FLUVIAL PALEOCHANNELS

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ABSTRACT

The width (w), depth (d), meander wavelength (l), gradient (s), shape (w/d), and sinuosity (P) of stable alluvial river channels are dependent on the volume of water moving through the channel (Q_w) and the type of sediment load conveyed through the channel (Q_s).

$$Q_w \propto \frac{w, d, l}{s}$$

and

$$Q_s \propto \frac{w, l, s}{dP}$$

Empirical equations developed from data collected along modern alluvial rivers permit calculation of the effects of changes of hydrologic regimen (Q_w, Q_s) on channel morphology. Conversely, these relations permit estimation of paleochannel gradient, meander wavelength, sinuosity, and discharge from the dimensions of the paleochannel as exposed in cross section.

The recognition of paleochannels within valley-fill or other complex fluvial deposits is a major problem, but criteria for the delineation of paleochannel cross-sectional shape and dimensions have been developed from studies of shapes and sediment characteristics of Australian paleochannels.

INTRODUCTION

Numerous detailed studies of modern river systems have been made by geomorphologists, civil engineers, and sedimentologists, and one would assume that a means of predicting both the third-dimensional character as well as the hydrology of a paleochannel from information obtained at an exposure of the channel cross section in outcrop is possible. This sanguine expectation, however, has not been realized due primarily to two factors. First, the statistically significant relations between channel morphology and water discharge are not sufficiently accurate for predictive purposes. As an example, a range of 50 to 100,000 cubic feet per second was obtained when Moody-Stuart (1966, p. 1113) used channel depth to estimate discharge in paleochannels of Devonian age in Spitsbergen. Secondly, the student of modern river systems frequently finds that the paleochannels of interest to his geological colleagues are an order of magnitude larger than anything that is familiar to him. Most modern alluvial rivers flow in wide valleys and on valley-fill deposits that may be hundreds of feet thick; therefore, an explanation would seem to be that in one case we deal with a stream channel and in the other with a valley-fill deposit. For example, a comparison of river and valley meanders reveals that valley meander wavelength is about ten times that of the river which occupies the valley (Dury, 1964).

The research of the fluvial geomorphologist is aided by the complete exposure of the object of his study. He can obtain complete data on channel morphology, but it is a rare occasion when he has the opportunity to observe the sedimentary deposits that comprise a flood plain and valley-fill. Conversely, paleochannels are commonly observed only in cross section or they can be studied in even less detail from a series of well logs. Hence, a stream channel may be difficult to distinguish within a larger valley-fill deposit, and therefore, quantitative geomorphic relations may be of limited use.

In spite of the pessimistic statements made above, procedures for the estimation of the third dimensional character of paleochannels (gradient, meander wavelength, sinuosity) and the hydrology of the system (mean annual discharge, mean annual flood) will be developed and evaluated.

ACKNOWLEDGMENTS

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FLUVIAL MORPHOLOGY

The morphology of river channels and their adjustment to changing hydrologic and hydraulic conditions have long been of interest to man. Most of the relevant literature on this subject is reviewed in Leopold, Wolman and Miller (1959) and Morisawa (1968). All studies confirm the fact that the greater the quantity of water moving through a river channel the larger will be the size of that channel. In general, as water discharge (Q_w)[1] increases, width, depth, and meander wavelength increase and gradient decreases. Usually with increasing discharge downstream channel width and depth increase (Leopold and Maddock, 1953). However, if discharge did not increase in a downstream direction then neither would channel width and depth. The Finke River of Central Australia provides an example of this reversal of downstream trends. Near its headwaters west of Alice Springs, the river is 380 feet wide and 6 feet deep, but about 250 miles downstream at Finke it is 250 feet wide and 4 feet deep. Further downstream a progressive decrease in size occurs until the channel eventually disappears in the sands of the Simpson Desert. Thus, size changes in a downstream direction are, indeed, dependent on discharge. If discharge decreases, when a river flows into a progressively more arid region, the dimensions of the channel will decrease.

