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Discussion of Diversions From Alluvial Streams

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DISCUSSION OF DIVERSIONS FROM ALLUVIAL STREAMS
(Published in January, 1951)

By T. Blench, Serge Leliavsky Bey, A. R. Thomas,

WATERWAYS DIVISION

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* Readers are urged to submit discussion applying to current papers. Forty free Separates per year are allotted to members. Mail the coupon order form found in the current issue of *Civil Engineering*.

DISCUSSION

T. Blench,[10] M. ASCE.—Valuable features of this interesting paper include the following:

1. A quantitative example of the effect of storage in producing the well-known difference between rising-stage and falling-stage river rating curves;
2. A nonmathematical discussion of unsteady flow; and
3. A qualitative discussion of the interconnection of water and sediment diversion, and their effects on regime.

The phenomenon of item 1 is often attributed to sediment movement only. The example shows that it can be explained entirely by capacity effect. It also shows that the relieving effect of a floodway may be much less than the floodway discharge. However, there is no statement of the volume of storage assumed, and no statement as to whether it would correspond to a lake (implying no sediment downstream), to the spill of a plains river at high stage, or to the capacity of an incised river. Would the author kindly elucidate?

Item 2 should be valuable because the intractability of the differential equations tends to drive engineers away from the subject. Their fear is unfortunate, for mathematics answers "how much," but common sense and perseverance answer "how" and, often, "approximately how much."

Item 3 quotes exhaustive and good American information. Experience gained in India can confirm and extend the information from America. The movement of coarser bed sediment to the inside of a curve must have been forced on the attention of oriental inundation canal builders from time immemorial, and the writer has found that illiterate cultivators on Indian canals know about it. The phenomenon is the basis of action of all sediment-excluding devices for canals, and has been examined in models and verified from prototypes by Sir Claude Inglis,[11] M. ASCE. Perhaps its most striking use was the construction of a curved approach to the Sukkur Barrage, on the Indus River in Sind, Pakistan, on Sir Claude's recommendation, to cause coarse bed sediment to deflect away from the canal heads and over the barrage. The writer can confirm that the coarser grades of bed material are more susceptible to the differentiating action of curvature of flow, so that excluders for very coarse sand and fine gravel can be 100% efficient, whereas for 0.20-mm sand they cannot be expected to achieve much; the reason presumably lies in the different settlement velocity laws. Experience in India also indicates that the size of the bed sediment is a major factor in determining regime slope, whereas the suspended load is of little importance.

Note.—This paper by C. P. Lindner was published in January, 1952, as *Proceedings-Separate No. 112*. The numbering of footnotes, tables, and illustrations in this separate is a continuation of the consecutive numbering used in the original paper.

[10] Cons. Engr. and Associate Prof. of Civ. Eng., Univ. of Alberta, Edmonton, Alta., Canada.

[11] "The Behaviour and Control of Rivers and Canals," by Sir Claude Inglis, *Research Publication No. 13*, Central Waterpower Irrig. and Nav. Research Station, Govt. of India, Poona, Bombay, India, 1949, Chapter 6.

The writer would modify the author's conclusion that "* * * model experiments offer the most promising method of securing a quantitative approximation of results in which confidence may be reposed." Bed material in models is often quite unlike that of the prototype; investigators probably never make any attempt to show the difference in bed material between parent and offtakes and are handicapped by the fact that the bed-load charge cannot be measured in the prototype. Such models cannot deal with regime developments arising from sediment differentiation into offtakes, as so ably discussed by the author; for answering questions about rate of development of sediment phenomena the models must be equally unreliable. They would improve if devised to take cognizance of the sediment behavior of the prototype (assuming that the scale is large enough to keep in the proper range of behavior). This fact requires that they should be used along with scientific analysis of the prototypes, requiring patient field investigation. For scientific field analysis, there is a need for a basis of theory, which is provided at present by regime theory.[12,13] Consequently, the writer would state the requisites of a proper investigation to be (*a*) models, (*b*) field observation, and (*c*) theory applied to field and model results.

Generally, all three are required to reinforce one another, but items (*b*) and (*c*) combined should render item (*a*) unimportant in many cases, whereas

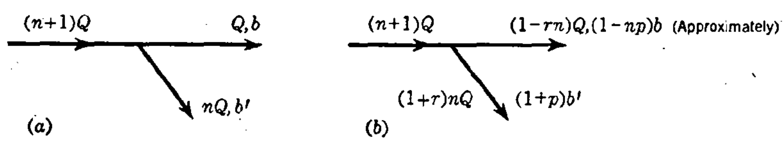

FIG. 6

item (*a*) alone is of little value without the others. Of course, this view refers to the use of models for the problems under discussion, not for problems of a quite different type.

In the writer's experience, theory has been found to fit river data very well where special circumstances have allowed it to be checked. For example, the distribution of bed sediment size between parent and diversion, after regime has been attained, fits with discharges and slopes according to regime theory; the size of assisted cutoff (for a meander) that will develop itself when opened is given reasonably by theory. The following problem should indicate what theory can do, why the author's appreciation of the factors controlling behavior is so important, and why models should be devised to work in terms of those factors if their present status is to be improved; the problem was suggested to the writer by the Atchafalaya Diversion, as described by Leo M. Odom,[14] M. ASCE.

Fig. 6 (*a*) shows a parent channel of dominant discharge $(n + 1)Q$ splitting into a diversion of dominant discharge $n\ Q$ and a residue of Q. Because of the

[12] "Hydraulics of Sediment Bearing Canals and Rivers," by T. Blench, 1951 (available from author).

[13] "Civil Engineering Reference Books," by E. H. Probst and J. Comrie, Butterworth's, London, England, 1951 (Chapter on "Canals, Channels and Rivers").

[14] "Atchafalaya Diversion and Its Effect on the Mississippi River," by Leo O. Odom, *Transactions*, ASCE, Vol. 116, 1951, p. 503.

last sentence should be modified to read, "Even in a stream having erodible banks * * *." In a stream having fixed banks, the bed material introduced at the head of a reach may be expected to continue downstream unless it is so coarse or heavy that the currents cannot move it.

The writer feels that the discussions of his paper have been outstanding and is properly grateful to each of the discussers. The ideas they have contributed, the examples cited, and the data presented may assure that the paper will be of value to the profession.

