) would increase stages downstream about as much as it reduced them upstream. This belief was either inspired or supported by observation of a cutoff on the Mississippi River that occurred quickly at high stages. Discharges and stages were promptly increased below, which was natural since the rapid lowering of stages above the cutoff withdrew water that was in detention storage. The same results will follow the sudden opening of a diversion at high stages.

Effect on Discharge With Storage Area Below the Diversion.—With the diversion located just above a large natural storage area, the loss in effectiveness downstream may also be serious, for the net reduction immediately below the diversion is greater than at points farther downstream. To illustrate: in one case it

In the case of the hypothesis that the bed load is reduced by the diversion but the amount of water below the diversion is not changed, the initial action when both bed and banks are easily erodible will be much the same as the case in which only the bed was erodible. The bed and banks of the first reach below the diversion will scour and supply bed load to the next and succeeding reaches. As scour occurs in the first reach below the diversion, the cross section there is enlarged and the slope and velocity are reduced. The rate of erosion diminishes so that sufficient material is not supplied to the next downstream reach to maintain its balance. The bed and banks of the next reach begin to scour and so on throughout the whole stretch of the river below the diversion, or of that part that has erodible bed and banks. Eventually, the cross-sectional area is increased, and the slope is reduced to reach a balance between transporting capacity and the amount of material moved as roughly represented by the amount passing the diversion. Thereafter, the river below the diversion will act as a balanced stream flowing through erodible material. To a great extent the material passing the diversion will be deposited on the next point bar, and bank caving and meandering should proceed at a rate that will compensate for this deposition. Since the amount of material passing the diversion was assumed to be less than before diversion, even though the condition of no reduction in discharge was imposed, bank caving should be retarded. It should be noted, however, that velocities were reduced, and banks that may be considered freely erodible at one velocity may not be so freely erodible at a lower velocity. Accordingly, some of the bed load carried past the diversion may not be deposited on the next point bar but may be carried farther down the channel in the manner represented by the central diagram of Fig. 5. The result of this action would be a further reduction in the rate of bank caving.

In the case of an actual diversion in which bed load is withdrawn in disproportionately large amounts in relation to the quantity of water diverted, the flattening of the slopes below the diversion will reduce stages at its entrance, thereby lessening the amounts diverted and increasing the slopes and bank caving upstream. These results will tend to cause more bed load to pass below the diversion entrance. Thus, the flattening of the slopes below the diversion is partially resisted by the effects that it causes. But the rates of accelerated bank caving above the diversion are gradually reduced as the steepened slopes are extended farther and farther upstream. Finally a balance is reached in which the slope and rate of erosion below the diversion are less than before commencement of diversion, but greater than were the caving upstream from the diversion not accelerated and the amount of diversion not reduced by the lowered stages resulting from the flattened slopes downstream.

Action in the Diversion Channel

The action in the diversion channel is no different from that in any stream channel. If the diversion has been so located that it withdraws a large proportion of the bed load, its slope, cross section, and the amount of water diverted must be adequate to transport the material; or filling in the diversion channel will occur. The filling will reduce the water and bed load entering the diversion and thus raise stages at the head of the diversion. This increases the slope stream changes in its cycle from high water to low water, so that although the diversion may withdraw a large part of the bed load at one phase of the hydrograph, it may withdraw a much lesser proportion at another phase.

Effect Below Diversion When the Bed Is Erodible and Banks Are Resistant.—The preceding discussion applies equally well to channels with erodible beds and to those with erodible banks. There are some minor variations, however. In a channel with erodible bed but resistant banks, a reduction in the discharge without a corresponding reduction in bed load will reproduce almost exactly the action that was described for the nonerodible channel. Bars will enlarge, and the bottom will elevate to produce a slope capable of transporting the bed load with the lesser volume of water. If the bed load is reduced without proportionate reduction in discharge and if a balance between transporting capacity and bed load originally existed, the bed of the stream just below the diversion will start scouring immediately. If, in the first reach or two below the diversion, sufficient material is placed in motion to replace the material withdrawn by the diversion, the channel farther downstream will experience no effect from the diversion for some time. The scour in the upper section will reduce the slope, and the capacity to erode and move material in that section. Thus, the stream enters reaches farther and farther downstream with unsatisfied transporting capacity. As a result, the scour of the bed proceeds in a downstream direction. This differs somewhat from the stream with bed and banks that are difficult to erode. At no location will the latter have its transporting capacity satisfied, so slow erosion may occur simultaneously throughout the entire stretch of the stream below the diversion.

Effect Below Diversion When Bed and Banks Are Erodible.—Should the condition be such that both the bed and banks below a diversion are eroded with relative ease, a reduction in discharge without a reduction in bed load will probably result in a retardation of the bank caving for a period except at points that are not well accommodated to the curvature appropriate for the reduced flow. The bed will rise, and bars will grow rapidly until the slope has been increased to an extent that will enable the stream to transport the bed material being delivered to it. Filling and bar building will proceed in a downstream direction, as the bed load will be deposited first in the reach immediately below the diversion. It is at this point that the effect of reduced transporting capacity is first felt. This reach will fill and increase its slope rapidly. As soon as filling has proceeded sufficiently, bank scour will be accelerated. Material will be carried to and perhaps beyond the next point bar, and the cycle is repeated there and continues downstream. The lag in the downstream direction occurs only in the beginning of the cycle. No cycle is completed before activity in the next bend or reach begins. The net result is that the slope of the entire stream below the diversion is increased, and cross-sectional area is modified until there is a balance between bank caving and material deposition. Thereafter, if the banks erode with the necessary ease, the amount of material caved from the banks should be about the same as it was prior to diversion, since there was assumed to be no change in the amount of bed load moved and presumably deposited on point bars which must be compensated for by scouring of the opposite bank.

was assumed that the next reach below the diversion had the same storage and discharge characteristics as the reach above, for which Fig. 1 was prepared. Through this reach were routed the flows shown in Fig. 1 for the total discharge with the floodway not operating, and for discharge in river below floodway, the flows remaining in the river after floodway withdrawals. Peak discharges were found to be 1,182,000 cu ft per sec with the floodway not operating and 1,097,000 cu ft per sec with the floodway operating. The difference of 85,000 cu ft per sec is the effect of the diversion at the lower end of the next reach downstream. Since the net reduction immediately below the diversion was about 140,000 cu ft per sec, the reduction was diminished about 39% in the next downstream reach.