The nature of the sediment load moved through the channel also has a significant effect on channel morphology, and an attempt has been made to classify alluvial channels on the basis of the type of sediment load that is moved through the channel (Schumm, 1968). On Table 1 three types of stream channels are distinguished as follows: relatively narrow, deep and sinuous suspended-load channels that on the average transport less than three percent of sand size or larger sediment; relatively wide, shallow, and straight bedload channels that on the average transport greater than eleven percent of sand size or larger sediment; and mixed-load channels which have morphologic and sediment characteristics intermediate between these two end members. There apparently is a continuous series of channel types both single and multiple, depending on the nature of the sediment load moved through the channel.

Analysis of data collected at 36 river cross sections in Australia and on the Great Plains of the western United States supports this classification. For example, it has been demonstrated that channel shape expressed as a width-depth ratio (F) and channel sinuosity (P) are controlled primarily by the type of sediment load, such that a bedload channel has a high width-depth ratio but low sinuosity (Schumm, 1963). Numerous other studies have demonstrated that channel width (w), depth (d), gradient (s), and meander wavelength (l) are related to water discharge (Q_w) as follows:

$$Q_w \propto \frac{w, d, l}{s} \tag{1}$$

The above relation indicates that channel width, depth, and meander wavelength will increase with an increase in discharge, but channel gradient will decrease. However, for a constant discharge a change in the average quantity of bedload (Q_s) moved by the stream, that is the percentage of the average total load that is sand size or larger (percentage of bedload), is related

[1] See appendix for definition of symbols.

TABLE 1.—CLASSIFICATION OF STABLE ALLUVIAL CHANNELS

Type of sediment transport	Channel sediment (percentage of silt and clay)	Bedload (percent of total load)	Type of River: Single Channel	Type of River: Multiple Channel
Suspended load and dissolved load	20	<3	Suspended-load channel. Width-depth ratio less than 10; sinuosity greater than 2.0; gradient relatively gentle.	Anastomosing system
Mixed load	5–20	3–11	Mixed-load channel. Width-depth ratio greater than 10, less than 40; sinuosity, less than 2.0, greater than 1.3; gradient moderate. Can be braided.	Delta distributaries Alluvial plain distributaries
Bedload	5	>11	Bedload channel. Width-depth ratio greater than 40; sinuosity, less than 1.3; gradient relatively steep. Can be braided.	Alluvial fan distributaries

to channel morphology as follows:

$$Q_s \propto \frac{w, l, s}{d, P} \quad (2)$$

Equation 2 shows that as the sand load or bedload (Q_s) increases, channel width (w), meander wavelength (l), and gradient (s) increases, whereas channel depth (d) and sinuosity (P) decrease. Width-depth ratio will increase under these conditions.

The above generalizations, which are based on the statistical analysis of data from very different types of rivers (Schumm, 1968), suggest that a change in discharge and type of sediment load will induce major adjustments of river morphology. Except under controlled laboratory conditions, a change in discharge will be accompanied by a change in the type of sediment load. The channel response to these changes will be complex. For example, if both discharge and percentage of bedload increase (direction of change of each variable is indicated by a plus or minus exponent), channel morphology will be affected as follows:

$$Q_w^+ Q_s^+ \propto \frac{w^+ l^+ F^+}{P^-} s \pm d \pm \quad (3)$$

The effects of increased discharge and percentage of bedload combine to increase channel width, meander wavelength, and width-depth ratio and to decrease sinuosity. However, their effects are opposed so that an increase in discharge will act to decrease gradient and increase depth, but an increase of bedload will increase gradient and decrease depth. The ultimate changes depend on the magnitude of the changes of discharge and type of sediment load, but in the above case if sinuosity decreases then gradient should increase, and if both width and width-depth ratio increase then depth should decrease or remain unchanged. Of course, if both discharge and percentage of bedload decrease, their effects would be the opposite of these shown by equation 3. For a discussion of the effects of other changes of water and sediment discharge on channel morphology, see Schumm (1969).