Corrections for Transactions.—On page 8, line 24, change + to −; and in Table 2 transpose the footnotes [b] and [c] to read "[c] Not tested," and vice-versa.

more uniform distribution of sediment with depth than the "Smooth Bed Area." This is to be expected with conditions being identical. However, the conditions are not the same, but may contain compensating influences. For example, the rates of change of velocities are greater at the "Smooth Bed Area" location. This condition would tend to produce more turbulence transfer and appears to be an anomaly because the greater turbulence (and turbulence transfer) would normally be expected where there is a rough bed. However, where the roughness is considerable, it may tend to equalize velocities by producing a large amount of turbulence that results in intimate mixing of water from various levels. Possibly this can be explained, also, by the difference in velocities, and by the fact that the effect of roughness may be relative, depending on the velocity. Despite the lesser velocities and the rates of change of velocity at the "Rough Bed Area" location, the coarser particles are projected higher in the stream than in the "Smooth Bed Area." This may not be caused entirely by the difference in the nature of the beds. The "Smooth Bed Area" appears to have had a larger amount of total solids, especially in the intermediate sizes, and only a small amount of the larger sizes of sand. This high concentration of solids, especially in the lower levels, may have offered a resistance to the projection of the larger sizes upward. Both sets of curves show that materials in suspension above points at five tenths of the depth or six tenths of the depth are distributed relatively uniformly, that the finer fractions have comparatively uniform concentrations from top to bottom of the stream, and that concentrations of coarser particles increase enormously with depth in the lower levels. It is believed that these differences would be accentuated in a deeper stream.

Mr. Bondurant properly has pointed out that material carried in a stream may be transported for long distances and not deposited on the next point bar downstream. This was mentioned in the paper (see under the heading, "Withdrawal of Sediment by Diversion") and reference was made to Mr. Friedkin's experiments. The writer observed Mr. Friedkin's experiments many times and often discussed them with him. Therefore, the fact that the material moved along the bed either in close contact therewith, or by saltation, can be rather authoritatively confirmed. However, the discussion of this item in the paper was not restricted to material moving on the bed, nor was it intended to imply that all the material from a caving bank would deposit on the next point bar when it was asserted (see under the heading, "Withdrawal of Sediment by Diversion"): "* * * the material from the caving bank moves downstream and deposits on the next point bar on the same side of the river." Obviously, some of the material will be in a highly suspended state and other portions of it will remain suspended at high levels for a sufficient time to by-pass the next point bar. The material that is deposited on a point bar can be either that which moves along the bed or that which is carried in suspension (especially in the lower layers) and can come to rest because of slackened velocities in the vicinity of the bar. For completeness (as suggested by Mr. Bondurant), the paper should have mentioned that suspended sediment, even if that sediment is sand, can be carried for long distances without permanent or temporary deposition. It is believed that the first clause of Mr. Bondurant's

approach conditions to the diversion, its bed factor is b' whereas that of the residue is b. The system is in regime. Fig. 6 (b) shows the conditions just after engineers have developed the diversion to take discharge of fractional amount r in excess of the previous amount, and have altered the approach conditions into the diversion, so that the bed factor there exceeds the previous one by a fraction p. What will happen?

The answer, qualitatively and very briefly, assuming that p and r are positive, is that the regime slope of the diversion will be reduced by the

TABLE 3.—INITIAL PERCENTAGE INCREASE IN REGIME SLOPE, FOR n = 30%

Values of p	(a) Percentage increase of regime slope in diversion after excavating and altering approach conditions				(b) Corresponding increase in the residue's regime slope			
	Values of r, the fractional flow in excess of the previous amount:							
	1.0	0.5	0.25	0	1.0	0.5	0.25	0
0.0	$-16\frac{2}{3}$	$-8\frac{1}{3}$	$-4\frac{1}{6}$	0	+5	$+2\frac{1}{2}$	$+1\frac{1}{4}$	0
0.1	$-8\frac{1}{3}$	0	$+4\frac{1}{6}$	$+8\frac{1}{3}$	$+2\frac{1}{2}$	0	$-1\frac{1}{4}$	$-2\frac{1}{2}$
0.2	0	$+8\frac{1}{3}$	$+12\frac{1}{2}$	$+26\frac{2}{3}$	0	$-2\frac{1}{2}$	$-3\frac{3}{4}$	−5

increased discharge, but increased by the enhanced bed factor. The diversion will tend to grow or shrink according to whether the resulting regime slope is less or more than the original available slope; it may reach a new equilibrium if b' grows suitably as the diversion develops. A similar solution applies to the residue channel. Table 3 shows the quantitative answers from regime theory, and would direct an investigator to observe the proper site data and to make a suitable model.

SERGE LELIAVSKY,[15] M. ASCE.—The problem of the withdrawal of sediment from alluvial rivers into side channels is ably discussed in this paper. Apart from its general importance, it is of specific interest to irrigation engineers in connection with headwork design because the volume of heavy sediment which is deviated from the parent channel into a distributory or main canal determines to a large extent the operational maintenance expenditure of an irrigation system. If one realizes that the annual cost of canal clearances in the budget of the Egyptian Irrigation Service is measured in millions of pounds, it will be obvious that the problem under consideration must be a matter of deep concern to those in charge of these works.

In particular, within the last decade, a new approach to this problem has been initiated by a group of designers led by Abdel Azim Ismail Bey,[16] Director General of Reservoirs. They center their attention on the local asymmetry of the flow pattern at the intake of the siding. The importance of this pattern lies in its adverse effect on the efficiency of the defensive devices

[15] Cons. Engr., Cairo, Egypt.

[16] "Treatment of Heavy Silt in Canals," by Adbel Azim Ismail Bey. Report to the Second International Technical Congress, Cairo, Egypt, 1949.

commonly used to reduce the part of the bed load taken by the side channel, such as the various types of sand screens, sills, and weirs.

As a main parameter of the asymmetry of the flow, the analyst usually takes the angle between the parent channel and the diversion, which is termed the "angle of twist" by the new school (apparently the "angle of diversion" according to the author's nomenclature).