Modification of Water Surface Slope.—

Flood-Wave Flow Characteristics.—It is well recognized that a diversion increases the water surface slope in the main channel upstream. The effect of a diversion on the slope downstream has been given little attention. An understanding of flow characteristics is necessary for a complete realization

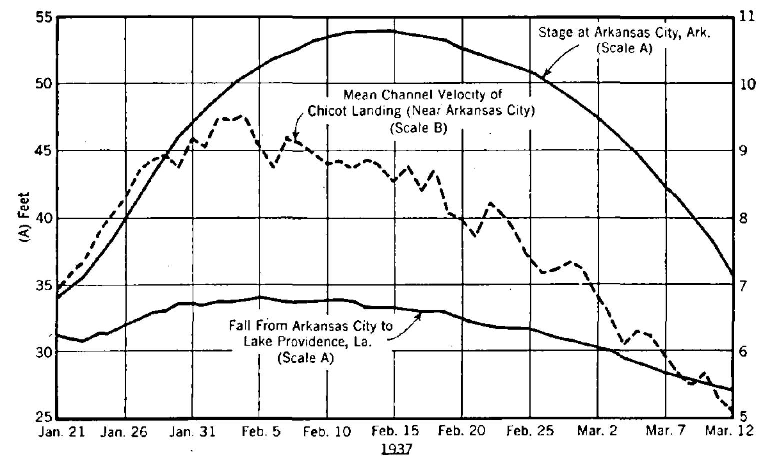


FIG. 2.—MISSISSIPPI RIVER—1937 FLOOD

of the effect on downstream slopes. In Fig. 2 the stage hydrograph and the mean channel velocities of the 1937 flood in the Mississippi River at Arkansas City, Ark., have been plotted as has the fall from Arkansas City downstream to Lake Providence, La. This fall is indicative of the river slope below Arkansas City. The slope on the rising limb of the hydrograph is steeper than at corresponding stages on the falling limb. As a result, the velocities are greater on the rising limb, and it follows that the discharge for any given stage is greater also. The maximum discharge rate may occur before the crest stage when the slope is still greater than at the crest.

The steeper slope on the rising limb of the hydrograph is caused by the fact that the rise at any point precedes the rise at a point below. The difference is increased by valley storage which lengthens the time lag and reduces the stage at the downstream point by lessening the rate of flow at the crest and on the rising limb of the hydrograph. On the falling limb of the hydrograph reverse conditions prevail. At the instant of crest, the water surface downstream is still rising, thus lessening the slope. The reduction in slope continues as the stage downstream rises to crest and then falls less in each coinciding period of time than does the stage at the point upstream to which the hydrograph applies. The reduction is augmented by withdrawal of water from valley storage below the gaging station. This increases rates of discharge at downstream points and causes high stages there to persist.

Flood-Wave and Steady-Flow Slopes Compared.—At peak stage the slope is greater than it would be if the flow that occurred at that stage continued sufficiently long to create steady flow conditions. Under the latter conditions all points are at stages corresponding to the same flow. Thus, if the discharge were to rise to a given quantity and then continue at that rate for an indefinite period, the stage at any station would continue to rise slightly after the given rate of flow was attained, until a constant slope was established. This slope would be less than the slope at the peak of a normal hydrograph and the stage would be higher. At the time the given rate of flow was attained at the station, the conditions would approximate those at the peak of a normal hydrograph, for downstream stages and discharges would still be rising. Thereafter, downstream stages would rise more than the stage at the upstream station, for the downstream stages would be increased both by flattening of the water surface slope and increase in discharge whereas the stage at the upstream station would be increased only by flattening of the slope. Thus it is demonstrated that the slope under steady flow conditions is flatter than the slope at the peak of a normal hydrograph. Furthermore, since rising stages have steeper slopes than the peak, the slopes on the rising limb of the hydrograph are steeper than those under steady flow conditions.

On the falling limb of the hydrograph the slope continues steeper than that occuring in steady flow conditions until those conditions are approximately attained by the falling of the upstream discharge hydrograph and the rising of the downstream discharge hydrograph to the same rate of flow. This point is the same as or equivalent to the crossing of the inflow and outflow hydrographs, well recognized in river hydraulics as the peak of the outflow hydrograph. Thereafter the upstream hydrograph will fall faster than the downstream hydrograph, and slopes at and below the upstream station will be flatter than those occuring in steady flow conditions. When the equality of discharge rates at 2 points is used to approximate steady flow conditions, the length of the reach between the points should be so limited that the contained storage can be related to the stage or discharge at the downstream point. In addition, the reach should be long enough to prevent changes below the reach from affecting stages at the upstream end of the reach. There should also be no material inflow within the reach; or intermediate inflow should be removed by analytical adjustment. In the case of a reach so selected, at the time the discharges at the head and foot of the reach are equal, the flows at intermediate points should

erosion, the diversion may have little effect on that channel except over a long period of years, and the material carried past the diversion may pass downstream without consequence. If the bed load is lessened more than the transporting capacity of the river, there may be a depression of the water surface elevations in addition to that attributable to lowered discharge, because the channel section formerly occupied by bed load will, after diversion, be occupied partly by water. It should be remembered, however, that the channel was carved to its existing size and shape through the interaction of varying the discharge rates, the slope, and the bed load. The regimen will have been disturbed by the diversion so that the process of adjustment will be activated. To visualize the interaction of these features, first assume that the stream before diversion was transporting bed load to the limit of its capacity and that the diversion reduces the discharge but does not change the amount of bed load delivered to the channel downstream. The transporting power of the stream will have been reduced so that deposits will occur in the channel. These deposits may manifest themselves both as a general filling of the bed and in the formation of bars that reduce the cross section of the channel to conform to the changed discharge rates. The slope is increased by the reduction in cross section, and as the slope increases, the transporting power of the stream increases until eventually it is able to transport the material delivered to it. The filling should be most rapid in the first reach below the diversion and gradually work downstream.

Now assume that bed load is diverted without reduction in downstream discharge. This is a hypothetical condition that could be induced only through an increase in the discharge above the diversion in amounts equal to the water diverted. Presupposing a balance below the diversion before its construction or occurrence, at the existing slopes the stream will easily be able to transport the material that passes the diversion. Because of the reduced quantity of bed material, stages and slopes will probably be lowered slightly, but since the bed and banks are resistant, no other changes should be evident for many years. Slowly, however, the stream will erode its channel so that eventually it creates for itself a channel area and slope that is in balance with the bed material transported.

With a decrease in the water quantity below the diversion, the bed tends to build and bars tend to form so that the slope is increased; and with the bed load decreased, the bed tends to scour and the slope tends to diminish. With both water quantity and bed load decreased, the course of action will be determined by the change that is predominant. From preceding discussion, it appears that unless the diversion is located with respect to river bars, bends, and sediment path, in such a manner as to withdraw a minor portion of the bed load, the transported material will be reduced disproportionately to the reduction in discharge. Thus, the channel below the diversion should transport the bed material carried past it without filling, and there should be a long-time trend toward scour. Before the conclusion can be drawn that a disproportionate amount of the bed load will be diverted, however, the locations of the bed, bar, and paths of sediment near the entrance to the diversion at all stages should be studied. It should be remembered that the configuration of the stream causes slopes above the bendway in question to increase once more. In turn, this causes a whole series of counterreactions tending toward the re-establishment of the original conditions. The foregoing assists in partial visualization of the continual changes taking place. Realization of this fluid condition and the knowledge that erodibility varies from place to place furnishes an understanding of the serpentine movements of an alluvial stream. There is no true balance since the condition viewed as balance presupposes a condition of change.