The influence of water discharge and type of sediment load on alluvial channels has been demonstrated by an analysis of data collected from rivers on the Great Plains of the United States and along the Murrumbidgee River of New South Wales, Australia. In these studies (Schumm 1968, 1969) the percentage of silt and clay (sediment finer than 0.074 mm) in the perimeter of the channels (M) was used as an index of type of sediment load (Q_s). The relation is inverse with high silt-clay content being characteristic of low percentage of bedload (Table 1). Empirical equations were developed which are statistically very significant and which can be used to predict channel morphology from the discharge and the percentage of silt and clay in the bed and bank sediments. The empirical equations are based on data obtained from rivers that transport only sands, silts and clays in a stable (no progressive aggradation or degradation) alluvial channel composed of sediments that are moving through the channel. In addition, the channels are not located near the coast, and all are in subhumid or semiarid environments.

ESTIMATE OF PALEOCHANNEL MORPHOLOGY AND HYDROLOGY

The independent variables that influence the morphology of both modern and ancient channels are water (Q_w) and type of sediment load (Q_s). Obviously data on water discharge and type of sediment load are not available for paleochannels, and it is necessary, therefore, to attempt to estimate these variables from information that can be obtained from cross sections of the paleochannel. A possible solution to these difficulties is at hand. The width-depth ratio (F) of modern channels is closely related to channel silt-clay content (M) as follows:

$$F = 225\, M^{-1.08} \quad (4)$$

Width-depth ratio, therefore, can be substituted for M and will reflect the nature of the sediment in the paleochannel as well as the type of sediment load. Channel cross-sectional area should be a useful index of discharge when combined with width-depth ratio. For the rivers from which the basic data were obtained, channel width is significantly related to channel cross section and to discharge, as other investigators have demonstrated (e.g., Leopold and Maddock, 1953). Although not independent variables, channel width and depth are significantly related to other morphological characteristics of a channel and to its hydrology. Therefore, an estimation of paleochannel gradient, meander characteristics, and hydrology can be obtained by using width-depth ratio as an index of type of sediment load and width as an index of discharge.

Multiple regression analyses of width-depth ratio (F) and channel bankfull width (w) on meander wavelength (l) and gradient (s) were performed. The equations obtained are as follows:

$$l = 18\,(F^{.53} w^{.69}) \quad (5)$$

or in log form

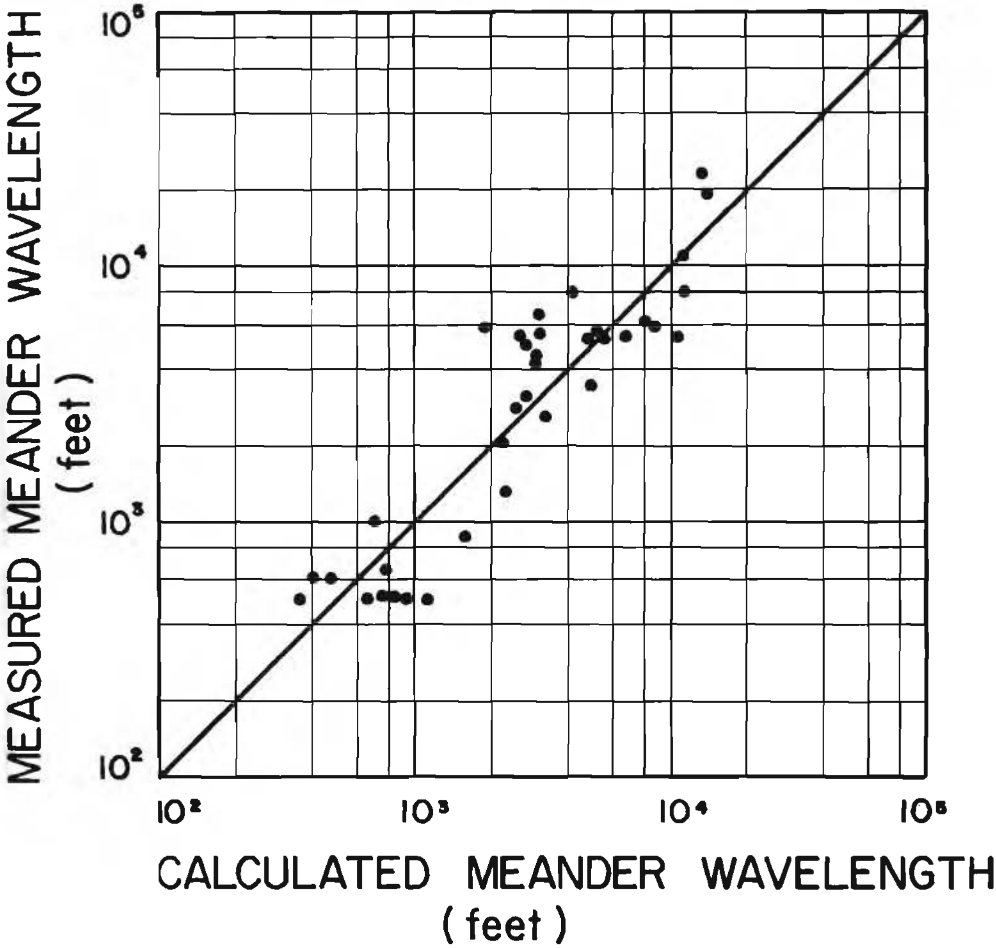

FIG. 1.—Relation between measured meander wavelength and calculated meander wavelength. Meander wavelength was calculated by use of equation 5.

$$\log l = 1.27809 + 0.52822 \log F + 0.68774 \log w$$

$$r = .91$$

$$Se = .21 \text{ log unit}$$

$$s = 30\left(\frac{F^{.95}}{w^{.98}}\right) \quad (6)$$

or in log form

$$\log s = 1.48085 + 0.94774 \log F - 0.87937 \log w$$

$$r = .84$$

$$Se = .16 \text{ log unit}$$

In the above equations width-depth ratio is directly related to meander wavelength and gradient. Width is directly related to meander wavelength and is inversely related to gradient, and these are the expected relations. That is, an increase in width-depth ratio reflects a greater percentage of bedload, which is associated with a larger wavelength and gradient. Channel width increases with discharge, which is associated with a larger wavelength but smaller gradient.

In order to show graphically the accuracy of the predicting equations, calculated and measured values of meander wavelength and gradient are plotted on figs. 1 and 2. The plotted points fall within a half log cycle, and it is doubtful that a better relation can be obtained with the present state of knowledge concerning river morphology.

Multiple regression equations of width-depth ratio (F) and channel bankfull width (w) on mean annual flood (Qma) and mean annual discharge (Qm) were performed. The equations obtained are as follows:

$$Qma = 16\left(\frac{w^{1.56}}{F^{.66}}\right) \quad (7)$$

or in log form

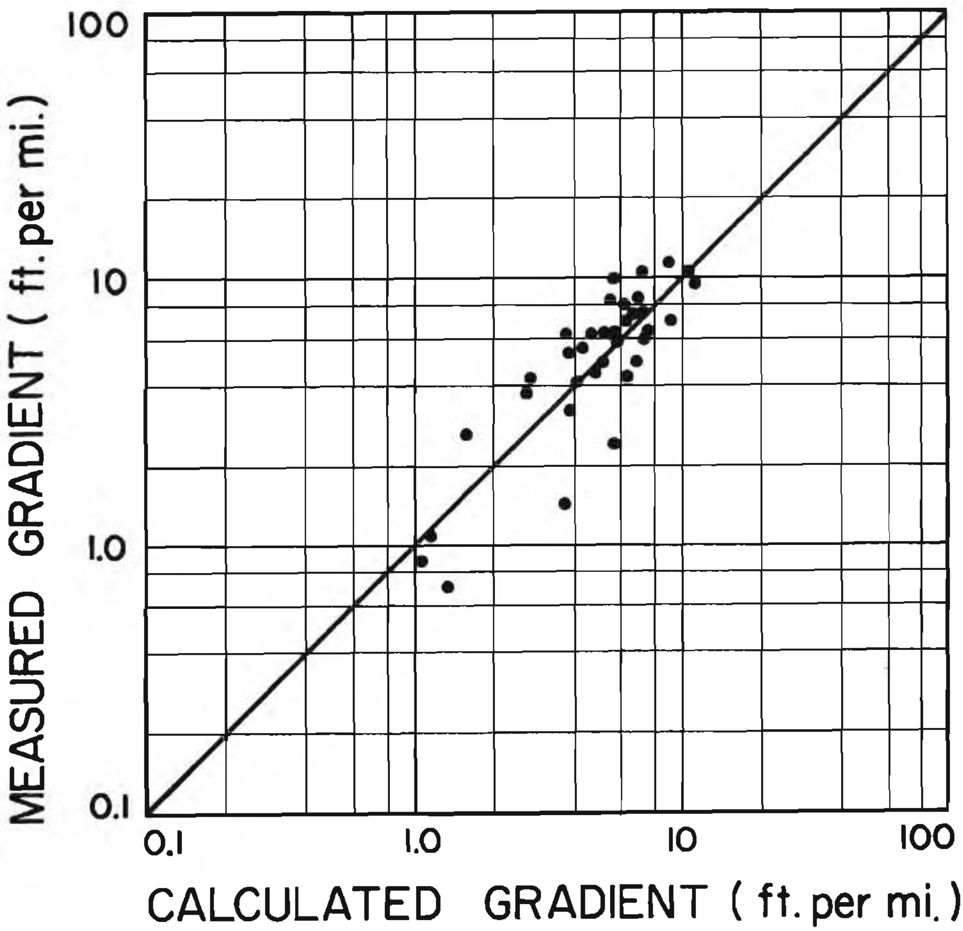

FIG. 2.—Relation between measured channel gradient and calculated gradient. Gradient was calculated by use of equation 6.

$$\log Qma = 1.19416 - 0.66227 \log F + 1.55584 \log w$$

$$r = .90$$

$$Se = .20 \text{ log unit}$$

$$Qm = \frac{w^{2.43}}{18\, F^{1.13}} \qquad (8)$$

or in log form

$$\log Qm = -1.24661 - 1.13327 \log F + 2.42853 \log w$$

$$r = .90$$

$$Se = .31 \text{ log unit}$$

As expected, discharge is directly related to width in equations 7 and 8. Width-depth ratio previously has not been found to be dependent to a major extent on discharge; therefore, the inverse relation of width-depth ratio to discharge in equations 7 and 8 requires explanation. Both equations reduce to an approximation of channel area. Channel area is, of course, closely related to discharge.

The plot of calculated versus measured mean annual flood is truly impressive (fig. 3). It is generally agreed that the channel-forming discharge is a discharge that approaches bankfull; therefore, mean annual flood should bear a close relation to channel dimensions. This is demonstrated by the plot of Figure 3, except for one point located at the lower end of the plot. In this case the calculated mean annual flood is 5 times that of measured mean annual flood. The explanation seems to be that this river drains from the Sand Hills of Nebraska, and it is fed primarily by ground water. The discharge of this channel is very regular and flood peaks are not high. Nevertheless the channel is relatively wide and has a high width-depth ratio as a result of a high sand load. This combination yields an erroneously high estimate of mean annual flood. Such an error probably will occur only in the unusual situation of a stream that is dominated by ground water discharge from a drainage basin of high permeability.

The plot of calculated versus measured mean annual discharge (fig. 4) is less impressive and