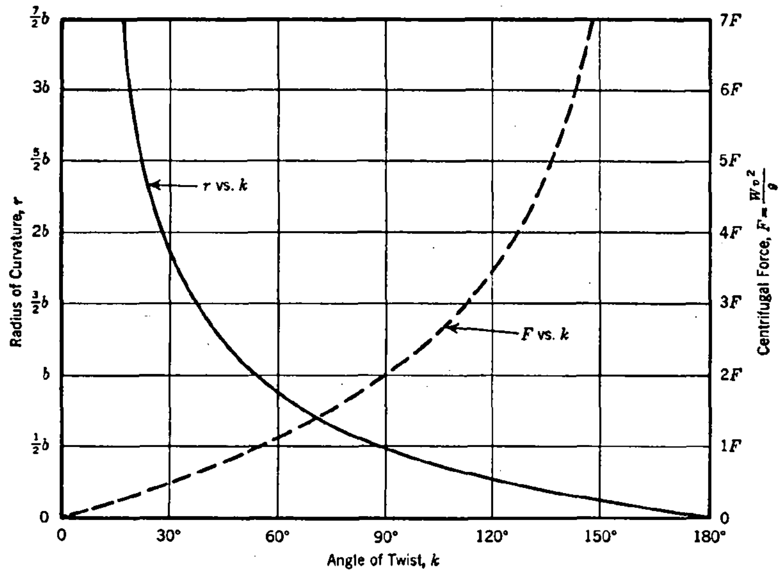

FIG. 7.—CENTRIFUGAL FORCE RELATED TO ANGLE OF TWIST BY THE RADIUS OF CURVATURE

Egyptian practice tends to show that this angle is far more important than is indicated by the data given by the author under the heading, "Bed Load: Angle of Diversion." This difference is presumably due to the very narrow width of the experimental channels from which these data were derived.

The angle of twist determines the intensity of the centrifugal force produced by the curvature of the trajectories at the entrance to the diversion. Egyptian engineers of the new school therefore believe that the division of sediment between the main and secondary channels is a function of this angle. Fig. 7 is a tentative diagram giving the average radius of curvature in terms of b, the bed width of the diversion, and as a function of the angle of twist. In the expression for centrifugal force, W is the weight, v is the velocity, and g is the acceleration produced by gravity. The chart was prepared by the writer from theory, experiments, and observations.

The centrifugal forces constitute the main local factor governing the behavior of the sediment at the entrance to the diversion. The difference between the centrifugal force at the surface and that at bed level produces a helicoidal flow pattern in which the heavily silt-laden filaments of the water in the main channel rise to the surface, entraining their charge of coarse bed load

bottom of the stream. As mentioned in the remarks concerning the discussion of Mr. Leliavsky, factors outlined in the paper depend upon this difference. It does explain to a considerable extent why a diversion, when located so as to be exposed to the sediment path, will withdraw a disproportionately large amount. However, the variation of sediment withdrawal with change in the angle of diversion cannot be explained solely on difference in velocity, nor will this difference cause a diversion to withdraw sediment if that diversion is not exposed to the path or to a source of sediment. For these reasons, the writer found it necessary to develop a breakdown into the factors influencing diversion of sediment.

Mr. Thomas has cited a very outstanding instance of the reduction in diversion of sediment that can be accomplished by proper location of the entrance. Such examples add convincing support to the paper.

Referring to Mr. Bondurant's discussion, the writer realized that it is difficult to differentiate or fix a fine line of demarcation between bed load and suspended load. Certainly, it was not intended that the term "bed load" should apply only to material moving on the bed of the stream. Rather, for want of a better term, it was used to describe material moving with heavy concentrations in the lower levels of the stream. A studied reading of the descriptions of the factors influencing diversion of bed load will indicate this.

By his statement that Red River sand is rather fine, so that some sand may have been carried in suspension, the writer did not intend to infer that only fine sands are carried in suspension. However, fine particles can be driven higher in the stream with less energy than coarser particles of the same specific gravity unless, of course, the specific gravity is less than 1.0. The writer referred to a publication[4] with which it must be presumed that the writer was familiar, and in which it is shown that sand is carried in suspension even to the top levels in the Mississippi River. It shows, also, that the greatest concentration occurs in the lower levels of the stream, usually in about the lower 10 ft. Above this level, the sand distribution is relatively uniform with depth. This high concentration of the coarser particles near the bottom is to be expected because the rate of change of velocity—and hence probably the turbulence transfer—is greatest in the lower levels of the stream. The Mississippi River measurements indicated that the concentration of silt sizes was nearly uniform from top to bottom.

Mr. Bondurant has presented very valuable and enlightening data in Fig. 13, showing the vertical distribution in the stream of various fractions of the sand. These are the only data with such a complete breakdown that have come to the attention of the writer. Of course, the curves apply to the sites where the data were obtained and cannot be used elsewhere except for purposes of drawing general conclusions and to serve as a guide for similar investigations. The data will probably change with velocity, with character of the bed, with curvature, with total solids, and with amounts of the various fractions. One set of curves has been designated "Rough Bed Area" and the other "Smooth Bed Area." As pointed out by Mr. Bondurant, the "Rough Bed Area" shows a

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

centrifugal force influences somewhat the vertical velocity effect and the slope factor. Thus, it seems that much more emphasis was placed on the angle of diversion in the paper than is evident.

The paper implies the importance of the angle of diversion by stating that these factors furnish at least a partial explanation of the changes in proportions of bed load diverted with variation in the angle of diversion. All factors may operate together, but the relative importance of each changes as the angle is modified. To illustrate—assume that the diversion channel carries the same quantity of water as the main channel below the point of diversion. Then, for small diversion angles, the water is deflected into the branch channel with relative ease so that the differential velocity, vertical velocity, and slope factors have little influence, but the meander pattern and the angularity factor are favorable for the diversion of bed load. As the angle between the straight channel and the branch channel becomes greater, the differential velocity, vertical velocity, and slope effects increase, but the meander and angularity influences become less favorable. It is doubted that the angularity factor changes much for angles greater than 90°, but the meander pattern effect, even though reducing, may persist for angles of diversion that are somewhat greater. The differential and vertical velocity influences increase to a maximum at an angle of 90°, or slightly greater, and probably remain rather constant for greater angles. As long as the same amount of water is diverted into the branch channel, the effect of the slope factor will grow with increasing angles, and the velocity factor will be equally operative at all diversion angles.

Mr. Leliavsky stated that Fig. 7 was prepared by him from theory, experiments, and observations. It appears that only the curve for radius of curvature is directly based on experiment and observations. The curve for centrifugal force is derived from the radius of curvature curve by assuming that $1\,F = \frac{W\,v^2}{g\,b}$. Thus, where the radius is $\frac{1}{2}\,b$, the centrifugal force is $2\,F$, etc. This being the case, Fig. 7 would be clearer if b were added to the denominator of the right-hand side of the equation that designates the scale for centrifugal force.