The only differences between a stream with freely erodible bed and banks and a stream with bed and banks that are more difficult to erode are variations of degree and time. If a large amount of material is delivered to a reach that is not readily erodible, slopes and channel dimensions will be established so that part of the material is transported downstream past the point bars. The amount deposited on the point bars will be the amount sufficient to compensate for the scour on the opposite bank. It can easily be seen that in a reach in which the bed and banks are practically nonerodible, the material delivered will deposit only in sufficient amount to create the necessary transporting capacity. Thereafter, material delivered will be carried through the reach.

Effect of Diversion on River Channel

Effect Above the Diversion.—Since the stage is reduced at the point of diversion, the slope of the water surface upstream is increased. This effect may be either permanent or temporary depending on the erodibility of the bed and banks upstream. If the banks are relatively resistant to erosion and the bed is easily erodible, the channel will deepen. The slope will gradually flatten immediately upstream from the diversion while the slope further upstream will steepen. With this progressive erosion of the bed, stage reduction caused by the diversion will extend farther and farther upstream. The extent of this reduction influence depends on the ability of the bed to support a steeper slope than the river had before the diversion was made. Resistant areas in the river bed will have a great effect on the extent of diversion influence or at least will delay its upstream movement. Except for the existence of resistant areas and the possibility of the bed supporting slightly increased slopes, no limit can be visualized under the conditions assumed, unless the diversion and the river below it are incapable of transporting the bed load carried to the point of diversion. In this case, the building up of the river and the diversion will limit, at least temporarily, the upstream effect of the diversion by lessening the stage reduction.

If the bed and banks upstream from the diversion are easily erodible, deepening of the channel probably will still occur but only temporarily, for bank caving will be accelerated. The bank caving will operate to lengthen the channel and thereby reduce the slope. In this instance, also, the effect of the diversion on the river above may be reduced by the inability of the diversion and the river below the diversion to carry away the added bed load resulting from the accelerated bank caving.

Effect Below Diversion When Bed and Banks Are Resistant.—Should the banks and bed of the river channel below the diversion be highly resistant to

be equal to the flows at the ends of the reach. Accordingly, substantially steady flow conditions exist.

The Stage-Discharge Relation.—Because higher slopes and velocities exist on the rising limb of a flood wave than at equal stages on the falling limb, the stage-discharge relation (or rating curve) takes the form of a loop. Fig. 3 is an

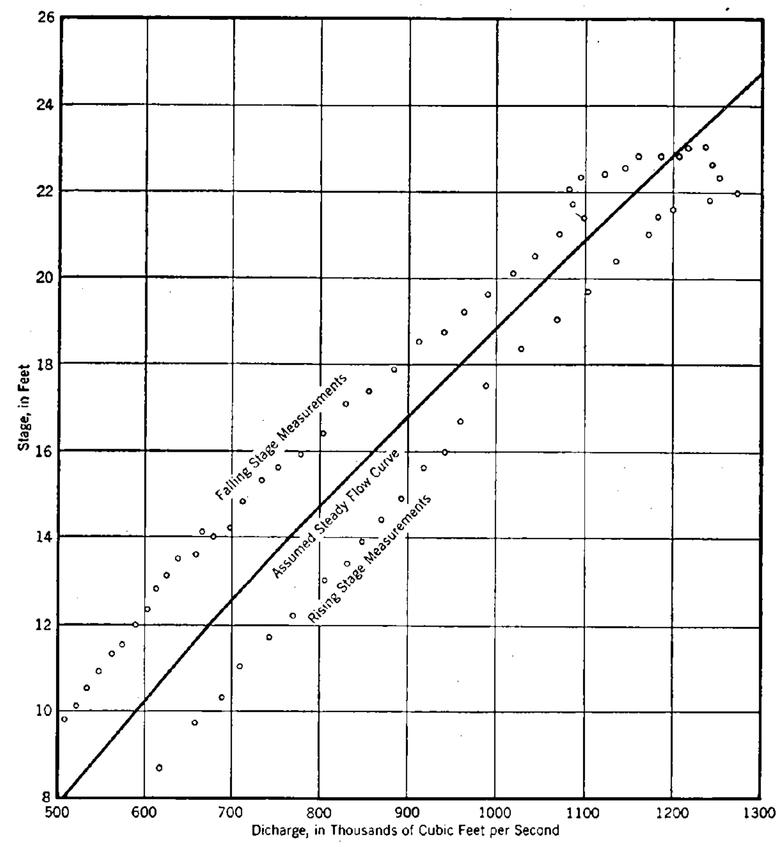


Fig. 3.—Example of Stage-Discharge Relations, Mississippi River

example. The mean rating curve, drawn as an average between the rising and falling segments of the loop, does not necessarily represent steady flow conditions. If the rise of the flood is rapid and the fall is slow, discharges taken from the mean rating curve will be higher than those for steady flow conditions. The reverse will be true if the rise is slow and the fall is rapid. In the absence of other changes, a composite mean rating curve obtained from many flood waves should approximate a steady flow rating curve. Care should be exercised, however, in passing the curve through the top of each flood loop. If the point near the top of each loop is selected in accordance with suggestions contained in the preceding paragraph, these points should approximately represent steady flow conditions. These points may be expected to lie toward the falling stage side of the loop from the peak stage unless the maximum flow was of sufficient duration to establish steady flow conditions. Since an alluvial stream is continuously changing because of erosion, a mean curve obtained from several flood waves may not have great significance. In such a situation the engineer has little choice other than to use a rating curve plotted from the most recent flood wave, with such adjustments as he has good reason to make.

Results of Flattening the Hydrograph.—From the foregoing it is evident that, if an attempt is made to decapitate the hydrograph by means of a controlled diversion, the slopes in the main river downstream of the diversion will be flattened. Decapitation is defined as the slicing off of the highest portion of the flood wave so that the stage or discharge remains constant for an appreciable period of time. If the discharge hydrograph is decapitated, the stages downstream will continue to rise after the diversion is begun by an amount equal to the difference (at the decapitated rate of discharge) between the rising stage rating curve and the steady flow rating curve. When decapitation of the stage hydrograph is attempted, once diversion has begun it must increase by the amount of rise of the inflowing discharge hydrograph (including the increase caused by lessened valley storage effect) plus the difference in discharge between the two rating curves at the decapitated stage. To clarify, assume that diversion is begun at a 16-ft stage with the intention of holding that stage throughout the flood. Referring to Fig. 3, diversion will begin on the rising stage segment of the rating curve when the discharge is about 940,000 cu ft per sec. At a 16-ft stage the discharge for steady flow conditions is indicated as 865,000 cu ft per sec. If, after diversion is begun, the discharge ascends to a peak flow of 1,200,000 cu ft per sec the diversion required to hold the stage to 16 ft is not 1,200,000 cu ft per sec minus 940,000 cu ft per sec = 260,000 cu ft per sec but 1,200,000 cu ft per sec minus 865,000 cu ft per sec = 335,000 cu ft per sec. This is true unless the decapitation involves too short a period to create steady flow conditions downstream before the peak flow occurs, in which case a lesser increase in the diversion will be made necessary by the flattening of downstream slopes.