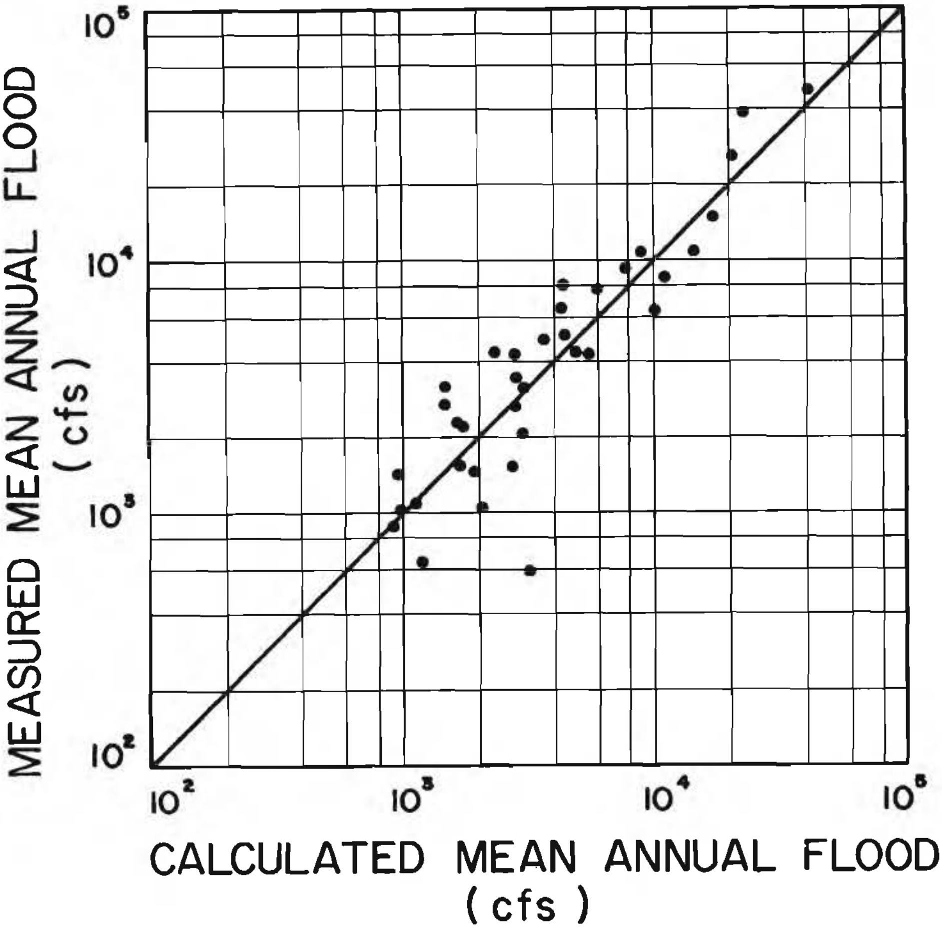

FIG. 3.—Relation between measured mean annual flood and calculated mean annual flood (recurrence interval of 2.33 years). Mean annual flood was calculated by use of equation 7.

appears to reflect a climatic influence. If as stated above the dimensions of a channel are established primarily by a flood event, then mean annual discharge will be less closely related to channel morphology than will the mean annual flood. This occurs because two channels, one carrying infrequent ephemeral flow and the other carrying perennial discharge, can both have similar dimensions dependent on a near bankfull discharge. At the lower end of the plot of Figure 4 scatter is greatest. All of the points in the upper half of the plot cluster closely about the line, and these points represent perennial streams. Those that fall well below the line in the lower half of the plot are ephemeral streams draining semiarid regions. The equation yields a much higher estimate of mean annual discharge than is appropriate for ephemeral-stream channels. Therefore, if evidence exists that a paleochannel is associated with a dry climate, an estimate of mean annual discharge based on equation 8 should be reduced by one-half.

The statistical relations are very good and suggest that if paleochannel width and depth can be obtained at an outcrop or from well data, then an estimate of both paleochannel gradient, meander characteristics, and hydrology can be obtained.