Mr. Leliavsky would do the engineering profession, especially in the United States, an additional service if he were to submit the data upon which his radius of curvature curve was founded, together with its derivation. An explanation of his method of determining the profile of the vortex that establishes the slope of the sand screen would be of great value, also. It is possible that the profile of the vortex can be approximated from the radius of curvature and centrifugal force curves by assuming that the difference in centrifugal force from the inside to the outside of the bend is balanced by the superelevation of the water surface, but there will be velocity differences in an actual case, for which compensation must be made. Theoretical development supported by experimental data and field observations would be helpful.

Mr. Thomas has presented a clear and perhaps more fundamental explanation of the effect of curvature than was given in the paper. He treats the same forces as discussed by Mr. Leliavsky in somewhat different terms. Both refer to differences in momentum, centrifugal force, or velocity from top to

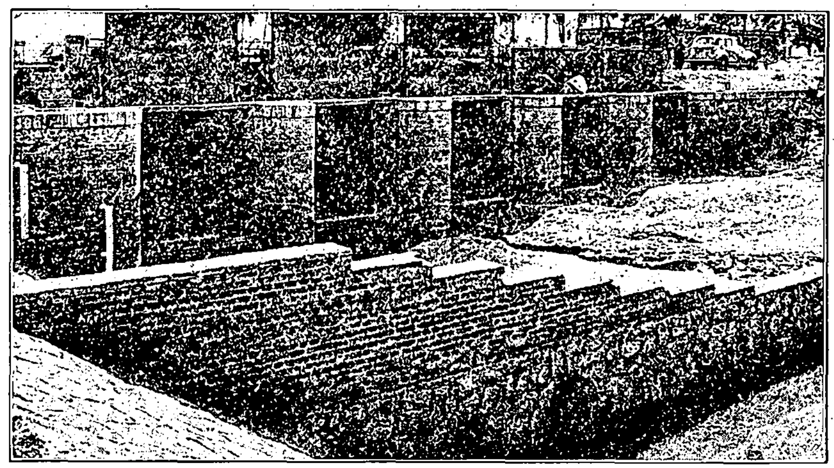

Fig. 8.—Sand Screen with Sloping Sill at Abou-El-Ahdar

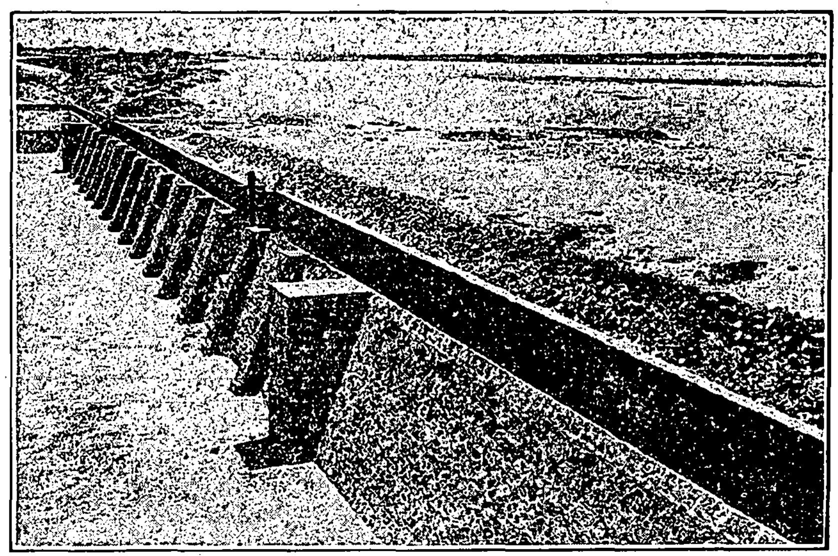

Fig. 9.—Head Regulator of Kelabia Canal, with a Discharge of About 8,500,000 Cubic Meters per Day (About 12,507,000 Cu Ft per Hr)

into the diversion over the sill of the sand screen. When there is no sand screen, the same three-dimensional mixing effect, by upsetting the pattern of sediment distribution typical of straight channels, increases the volume of the coarse bed load being deviated into the siding. For this reason, the angle of twist may play a more important part than would appear from the paper.

The individual links in the logical chain which led to this conclusion have been either confirmed theoretically or verified by model tests at the Delta Barrage Laboratory in Egypt. Characteristically, the final proof of this chain is believed to be supplied by the consistently satisfactory performance works designed on the angle-of-twist principle. In fact, in order to fight asymmetry of flow, the screen itself must be asymmetrical; that is, the sill of the sand screen must not be made level but should be on a slope determined by the angle of twist.

Fig. 8 illustrates one of the earliest designs prepared according to this idea. The steep slope of the rigid sill of the permanent sand screen should be noted. This design decreased the silt deposits in the controlled canal, but was not fully satisfactory, as evidenced by the bank or shoal that is seen to have formed

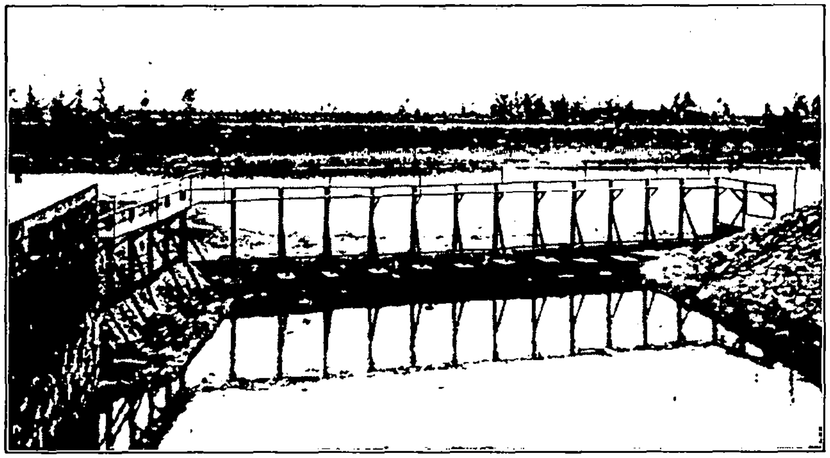

Fig. 10.—Sand Screen with Uprights for Flush Boards. at Bahr Tira Canal; Discharge About 2,500,000 Cubic Meters per Day (About 3,700,000 Cu Ft per Hr)

on the upstream side of the entrance. Such a shoal (and its counterpart, the scour hole on the downstream side of the entrance) is the result of the helicoidal flow pattern, and, therefore, increases with the angle of twist, if its effect is not counteracted by a properly designed sloping sand screen. It is usually symptomatic of heavy silt deposits in the canal.