With the exception of diversions that are specifically operated to avoid the effects accompanying decapitation of the hydrograph resulting from the reduction of river slopes downstream, these effects are experienced to a degree in all diversions from streams having significant amounts of valley storage below the diversion, whether or not the diversions are controlled. This follows from the fact that diversions generally flatten the hydrograph.

Stage Reduction.—Above and below a diversion, stages in the main stream are reduced. Above the diversion, slopes are steepened, and the reduction in stage diminishes in accordance with backwater principles. Below the diversion, slopes usually are flattened, thus increasing the stage required to transmit flows and reducing the effectiveness of diversion in terms of stage lowering. In addition, if there is appreciable valley storage above the diversion, the maximum

lower stages the velocities are generally lower. The stream can be turned around bends with greater ease when velocities are lower, and hence there is more deflection in the upstream portion of the bend. In a natural stream, the stage and slope vary continuously, and as a result the bed-load path and the points at which maximum and minimum withdrawal of sediment through diversion would occur also change continuously. This fact should be taken into account in planning diversions from natural streams.

In many diversions the bottom of the branch channel may be at a considerably higher elevation than the bottom of the main channel. Assuming both banks to be steep and velocities to be of such magnitude that bars of appreciable vertical height cannot build, the bed load will travel along the bottom of the main channel; and the side channel will of necessity derive its water from comparatively high layers of the main stream. Under these conditions little bed load will be diverted. Should the diversion quantities be large, it is probable that a bar will build near the head of the diversion, because of the change in velocity and transporting capacity there. If the bar is raised to a level within the range of influence of the diversion, the latter will then withdraw bed load, and the proportion withdrawn will increase with the continued elevation of the bar. In predicting consequences of this nature to be expected from a high-level diversion, the relative amount of diverted water and the location of the bed-load path must be considered.

An Adjusted or Balanced Stream

When the bed load, slope, quantity of water, and channel size are adjusted so that point bars build at the same rate as opposing banks cave, the stream is considered in this paper as being in balance. The condition can best be understood in the instance of a stream having freely erodible banks and bed. The channel is a relatively continuous series of reversing bends. In each bend the concave bank caves and a bar, known as a point bar, builds on the convex bank opposite. The material caved from the concave bank is deposited on the next downstream point bar that is on the same side of the stream as the bank from which the material caved. This tends to constrict the channel, but to compensate for the constriction the concave bank caves across the river from the point bar on which the deposit occurred. When the caving and deposition process is such that the average cross-sectional area does not change materially except for changes that must accompany alterations in shape to maintain transporting capacity, the stream may be said to be in balance. Banks will cave, and bars will build at compensating rates. However, as bends lengthen or are eliminated by cutoffs, the elements that must be adjusted to attain the condition of balance are changed. It is doubtful, therefore, that an alluvial stream is ever quite in balance. The growth of a long bend, for example, can flatten slopes upstream, and consequently for a short time erosion above and the material delivered to the point bars in the bend are reduced. Erosion in the bendway continues, enlarging the channel and lessening the slope and velocity. This action reduces erosion in the bendway, and as a result of the diminishing amount of bed load reaching the next bar downstream a similar reaction occurs there and so on down the river. The flattening of slopes down-that in meandering streams the path of the bed load does not follow the thread of the stream. Accordingly, the angle between the channel and the bed load path must be taken into account in planning a diversion. For example, if the angle between the diversion and the bed load were less than the angle between the channel and the diversion, the effect of the angularity and the differential and vertical velocity factors will be augmented, with no change in the impact of the other factors. Thus, the proportion of the bed load withdrawn will probably be larger than if the angles were the same. If, instead, a lesser angle exists between the channel and the diversion than between the latter and the bed-load path, the proportion of the bed load withdrawn probably will be diminished.

The conclusions drawn with respect to effect of location of diversion in a river bend were substantiated by other tests conducted at the Waterways Experiment Station.[8] In these tests diversions were located in a reproduced Mississippi River bendway at four points, as shown in Fig. 4. The diversions were approximately at right angles to the river channel, with two exceptions that have been mentioned previously in the discussion of angle of diversion. Runs were made at two water surface elevations, one corresponding to a 40-ft prototype stage and the other to a 20-ft stage. In both instances diversion channel areas 30 ft deep by 300 ft wide were available below the water surface at diversions Nos. 1, 2, and 3. Diversion No. 4 was cut to thalweg depth. The amounts of flow withdrawn were needed to produce velocities sufficient to move bed load into and through the diversions. Test results showing the effect on bed-load withdrawal of the location of a diversion in a river bend are shown in Table 2. For each run at a given stage the same amount of water was diverted as for all other runs at that stage.

TABLE 2.—Tests Showing the Effect on Bed-Load Withdrawal of the Location of a Diversion in a River Bend

Diversion operating	Forty-foot stage	Twenty-foot stage
Water[a]	10%	20%
No. 1[b]	80%	...[c]
No. 2[b]	75%	89%
No. 3[b]	20%	87%
No. 4[b]	0	0

[a] Percentage of water withdrawn. [b] Not tested. [c] Percentage of bed load withdrawn with Diversion No. 1, etc., operating.

The concave bank could not erode because it was constructed of concrete. Had this bank been of friable material, it is likely that some of the material that would have caved from the bank above Diversion No. 4 would have been withdrawn by that diversion. The small amount of material withdrawn by Diversion No. 3 during the 40-ft stage tests is indicative of the importance of the proximity of the sand path to the diversion entrance. The bed load did not concentrate on the bar side until it reached the vicinity of Diversion No. 2. A large portion of the bed load was far out in the channel from Diversion No. 3, so that it could not be deflected into the diversion. By prior runs without diversions it was ascertained that the bed load concentrated on the bar (or convex) side of the bend further upstream for the 20-ft stage than for the 40-ft stage. Comparison of the withdrawals through Diversions No. 2 and No. 3 confirms this observation. The explanation probably lies in the fact that for

rates of flow immediately above the head of the diversion are increased so that neither stages above nor below the diversion are lowered in magnitude corresponding to the rate at which water is withdrawn. Furthermore, with a substantial amount of valley storage below the diversion, the lowering of stages downstream diminishes with distance from the diversion. It should be remembered also that increments of discharge per foot change in stage usually increase in a downstream direction. Thus, even in the absence of other factors tending to diminish stage lowerings, a reduction of water surface elevation immediately below a diversion may be equivalent to a much lesser reduction at points farther downstream.