It is possible to obtain additional information concerning paleochannel hydraulics. For example, if mean annual flood (Qma) is considered to be approximately equal to bankfull discharge, then when it is divided by channel area (A) an estimate of the velocity (V) of flood discharge is obtained as follows:

$$V = \frac{Qma}{A} \tag{9}$$

Information can also be obtained concerning the valley through which the paleochannel flowed. Sinuosity (P) is the ratio of valley

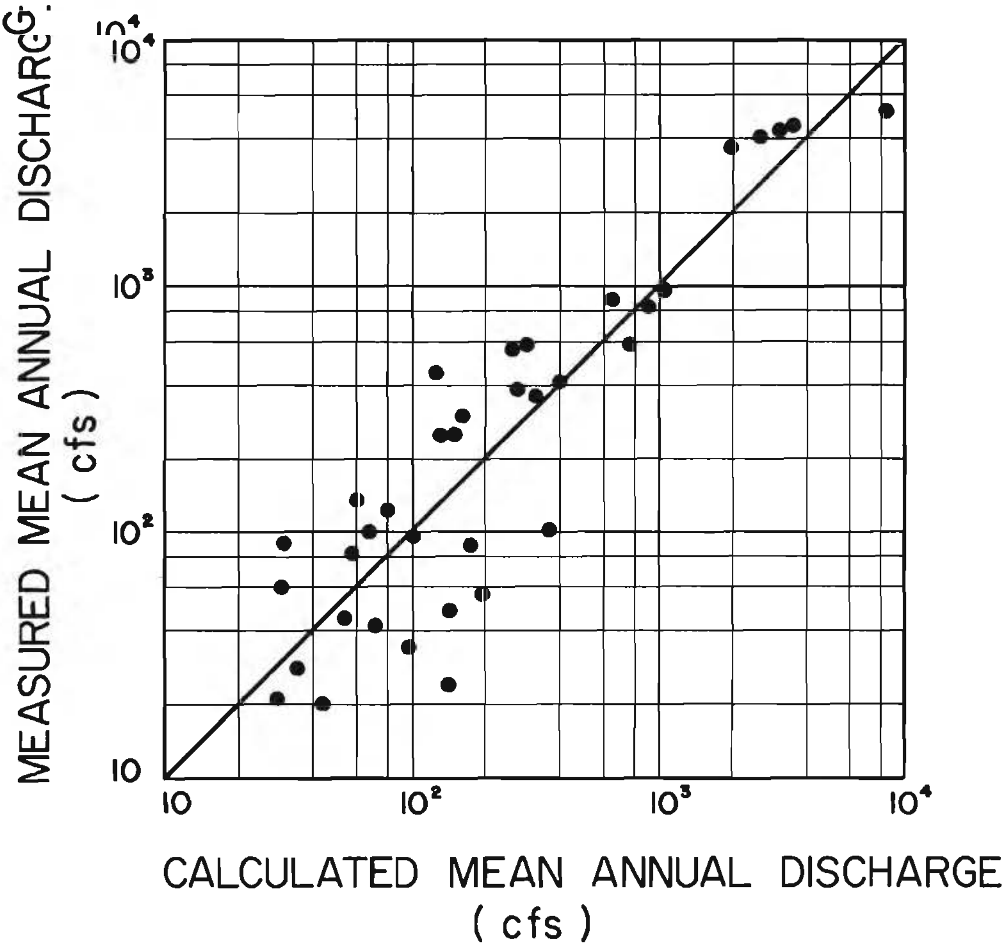

FIG. 4.—Relation between measured mean annual discharge and calculated mean annual discharge. Mean annual discharge was calculated by use of equation 8.

gradient (Sv) to channel gradient (s). An estimate of sinuosity from width-depth ratio alone can be obtained as follows:

$$P = 3.5 \quad F^{-.27} \tag{10}$$

Depending on the history of the river system any estimate of sinuosity can involve major errors (Schumm, 1963). However, when gradient (s) is calculated from equation 6, the slope of the surface over which the paleochannel flowed, the valley gradient, (Sv), can be obtained as follows:

$$Sv = s.P \tag{11}$$

Further, an estimate of meander wavelength from equation 5 provides the spacing between meanders. Combined with an estimate of sinuosity a fair picture of the pattern of a paleochannel can be developed.

Determination of Paleochannel Dimensions

The problem of distinguishing between a paleochannel and valley-fill deposits is a major one. Unless the dimensions of a paleochannel can be obtained, the quantitative relations developed for modern rivers cannot be applied to paleochannels.