Further ameliorations of the idea were as follows: (*a*) The sloped sill was extended over the entire width of the weir so that the sill slope approximated more closely that of the surface of the vortex as shown in Fig. 9, and (*b*) the level of the sand screen was made adjustable, depending on the changes of water level in the parent channel. A design embodying these improvements is shown in Fig. 10. The sand screen in this case is provided with metal uprights designed to carry flush boards. When in operating position, the tops of the flush boards are arranged step-wise, in accordance with the calculated slope.

The saving in clearances caused by these advancements in screen design is sufficiently great to confirm the angle-of-twist theory.

"* * * at the present time model experiments offer the most promising method of securing a quantitative approximation of results in which confidence can be reposed."

The phrase, "at the present time," was intended to carry its literal meaning. There was no implication that model experimentation would always remain as the most promising method. In fact, because of the cost and time involved in model studies, it is hoped that less costly and more exact and expeditious methods will be developed.

A proper investigation, as Mr. Blench asserts, includes (*a*) models, (*b*) field observation, and (*c*) theory applied to field and model results. However, the writer is inclined to place field observations first, with theory applied to those investigations, before undertaking a model study, unless it is believed that the latter will aid in guiding the field observations, which is often the situation. In that case, the model study and field observations should proceed more or less concurrently. In almost every instance, a model test of a natural stream requires a large number of field data before the model can be designed and constructed and the test can proceed.

The regime theory seems to offer promise for dependable analytical solutions in the future. However, the various factors are as yet difficult to appraise accurately, and at least one of the three basic equations[22] should be reduced to curves for expeditious solution. Referring to Table 3, the slope changes considerably with p, the change in the bed factor. It would be difficult to choose p accurately for any diversion modification, especially in view of the selection of bed and near-bed sediment that may be practiced by the diversion. For example, if the diversion before modification withdraws most or all of the coarse fractions of the sediment, the modification (assuming the sediment withdrawal to be increased thereby) must accomplish the increase through withdrawal of finer fractions. This will change the bed factor and make the selection of the value of p difficult. The foregoing is not meant to detract from the value of the regime theory nor to suggest that it is not now useful. On the contrary, it would seem to have great potentialities. However, it does offer the opportunity for further development. The probability of inaccuracy in choosing regime theory factors emphasizes the desirability of verifying, with a model study, designs of costly works based on that theory, or on the experience of the designing engineer. Such verification furnishes comfort and confidence to the designer.

Mr. Leliavsky has suggested that the writer did not sufficiently stress the importance of the concept of the angle of diversion or the angle of twist. There was no intention to minimize its importance. It was the variation of sediment withdrawal with the angle of twist that prompted the writer to seek an explanation and led to the conception of the factors influencing bed-load diversion. Most of these factors operate because of the angle of diversion and vary with it. The differential velocity effect, the meander pattern created by the branch channel, and the angularity factor are all intimately connected with the centrifugal force mentioned by Mr. Leliavsky. It may also be conceived that the

[22] "Regime Theory for Self-Formed Sediment-Bearing Channels," by Thomas Blench, *Transactions*, ASCE, Vol. 117, 1952, p. 383.

minds, the Bonnet Carré Spillway (Louisiana) and the reach of the Mississippi River from Red River Landing (Louisiana) to Bonnet Carré may be cited. In this reach, the river is closely confined by levees, or by levees and natural escarpments, so that overbank storage areas are extremely small. In fact, the storage in the reach is about one tenth that of the reach assumed in the paper. The inflow to the reach may attain a peak of 1,500,000 cu ft per sec, a rate only 300,000 cu ft per sec less than that used in the paper. The Bonnet Carré Spillway, at the foot of the reach, was designed to withdraw 250,000 cu ft per sec. This rate is comparable to the rate of withdrawal by the floodway cited in the paper. The stage at the foot of the reach is lowered a maximum of about 3 ft. This stage lowering gradually diminishes in an upstream direction, so that there is little or no effect at Red River Landing, the head of the reach. Thus, a wedge of storage is eliminated by the operation of the Bonnet Carré Spillway. This wedge is small because the entire volume of storage in the reach is not large in proportion to the flow quantities. Moreover, because the eliminated storage is wedge-shaped, the average stage lowering in the reach is probably only approximately one half the 3-ft lowering caused by the spillway at the foot of the reach. If the spillway is opened early on the approach of the flood, this decrease in stage is attained gradually over a period of two or three weeks. When it is remembered that the reach is bounded on both sides by levees and escarpments so that when water reaches these limits, the area for all practical purposes does not change with increase in stage, it can be realized that storage increments per foot of change in stage or per 1,000-cu-ft-per-sec change in discharge are not modified appreciably by spillway operation. Without change in storage increments, there can be no alteration in discharge. As a result, the operation of the Bonnet Carré Spillway does not noticeably increase the discharge during a flood.

From the foregoing it is evident that there are many factors that can influence the effect of a diversion upon discharge. Among them, but not previously mentioned, is the sharpness of the flood hydrograph. A rapidly rising flood, rather than one which rises more slowly, is affected more by valley storage. Therefore, the elimination of storage by reducing storage increments will increase the discharge of a flash type of flood more than that of a less "flashy" flood. Each case must be analyzed separately. However, if conditions correspond to those of the example presented in the paper (see under the heading, "Hydraulics of Diversions")—that is, although all scales and quantities are changed, if they are changed proportionately—the relative effects will be the same. The example in the paper emphasizes the fact that the withdrawal of water by a diversion does not necessarily reduce the flow downstream by the amount diverted. This fact applies to small streams as well as to large ones where there is a comparatively appreciable amount of valley storage within the influence of diversion drawdown. It has only minor application to incised streams because storage is small and storage increments on such streams do not increase noticeably with stage.