Velocity Changes.—Velocities may be expected to be modified by diversion in accordance with the slope changes. In the river above the diversion, velocities will be increased with the increase, growing less in an upstream direction and reaching zero at the first point above the diversion drawdown influence. Below the diversion, velocities will generally be reduced because of the lowering of the crest rates of discharge and the flattening of the slopes.

Summary of Hydraulic Effects of Diversion.—The hydraulic effects and results of diversion, assuming consequential amounts of valley storage in the main steam both above and below the diversion, are summarized as follows:

1. Stages are lowered above and below a diversion;
2. Velocities are increased upstream and reduced downstream from a diversion;
3. Valley storage effect is reduced upstream from a diversion, and the maximum rate of discharge is thereby increased;
4. By flattening the hydrograph, a diversion reduces valley storage effect in the main river downstream resulting in the loss of a part of the peak discharge and stage reduction that normally would be caused by storage;
5. When the hydrograph is flattened, steady flow conditions are approached downstream. This increases stages by causing coincidence or near coincidence of the peak discharge and peak stage, and also by causing crest or near crest stages to occur at downstream points when points above are at crest stage, thereby reducing water surface slopes.
6. The diminished valley storage effect downstream from a diversion (mentioned above) further reduces slopes by causing the stage and discharge reducing effect of the diversion to be progressively less effective in a downstream direction.

Operation

If a diversion is open at all times, so that it will withdraw water whenever the stage in the main stream exceeds the elevation of the bottom of the diversion, the flood hydrograph will be flattened roughly in proportion to the amount the peak stage is reduced, but it will not be decapitated. The valley storage effect in reducing flood peak discharge will be diminished both upstream and downstream from the diversion but will not be eliminated, for the normal shape of the hydrograph is retained even though its amplitude is reduced. If the hydrograph, as modified by the diversion, passes through sizable storage areas downstream, its peak flow and discharge rates are so affected by that storage that (barring additional tributary inflow) the peak flow continues to reduce. This reduction is not as great as it would be if the flood were unmodified by the diversion of water. Accordingly, as a modified flood wave continues downstream through an accumulatively increasing amount of valley and channel storage, the peak reduction diminishes. This situation can be contrasted with the situation in which the hydrograph is decapitated by operation of a control structure. In the latter instance there is a greater increase in discharge because of the elimination of upstream storage, for water can go into storage at that point only through tilting of the water surface. This is so because the stage at the lower end of the reach where the diversion is located is fixed or approximately fixed. As the flows represented by the decapitated hydrograph pass downstream through large storage areas, the rising limb of the hydrograph continues to be reduced by valley storage and the falling limb increased. The flat top is reduced in extent more and more until eventually a rounded hydrograph is formed once more. From the point of diversion to the nearest point downstream where the hydrograph no longer has a flat top, the peak discharge is constant; that is, the peak discharge is not reduced by the valley storage. In this stretch, the entire reduction in peak flow of the natural flood wave, unmodified by the operation of the diversion, is the amount that the peak-flow reduction caused by the diversion diminishes. Let R_u denote the reduction in peak flow of the natural flood wave before modification under the operation of the diversion; let R_s denote the reduction in peak flow of the flood wave modified by diversion; and, let R_d denote the reduction caused by the diversion immediately below it. Then $R_d + R_s + R_u$ is the net reduction caused by the diversion; but in the stretch in which the hydrograph is decapitated, $R_s = 0$. Accordingly, the reduction in peak flow and stage accomplished by the diversion will diminish faster in a downstream direction if the hydrograph is decapitated than if the diversion is operated to produce a normally shaped hydrograph. A diversion that is open at all times will produce such a hydrograph.

Decapitation of the hydrograph to produce a wide, flat crest can be accomplished only with a controlled inlet. If the purpose of the diversion is to reduce flood heights, decapitation should be avoided by judicious operational procedure. This is advisable unless there is little valley and channel storage above the diversion, within the range of its influence, or below the diversion to the location where flood height reductions are desired.

The harmful effects of excessive flattening of the hydrograph can probably best be avoided by providing no control structure, but where a structure is necessary, these effects can be mitigated by operating the structure so as to pass a flood wave of approximately normal shape. This can be achieved in the most practicable way by passing water through the structure relatively early on the rising stage of the hydrograph and paralleling as nearly as possible the stage hydrograph that would occur without diversion. For instance, if it is required that the controlled stage in the river not exceed 16 ft and if it is predicted that the peak stage without diversion would rise to 19 ft, operation should begin as soon as possible; and the rates at which water is withdrawn should be equivalent to 3 ft on the gage. Of course, if there is excess diversion capacity and no objection to using it, there should be no hesitancy in drawing

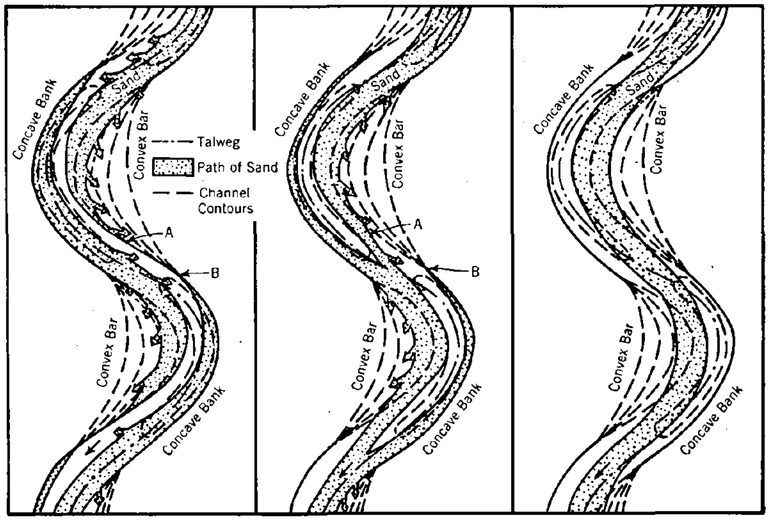
load withdrawn depends on the point in a river bend at which the entrance to a diversion is located. Evidence has been furnished which shows the path of sand travel in an alluvial stream.[9] Fig. 5 is reproduced from this study. When banks erode rapidly, the material from the caving bank moves downstream and deposits on the next point bar on the same side of the river. This is also true when banks erode with difficulty, but in this case the bed load also moves from the point opposite the caving bank and crosses the thread of the stream in the general vicinity of the crossing to the point bar below. Some of the material that reaches this point bar is deposited there, and a portion passes downstream, again crossing the thread of the stream to the next point bar. For this condition to exist, material must be entering from above the reach at a faster rate than the banks are caving in the reach under consideration. If this material is entering at the same rate as the banks are caving, sand will not move from point bar to point bar across the thread of the stream. In this case the distribution and path of the bed load will be similar to that described for rapidly eroding banks. Thus, the references to rapid erosion, and other comparable terms are relative only and do not apply simply to rate of bank erosion. Rather, the terms represent relations between rates of bank erosion and amounts of bed load carried in from points above the reach. Generally it may be said that the material moving from above cannot be less than that caved from the bank below, for the latter will eventually accommodate itself to the amount of material deposited on the point opposite. Fig. 5 also shows that in reaches in which there is no erosion, bed load entering the head of the reach passes through from point bar to point bar, swinging away from the concave bank in each instance.