In general, the writer concurs with Mr. Blench's remarks regarding model experimentation. In the conclusions to the paper it was stated:

A rather curious point about this theory is that it must have been felt intuitively by the ancient Arab engineers, who were in charge of Egyptian irrigation for more than a thousand years, because they always tended to place their intakes at the concave bank of the Nile (as suggested by the author) but with the axis of the diversion tangent to that of the river. The angle of twist was thus reduced to nearly zero. From this standpoint, the layout of diversion No. 4 in Fig. 4 is definitely an anomaly.

A. R. Thomas,[17] M. ASCE.—The tendency of branch channels to draw excessive bed load has for many years been a problem in India, where irrigation canals are supplied by diversion of water from alluvial rivers. Canals which draw water at points unfavorably located with respect to the curvature of the parent river quickly lose capacity through the deposit of sand or silt. Offtakes of subsidiary channels from the canals also are likely to create similar trouble if precautions are not taken, as is well illustrated by the author's quotations of percentages of bed load drawn into branches. Methods used to deal with these problems have been described by Sir Claude Inglis.[18]

The author has given several possible causes for the excessive bed load drawn into branches. In the writer's opinion there is one explanation which is fundamental and which, briefly, may be stated as follows:

1. Where water flows in a curve, a force is needed to produce the change of momentum of flow resulting from the change in direction of flow. In a river or curved channel, the water level rises toward the outer concave bank, the transverse slope of the surface representing the increase of pressure required to produce the change of momentum. This increase of pressure is uniform on

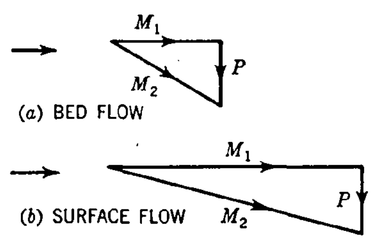

Fig. 11.—Vector Diagrams (M_1 = Initial Momentum, M_2 = Deflected Momentum, P = Lateral Force Due to Transverse Pressure Gradient, Equal in Each Case)

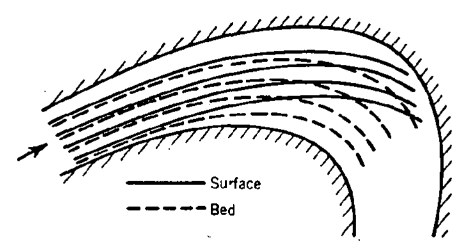

Fig. 12.—Diagrammatic Plan, Showing Flow Lines (Surface ——— Bed — — —)

any vertical; that is, at any point in plan the pressure increase is the same in the water near the surface as in the water vertically beneath. The forward velocity of flow is greater at the surface, however, than near the bed so that, with the same force acting on each, due to the same pressure gradient, the flow at the bed is deflected more than the flow at the surface, as will be clear from Fig. 11, showing vector diagrams of change of momentum of small

[17] Res. Engr., Stewart, Sviridov & Oliver, Queenstown, Union of South Africa.

[18] "The Behaviour and Control of Rivers and Canals," by Sir Claude Inglis, *Research Publication No. 13*, Central Waterpower Irrig. and Nav. Research Station, Govt. of India, Poona, Bombay, India, 1949.

imaginary prisms of water at the surface and bed. The difference between the angles is reduced by the interchange of momentum due to turbulence and by bed friction; but the general result is that the mean curvature of surface flow in plan is less than the mean curvature of the channel, whereas the mean curvature of bed flow is greater, as shown in Fig. 12, producing the well-known feature of cross flow at bends and surface water diving at the concave bank.

2. Similar action occurs at a branch. If the main channel is straight and the branch is at an angle to it, the flow entering the branch is curved and the slower-moving bed water will be deflected more sharply toward the branch channel than the surface water, with the result that the branch draws a larger proportion of bed water. If the branch begins on the concave bank of a curved channel, however, so that the flow is deflected less in entering the branch than in following the main channel, the branch will draw a larger proportion of surface water.

3. The division of sediment load between the main channel and the branch depends on its distribution in the stream. On a given vertical, fine sediment is distributed more uniformly than coarse sediment, the concentration of which increases toward the bed. The tendency, therefore, is for the fine sediment to be distributed in proportion to the ratio of the discharges and the coarse sediment (including the bed load) to be drawn in excessive proportion into the channel that deviates most from the straight, which may be a branch from a straight channel, a branch from the convex bank of a curved channel (as shown by the author in discussing the data relating to Fig. 4), or the main channel, if the branch is from the concave bank.

It follows that, if it is required that the branch must draw a minimum of coarse sediment—for example, to insure that the branch remains open—the branch should be located on the concave bank of a bend if possible. If this bank is eroding, sediment may enter the branch, as indicated by the author, but in such cases it would perhaps be preferable to take measures to prevent the bank erosion rather than to locate the branch at a less favorable point.

In India, Sir Claude developed the possibilities of using the curvature of flow to control sediment load and used this method in several cases. The most spectacular was perhaps at the diversion of the Mithrao Canal from the Eastern Nara River in Sind, where the angle of the diversion was acute and the canal was drawing excessive coarse sediment. After a series of model experiments, in which the directions of flow of surface, mid-depth, and bed water were clearly seen, the old diversion was closed, a bend was formed in the river, and a new approach channel (with a diversion on the concave bank) was provided for the Mithrao. The remedy was so effective that a canal with a diversion from the river downstream began to draw excessive sediment, and further measures had to be taken to increase the proportion of sediment drawn by the Mithrao.

It is to be noted that the control of sediment load by the curvature of flow requires a "normal" velocity distribution decreasing from a maximum at the surface to a minimum at the bed. If the velocity is equalized by a contraction of

In describing an adjusted or balanced stream, the author states that material caved from a 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 is caved. This is indeed a statement that will be strongly supported by many river engineers and one which is largely derived from the experiments of J. F. Friedkin.[9] It is essentially correct in so far as the material moving along the bed, which is the basis of Captain Friedkin's studies, is concerned. It is also correct that caving and deposition through a reach must be equal if the reach remains in balance. It cannot be postulated, however, that bed material in suspension will not be carried through long reaches, or that the availability of sand size material in transport at any point is dependent upon the caving of a bend or bends upstream. Even in a stream having fixed banks, the bed-material size of sediments introduced into the head of a reach may continue downstream indefinitely, depositing or being lifted into suspension locally as the flow varies.

C. P. Lindner,[21] M. ASCE.—The hope that continued study and discussion would shed more light on the phenomena treated—so that, eventually, analytical methods will be developed that will assure reasonably accurate design—was implied by the writer in the conclusions to his paper. The discussions that have been presented have contributed toward that end. They have enhanced the value of the paper, and have made it more nearly complete. These discussions have also supplemented the information and data presented, and have indicated instances in which a knowledge of the phenomena has been successfully used, and the discussers have pointed out avenues for future investigation.

In discussing the determination of the effect on downstream flow of the withdrawal of water through a floodway or other diversion, Mr. Blench has asked that the writer indicate the volume of storage assumed and the characteristics of the body of water to which this storage would apply. The storage in the reach for a given elevation at the outflow point changes when the floodway operates. Even if the storage were related to the water surface elevation at the midpoint of the reach, the fact that a sloping stream was used with an unequal distribution of water surface area along its path would cause the storage for any elevation with the floodway operating to be different from the storage for the same elevation with the floodway not operating. It is believed that little purpose would be served by utilizing space to present 2 stage-storage or discharge-storage curves that do not apply to any specific river reach. The storage areas used varied with outflow stage from about 1,000,000 acres to 2,000,000 acres. This would correspond to a large reach on the Mississippi River, probably including a backwater area. Such reaches are used regularly with excellent results in routing flows through that stream.

As an example that may serve to relate quantities and effects in the readers'

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

[21] Chf. Engr., South Atlantic Div., Corps of Engrs., U. S. Dept. of the Army, Atlanta, Ga.

of flow was almost reversed. In this latter instance it might be anticipated that the flow regimen could be so changed locally that more of the sediment would be carried past the diversion.

In respect to diversions in which the bottom is considerably higher than the bottom of the channel, the author states that the diversion will of necessity derive its waters from the higher levels of the stream, and that little bed load will be diverted. In so far as the material traveling along the bed is concerned, he may be essentially correct. Large volumes of sand deposited on farm lands flooded by the Kansas and Missouri rivers indicate, however, that sand may be diverted at high levels. Large volumes of sand have also been noted below levee crevasses on the lower Mississippi River, but the evidence as to the immediate source of this material is inconclusive.

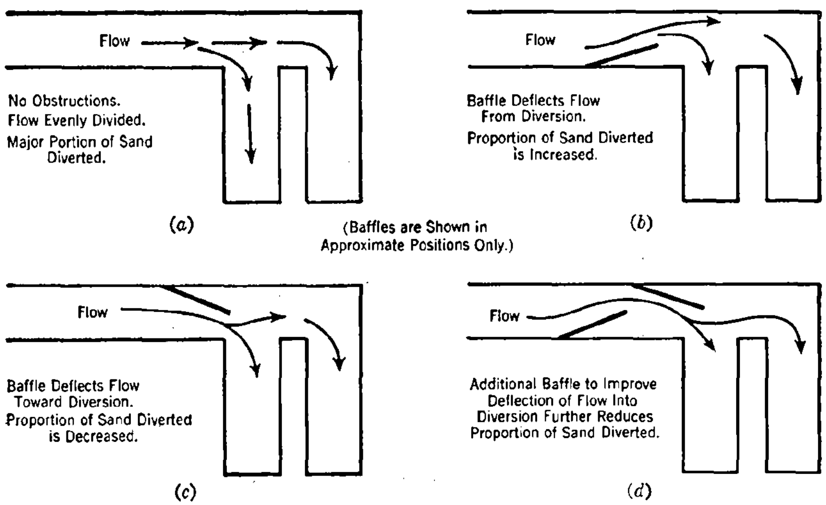

FIG. 14.—SAND BED FLUME WITH DIVERSION CHANNEL TO ILLUSTRATE DIVERSION OF SEDIMENTS

For demonstrating the diversion of sediments to his students at the University of California, at Berkeley, H. A. Einstein, M. ASCE, has used a very simple device (Fig. 13(*a*)), consisting simply of a diversion take-off at 90° and approximately equal division of flow. The student measures the quantities of sand transported, finding that the proportion diverted is much higher than the proportion of water. He is then asked to place deflectors in such a manner as to reverse the proportions of sediment, and on the first trial he usually tries to deflect the current from the diversion (Fig. 13(*b*)), which results in an even higher proportion of sediment diverted. It is only after the deflectors are so placed that the current is deflected into the diversion (Fig. 13(*c*)) that he finds the lesser part of the sediment being diverted. The least diversion of sediment occurs with two or more baffles arranged so that the current flows almost directly into the diversion outlet (Fig. 13(*d*)).

the channel immediately upstream from the diversion, excessive turbulence, or other cause, or if the sediment distribution is equalized, the sediment load will be divided in nearer proportion to the discharge. Models provide an excellent qualitative indication of what is likely to occur in the prototype, but as curvature effects are usually exaggerated in vertically exaggerated models, the effect of scales must be considered in judging the results.

D. C. BONDURANT,[19] A. M. ASCE.—The author's presentation of the withdrawal of sediment by diversion focuses attention on a phenomenon which is too frequently neglected in the planning of diversion systems. In distinguishing so sharply between bed load and suspended load, however, he has tended to obscure an important phase of the action. His description of the nature of the phenomenon would have been strengthened by greater emphasis on the role of the slower currents in the lower levels of the flow.

In his statement that Red River sand is rather fine, so that some sand may have been carried in suspension, the author infers that only fine sands may be carried in suspension. He proceeds from this inference to the statement that sand in suspension would divide approximately in proportion to the division of water quantities. This is in line with his prior concept that suspended load, as differentiated from bed load, divides at a diversion approximately in direct proportion to the division of water quantities. Actually, the suspension may contain sand ranging in size from fine to coarse. These sands are ordinarily found in greater quantities near the bed of the stream, with the concentration decreasing toward the surface. As noted by the author, the slower currents near the bed are the more easily diverted, and since the concentration of suspended sands is greater at that level, the suspension also contributes to the imbalance of the diversion.

The distribution of suspended sediments in a stream is a function of the size of sediments, turbulence of the flow, and material available. Materials in the size range of silts and clays, which settle in water in accordance with Stokes' law, are normally found to be evenly distributed throughout the flow. The finer sands may be fairly well distributed, but will be found in somewhat greater quantities near the bed. With the increasing size of the particle, the distribution becomes more unbalanced, and the proportion found at the lower levels of the suspension increases. With the increasing turbulence of the flow, the distribution of the sands in suspension becomes more even. At some stages of the flow, material that normally travels in the form of dunes along the bed is swept into semisuspension, traveling as a fluid mass near the bed.