To minimize the withdrawal of bed load, a diversion should be located, if practicable, in a reach in which there is no erosion. This alone will not insure a low rate of withdrawal, for, in addition, the entrance to the diversion should be in the concave bank an appreciable distance below the next upstream point bar in order that it will be as far as practicable from the path of sand travel. In reaches in which the banks are eroding there is little movement along the bank between points A and B in Fig. 5. This section of bank, however, is very close to and just below the next upstream point bar. If the entrance to a diversion is located there, it is possible that the diversion might be capable of influencing the path of the sand and of withdrawing material from the altered path or from the convex bar above. Therefore, it appears that the best point of diversion, to minimize withdrawal of bed load, is near point B or a short distance downstream where bank caving is still small. The optimum location can be determined only through study of the actual stream, but model tests will furnish valuable assistance.

Though proximity to the sand path and exposure to a source of bed load are major considerations affecting the movement of bed load into a diversion, once the exposure has been established other factors that have been discussed become of prime importance. Considerable mention has been made of the effect of the angle between the main channel and the diversion channel. Fig. 5 shows

[9] "A Laboratory Study of the Meandering of Alluvial Rivers," by Capt. J. F. Friedkin, U. S. Waterways Experiment Station, Vicksburg, Miss., May, 1945.

diversion angles the approaching particles have a component velocity in the direction of the branch channel, whereas for a 90° diversion the entire movement of each particle into the branch channel must be created by the diversion forces. For still larger angles a component of the movement down the main stream must be overcome as well. However, if the material comes to rest before it is drawn into the branch channel the angularity factor just described will be nonexistent.



(*a*) RAPIDLY ERODING BANKS (*b*) SLOWLY ERODING BANKS (*c*) NO BANK EROSION

Fig. 5.—Paths of Sand Travel in Meandering Rivers

A summary of the factors that influence the diversion of bed load is given at this point for convenience of reference:

a. The velocity factor or the reduction in velocity at the bifurcation;

b. The velocity in the branch channel. The velocity must be sufficient to transport the sediment presented;

c. Differential velocity effect;

d. The vertical velocity effect;

e. The slope factor which depends upon the relative slopes in the main channel and in the branch channel;

f. Meander pattern created by branch channel; and

g. Angularity factor.

With the exception of factor *b* which was not mentioned previously, these factors were discussed in preceding paragraphs in the order listed.

Additional Factors Affecting Bed-Load Diversion in Natural Streams.—Previously it has been implied that in natural streams the amount of bed

the stage below 16 ft simply because this action would flatten the hydrograph. The closest approach to eliminating the unfavorable results of flattening of the hydrograph can be made in reaches with constant storage increments per foot of stage. An example of such a reach would be one completely bounded laterally by levees or steep escarpments.

Withdrawal of Sediment by Diversion

Suspended Sediment.—Experiments conducted at the United States Waterways Experiment Station[2] showed that when loess was the transported sediment, the division of the material between the stream and the branch was very nearly in proportion to the water distribution. Since loess is an extremely fine material, it may be concluded that most of it was carried in suspension. Table 1 summarizes the results of experiments at Iowa State College[3] and lends a

TABLE 1.—Percentage of Total Sediment Passing Through a Branching Arm for Various Sediment Sizes[a]

Test number	Slope of channel	Percentage of flow in branch	Size of Sieve: ¾ Inch	4	10	20	40	60	80	100	200
1	0.0182	49.1	91.2 186	84.8 173	76.1 155	72.3 147	68.8 140	59.6 121	50.7 103	49.8 101	48.1 98
2	0.0214	27.8	64.3 231	60.1 216	57.2 206	55.5 200	42.1 151	34.1 123	32.3 116	28.2 101	21.0 76
3[b]	0.0214	25.6	61.3 239	58.4 228	55.2 216	47.3 185	40.6 159	33.2 130	30.0 117	26.4 103	19.9 78
4	0.0346	14.8	24.6 166	22.7 153	20.0 135	19.1 129	18.8 127	18.4 124	18.1 122	17.8 120	16.5 111

[a] The first line of values for each test is the percentage of the total sediment of the indicated sieve size passing through the branch. The second line of values is the ratio of that percentage to the percentage of total flow in the branch. [b] Outlet flow was retarded by perforated plates.

measure of support to this indication that suspended sediment divides in proportion to water distribution. In these tests the slopes were steep and except for Test No. 3, the outlets were free fall. Both channels were rectangular with dimensions 6 in. by 5 in., and the branching channel diverged 30° from the main channel. Slopes of all arms of channels were equal, but the actual relation of the surface slopes could not be determined from the test reports. The 100-mesh material in three of the tests divided almost exactly in proportion to the division of flow. The 200-mesh material divided approximately in proportion to flow in Test No. 1 and for all practical purposes behaved similarly in Test No. 4. In this latter test the difference in percentage of flow and percentage of 200-mesh material passing into the branch channel was only 1.7. However, the variation in division of the 200-mesh material in the various tests does not appear to be consistent with variations for other sizes. Channel sizes were small, and slopes were steep, so it may have been difficult

[2] "Movement of Bed Load in a Forked Flume," by Herbert D. Vogel, *Civil Engineering*, Vol. 4, February, 1934, p. 73.

[3] "Stream Sedimentation in a Divided Channel," by Albert Guy Dancy, thesis submitted to Iowa State College, Ames, Iowa, in 1947, in partial fulfilment of the requirements for the degree of Master of Science.

to obtain a natural distribution of the finer material in the channel above the diversion.

It has been concluded[4] that fine materials in transportation are distributed comparatively uniformly throughout the river cross section. In connection with the mechanics of withdrawal of water by a diversion this conclusion supports the concept that suspended sediment, as differentiated from bed load, divides at a diversion approximately in direct proportion to the division of water quantities.

Bed Load.—

Variation with Diversion Discharge.—Herbert D. Vogel, M. ASCE,[2] reported results of tsst runs using Red River sand. In these tests the rates of discharge in the main channel above the branch were held practically constant. Both channels were 2 ft wide and rectangular in section, and the angle of bifurcation was 30°. The results are summarized in the following tabulation:

Flow in branch channel as percentage of total flow	Deposits in branch channel as percentage of total deposits
65.0	85.1
49.4	75.9
48.8	75.2
34.9	63.6
30.2	45.3
29.9	51.3
24.2	37.1
23.3	38.2
15.9	17.9

Sand traps were not provided so sand carried beyond the ends of the flumes was lost. Later experiments indicated that sand was carried past the end of a branch channel before it reached the end of the main channel; such loss, if accounted for, would cause the percentages of material carried by the branch channel to be larger than the percentages of total deposits listed above. Red River sand is rather fine, so that some sand may have been carried in suspension. Sand in suspension would divide approximately in proportion to the division of water quantities. Therefore, if such sand actually were deposited below the bifurcation, the percentages of deposits in the branch channel also were reduced (because of the material in suspension) below what would have been recorded had the material been transported entirely as bed load. Such deposition appears possible, for later experiments indicated that slopes below the bifurcation were flattened by diversion. Since the slope in the main channel is smallest near and below the point of diversion, any deposition of suspended sediment that might have occurred was greatest in the main channel. Unbalanced deposition of this nature also would lower the percentage of deposits in the branch channel.

Variation with Particle Size.—Later experiments[2] utilized flumes of semicircular cross section, with bottoms as before on the same horizontal plane.

[4] "Study of Materials in Suspension, Mississippi River," *Technical Memorandum No. 122-1*, U. S. Waterways Experiment Station, Vicksburg, Miss., 1939.

It should be noted that the conditions of tests described resulted in a greater slope in the branching channel than in the straight channel below. In the Karlsruhe laboratory tests the same amount of water was drawn into each channel. Since the velocity was directed down the main channel, in order to compensate for the difference in velocity head, additional slope in the branch channel was needed. Thus, as the two channels were of equal size in the tests, the tractive force near the head of the branch channel exceeded that in the straight channel below the fork. Therefore, the diversion of a greater amount of sediment into the branch channel was promoted, and this will be the case whenever a similar condition exists. Attention is invited to observation made under "Bed Load: Channel Slopes and Effect of Slopes on Bed-Load Diversion," relative to the effect of increased flume slopes, substantiating the conclusions just reached. As the flume slopes increased, the velocities increased, and accordingly, for any given rate of diversion, the slope in the branch channel necessarily increased more to compensate for the velocity head directed downstream and for the greater difficulty of turning the higher velocity jets into the branch flume.

Another factor probably enters into the diversion of bed load. It is best appreciated by examination of a branching channel that departs from the main channel with a small angle. A side channel that diverges from the straight channel at 30°, for example, will have a tendency to create a meander pattern upstream from the bifurcation. The material moving on the stream bed will then tend to adopt a path with respect to the meander pattern similar to that shown in Fig. 5. The bed load will pass toward the inside of the bend at the upstream side of the branch channel. Thus it is drawn to the head of the branch channel and moves into that channel with the diverted water. In the case of exceedingly sharp bends, the normal pattern is disrupted, and deposition does not occur on the convex point. Accordingly, for high angles of diversion it may be expected that the meander effect will not assist in the diversion of bed load. It should be noted that a bendway which is an element of a meander pattern is in itself of the nature of a diversion. The first section of the stream that moves around the point or convex side of the bendway is diverted from the main stream, and each jet that moves around the bend successively outward from the point is diverted from the stream that is still continuing toward the concave side of the bend. Thus a bendway is a continuous succession of diversions. Each deflected jet will transport bed load in accordance with the effect on it of factors influencing bed-load diversion and with the amount of material presented for diversion. Therefore, the meander pattern effect is not an elemental factor affecting bed-load diversion but is a complex of other factors. However, since these factors operate within the meander to cause its peculiar pattern of bed-load movement and again act separately with respect to a branching channel, the meander pattern may be viewed as a separate factor in relation to bed-load movement into a branching channel.

If material is moving along the bed of a stream with a noticeable velocity, its diversion is affected by the magnitude of the angle through which the material must be turned. It is manifestly diverted through a small angle with greater ease and less force than is required for a large angle. For small the point bar at a location that had been found to be most favorable for diversion of bed load. At other locations the percentages of diverted bed load would have been less.

Factors Influencing Diversion of Bed Load.—Analysis of the experiments described has led to the identification of factors that cause a branch channel to carry proportionately more bed load from a flume—and from a river when conditions are right for the purpose—than the water diverted. These factors furnish, at least, a partial explanation of the changes in the proportions of bed load diverted with variation in the angle of diversion.

Immediately after a diversion is constructed the average velocity upstream from the point of diversion is greater than the velocity below that point. This is caused by the fact that there is more area to conduct the flow below the point of diversion, since instead of one channel there are two, and one of these channels usually is as large as the channel upstream from the diversion. The low slopes observed in the main flume near and below the head of the branch channel (mentioned previously under "Bed Load: Channel Slopes and Effect of Slopes on Bed-Load Diversion") support the conclusion that the velocity changes near the point of diversion. Thus, the tractive force is rather abruptly reduced below the value in the main stream above the point of diversion. Material cannot be moved from the vicinity of the diversion as fast as it is moved in, unless the channel above is transporting bed load at less than capacity. Under any circumstances the rate of bed-load movement slows at the point of bifurcation. Better opportunity is thus afforded the branch channel to withdraw bed load. This situation will continue until channel sizes have been reduced by deposition.

The highest velocities occur in the upper layers of the stream from 0.6 depth to the surface. These layers of water are deflected into the side channel with greater difficulty than the lower layers that have less velocity. Accordingly, a large portion of the water that flows down the straight channel below the junction is derived from the upper layers of the stream which do not carry bed load. A relatively dead water area results, so far as flow down the straight channel is concerned, near the bottom of the stream in the junction area. With the top water flowing down the straight channel there is little opportunity for the bed load to move in that direction, and a substantial portion of the water in the branch channel must be derived from the lower layers of water in the main channel. These layers transmit the bed load, and a large proportion of of this load is moved into the branch channel.

Even if the head of the branch channel is in a pool in which no appreciable differences in movement from top to bottom exist, it appears that the normal vertical velocity curve might not be established in the branch channel for the distance required to accelerate the water from no velocity in the pool to the velocity permitted by the slope and the frictional resistance in the branch channel. It might be expected, then, that the ratio between velocities near the bottom and upper layer velocities would be greater at the entrance to a branch channel than at other locations. This would encourage the diversion of bed load into the branch channel.