The distribution of sand-size sediments, as measured in the Missouri River near Omaha, Nebr., on October 18, 1951, is shown in Fig. 13, together with the velocity distributions and the bed material distributions determined with each series of measurements. These distributions (which are typical of a large number observed) were made from a boat anchored in a straight reach of open river which was relatively free from extraneous influences. Measurements were made at the depths shown on the velocity curve, velocities being observed

[19] Head, Sediment Section, Missouri River Div., Corps of Engrs., U. S. Dept. of the Army, Omaha, Nebr.

with a Price type current meter and sediment being sampled with a point-integrating (P-46) sampler.[20] Bed material samples were obtained at each vertical with a BM-48 (clamshell type) sampler which samples only the top 2 in. of the bed. The two verticals shown were measured on the same day at different points on the same cross section, and the two are presented to illustrate the variation of the distribution of sediments with the variation in turbulence of the flow. The measured data, plotted logarithmically by size fractions, fol-

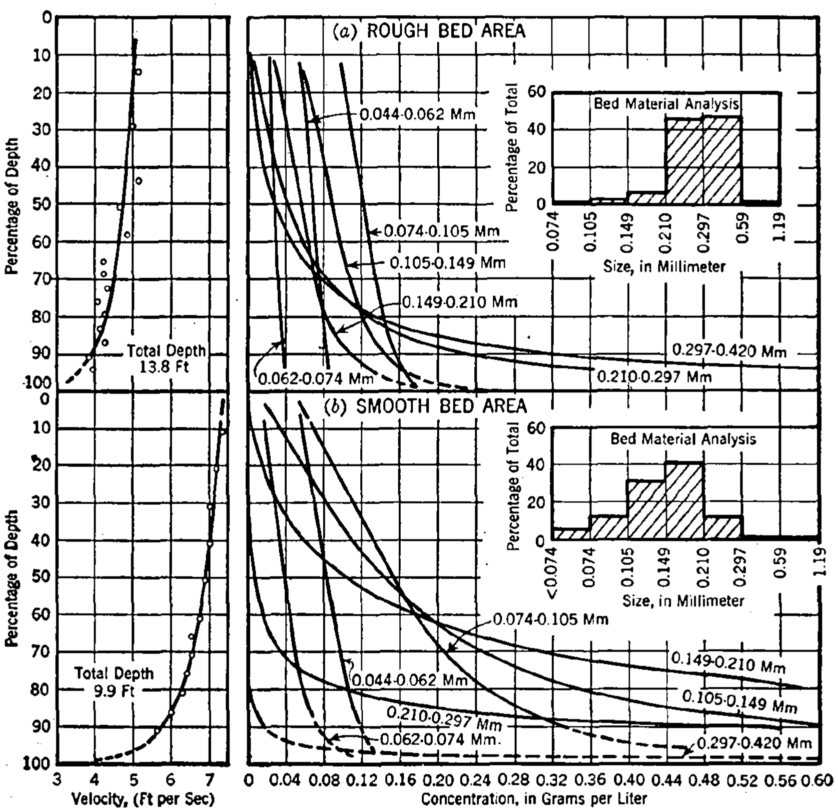

FIG. 13.—DISTRIBUTION OF SEDIMENT AND VELOCITY, MISSOURI RIVER AT OMAHA, NEBR.

lowed very closely a straight-line plot which was extended to obtain the concentrations below the lowest points measured (dashed parts of the curves). In the examples presented, materials finer than 0.044 mm are not shown.

It will be noted that the concentrations of the larger sand sizes increase as the bed is approached, and that this proportionate increase is greater as the size of the particle increases. There is also a distinct correlation between

[20] "Measurement and Analysis of Suspended Sediment Loads in Streams," by Martin E. Nelson and Paul C. Benedict, *Transactions*, ASCE, Vol. 116, 1951, p. 910, Fig. 11.

the predominant sizes of the sand-size material in suspension and the predominant sizes of the bed material. This latter correlation is emphasized when it is noted that it exists in both the examples shown, although the predominating sizes are at variance between the two. It is suggested that the bed samples are each representative of a fairly extensive bed area, rather than of a point, since each vertical was selected so as to be in an area of similar bed characteristics sufficiently extensive to permit the suspension to be representative. It is anticipated that the distribution of the sediment in any vertical would be representative of a part of the bed sufficiently far upstream to permit turbulent exchange to be completed.

The distribution of suspended materials tends to vary with the velocity distribution, which in turn is correlated with the rugosity of the bed. In the rough bed area, a condition of more fully developed turbulence is approached, and the distribution of both velocity and sediments tends to be more uniform. Actually, all the data shown in Fig. 13 follow closely the theoretical concepts developed by fluid mechanics, except that it becomes necessary to vary some parameters due to extraneous influences such as cross currents.

The foregoing exhibits and discussion are believed to support the concept that many of the materials forming the bed of an alluvial stream are transported not only along the bed, but also in suspension. The proportion of these materials transported, in accordance with their availability in the bed, decreases both with size and with distance above the bed, with the predominant portion of the materials being transported in the lower levels of the stream where the velocities of the flow are the least. It is easily shown by momentum concepts that where a stream is divided, the lower velocity components will turn most readily. It follows that the greater proportion of the sand size and the larger materials will be transported along the division having the largest deviation in direction. The silt and clay sizes, and often the finer sands, being more evenly distributed, will be divided in proportion to the division of the flow. The sand sizes will be more nearly divided in proportion to the flow in a highly turbulent section and less evenly divided as the flow becomes more quiet.

In a curved channel, it becomes necessary to consider the distribution of flow in the channel as well as in the vertical. Here, the deviation from a straight line is least on the outside, or concave, part of the bend and greatest toward the inside, or convex, part. As a result, the higher velocity flow near the surface tends to follow the outside path, whereas the slower currents near the bottom turn more readily to the inside path, carrying the heavy sediment load and often depositing a portion of it as a point bar. A diversion placed on the outside of a bend would have little opportunity to receive the coarser sediments even though it diverts the slower currents in the adjacent vertical. A diversion placed on the inside of the bend should receive a very high proportion of the sediment.

In a diversion having a minor take-off angle, the proportion of sediment diverted should be more nearly equivalent to the proportion of water diverted, since momentum forces would not be so predominant. With greater angles of diversion, however, it is doubtful that the degree of turn would affect the division of sediment radically until a point was reached at which the direction