The main channel had a 2-ft radius and the side channel a 1-ft radius. Sand traps were provided to make possible runs that were continuous over long periods of time. The approximate average results were

Type of sediment	Discharge in side channel as percentage of total discharge	Sediment entering side channel as percentage of total sediment
Red River sand	38	52
Polk Creek sand	36	65

These results do not confirm the results of the preliminary tests (and possibly rightfully not because of the different character of the channels and the altered test conditions). Since the Polk Creek sand was coarser than the Red River sand, the results do indicate that a greater percentage of coarser materials will pass into a side channel than is the case with finer materials. It is probable that a portion of the finer material becomes suspended or is in a partially suspended state, in which the grains are driven high in the water stream. However, this does not explain the difference in the diversion of coarse and finer materials, both of which have sufficient particle size to travel as bed load. Experiments conducted at Iowa State College[3] emphasize the need for further explanation of this phenomenon. The results of these tests are shown in Table 1. In addition to indicating in a general way the effect of changing the percentage of flow in the branching arm, Table 1 reveals that, without exception, as the particle size of the sediment is reduced, the percentage of the size diverted is also reduced. Particles of the $\frac{3}{8}$-in. and No. 4 sieve size should normally be transported as bed load by rolling, sliding, or saltation with small vertical amplitude. Yet a lesser percentage of the No. 4 size particles was diverted than of the $\frac{3}{8}$-in. size. An unsuccessful attempt was made to explain this phenomenon on the basis that the larger sized particles, having less surface area exposed to the action of the current per unit weight of the particle, travel more slowly along the bed and, therefore, could be deflected more easily. The greater percentage of diversion of the coarser particles shown by these tests appears to conflict with discussions and demonstrations by A. Schoklitsch[6] of sorting in bends.

Conditions of the Iowa State College experiments may have influenced the results in such a way as to cause the distribution in accordance with particle size as shown in Table 1. With the slopes rather steep it is possible that all sizes were carried more or less in suspension, but proportionately more of the larger sizes were able to settle into the bottom area near the head of the branch channel. It is believed that near the bottom of the channel the component of velocity in the direction of the main channel downstream is relatively low and the component in the direction of the side channel relatively high. Thus the distribution of particle sizes would occur as shown by Table 1, because the particles suspended at higher elevations in the stream would divide in accordance with the division of the water at each level. In the demonstrations conducted by Mr. Schoklitsch, as in natural river bends, conditions were not such as would cause the degree of unbalance of velocity components that in all likelihood occurs at the

[6] "Hydraulic Structures," by A. Schoklitsch (translated by Samuel Schulits), American Society of Mechanical Engineers, New York, N. Y., 1937.

head of a branch channel, especially a branch channel in a flume that has a relatively large cross section with respect to that of the main flume. Further investigation is needed to determine whether a diversion from a natural stream will withdraw a greater proportion of coarse than of fine materials and to furnish a convincing explanation of the distribution of particle size that occurs. Application of test results to natural streams is fraught with hazards unless conditions are in accordance with correct scale ratios or the mechanics of all observed phenomena is understood.

Channel Slopes and Effect of Slopes on Bed-Load Diversion.—In the article by Col. Vogel[2] two other points are mentioned that may be useful in developing a theory pertaining to the relatively large amount of bed load diverted by channels branching from flumes or from natural streams when the branch is so located as to facilitate withdrawal of bed load. First a series of experiments in which water surface profiles were recorded indicated that slopes were flattened in the main flume near the head of the branch channel and also downstream therefrom. The second point is expressed by the following observation made as a result of experiments conducted at Cornell University, Ithaca, N. Y., and is quoted from the article by Col. Vogel.[6]

> "For tests of short duration (6 hr) the percentage of bed load deposited in the side flume increased with an increase in slope throughout the flume. Such increase in slope was obtained by lowering the tailgates of the two flumes."

Angle of Diversion.—Experiments have been made at the Karlsruhe hydraulic laboratory to determine the amount of sedimentary material diverted by channels branching from a straight channel at various angles.[7] The following tabulation summarizes the results of these tests for sharp edges at the point of branching:

Angle of diversion from straight channel	Percentage of sediment in diversion	Percentage of sediment in straight channel below diversion
30	97.3	2.7
60	96.2	3.8
90	90.5	9.5
120	87.5	12.5
150	92.0	8.0

In these experiments the channels were rectangular, and the diversion channel and the main channel below the point of diversion were the same size as the main channel above the point of diversion. The width was 0.656 ft, and the bottom slope was 0.003. The evidence available indicates that the sediment used was sand. With the low slopes used it is probable that practically all of the sediment moved along the bed. At the point of diversion the volume of flow was divided equally between the two channels.

[6] "Movement of Bed Load in a Forked Flume," by Herbert D. Vogel, *Civil Engineering*, Vol. 4, February, 1934, p. 77.

[7] "Hydraulic Laboratory Practice," ed. by John R. Freeman (translation), American Society of Mechanical Engineers, New York, N. Y., 1929.

In experiments at the United States Waterways Experiment Station using a model of a Mississippi River bend[8] tests were made to determine the effect of the angle of diversion on the amount of bed load withdrawn. Three angles between the diversion and current were used: 45°, 90°, and 135°. Diversion site No. 1, as shown in Fig. 4, was selected for the tests, since the greatest amount of sand was withdrawn in model runs of a 40-ft river stage at this location. The 45° and 135° diversions were bent at the bank line and con-

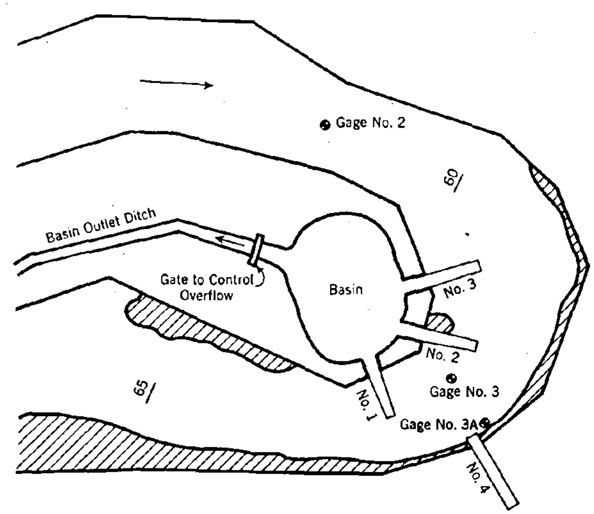


Fig. 4.—Location of Diversions in Model Study of Bed-Load Movement

tinued at those angles into the river. Landward of the bank line all diversions were approximately at right angles to the river channel. In the prototype the diversion channel dimensions were equivalent to widths of 300 ft and depths of 30 ft below the 40-ft stage at which these tests were run. The results are summarized as follows:

Angle of diversion in degrees	Percentage of bed load diverted
45	97
90	80
135	85

Although the experimental conditions were considerably different from those at the Karlsruhe laboratory, the results appear to give a qualitative check, especially with respect to the variation with angle of diversion. Although the percentages of bed load diverted seem to confirm the Karlsruhe results, it should be remembered that these diversions were excavated through

[8] "Model Study of the Movement of Bed Material Around Bends and Through Diversion Channels," *Technical Memorandum No. S-1*, U. S. Waterways Experiment Station, Vicksburg, Miss. (unpublished).