One means by which it may be possible to set limits to the dimensions of fluvial paleochannels is based on a comparison of channel size. The largest river in the world today is the Amazon. It drains an area of 2.3 million square miles with an average annual precipitation of 80 inches. The width of the Amazon ranges from 1 to 3 miles and the depth from 20 to 300 feet along the lower 900 miles of its course. At Obidos, where the U. S. Geological Survey has made measurement of discharge, the channel is 200 feet deep and about 7500 feet wide (Oltman, *et al.*, 1964).

In contrast, the Mississippi River, the world's fourth largest, (Morisawa, 1968), is about 2000 feet wide and 60 feet deep at Vicksburg. These channels are enormous, but they need to be in order to transport an average flow of about 5.5 million cfs and 0.75 million cfs respectively. The Amazon, in fact, transports 15 percent of all the fresh water running off to the oceans. It is unlikely that there are many paleochannels that have accommodated discharges of this magnitude, and most would probably be very much smaller, for example, on the order of a few hundred feet wide and up to 20 feet deep. Information on the dimensions of some paleovalley deposits (Table 2) reveals that most are smaller than the Amazon and Mississippi Rivers, but if they are assumed to be paleochannels they must have drained enormous areas of high rainfall. In many instances such huge source areas did not exist.

There can be little doubt that many paleochannel deposits are, in fact, valley-fill deposits composed of sediments deposited in a shifting and/or aggrading channel (see for example Rubey and Bass, 1925; Friedman, 1960; Howard and Showe, 1965; Siever, 1951; Charles, 1941; Lins, 1950). John Harms (1966) has made very clear that the "J" sand which is about 2400 feet wide and 60 feet deep is a valley-fill deposit. How then is it possible to identify and relate the dimensions of a paleo-river channel to the paleohydrology of the system? The answer lies in the fact that, although the relations between climate and runoff may have changed through geologic time, the laws of hydraulics did not. A flood was and is capable of moving only certain volumes of sediment of a given size range. Colby's (1964a, 1964b) work provides a basis for the estimation of sand load and bed scour during floods. Of major importance here is his conclusion that the scour of a channel during floods is not great. Certainly the evidence from paleochannels, where crossbedded units are on the order of a foot thick, indicates that the channel was not capable of setting in motion the previously deposited sediments to any great depth. Therefore, a channel must have occupied several positions in a valley. At one stage it must have flowed near the floor of the valley while eroding the bedrock floor, but when the upper few feet of fluvial sediment was being deposited, the channel was flowing across the upper surface of the valley-fill deposit just as the rivers of today commonly are flowing on valley-fill sediments that may be in excess of 100 feet. Nevertheless, the problem of identification and delineation of a paleochannel cross section in a paleovalley deposit remains.

TABLE 2.—PALEOVALLEY DIMENSIONS

Channel	width	depth (feet)
J channel (Harms, 1966)	1500 ft.	50 ft.
Rocktown channel (Rubey and Bass, 1925)	0.5 mile	25 (range 15–100 ft.)
Indiana channels (Friedman, 1960)		
New Goshen	0.5 mile	40
Terre Haute	0.25 mile	40
Winslow	2600 ft.	50
Englevale channel (Howard and Schowe, 1965)	0.5 mile	60
Pre-Pennsylvanian channel (Siever, 1951)	3.75 mile	200+
Bush City channel (Charles, 1941)	1000 to 2000 ft.	55
Tonganoxie channel (Lins, 1950)	14 miles	1000

An example will be used to demonstrate that estimates of paleochannel width and depth can be made. On the aerial photograph of Figure 5, a Holocene paleochannel on the Riverine Plain of New South Wales, Australia is visible. Borings into this channel reveal a lens-shaped sand deposit much like those described by stratigraphers investigating more ancient paleochannels (fig. 6). Although the maximum width of this deposit is about 1500 feet, the width of the channel that flowed on the surface of the deposit and that is still visible on the surface of the plain (fig. 5) was about 500 feet.

Several lines of evidence indicate that the Riverine Plain paleochannel was not deeper than about 10 feet, during at least the latter part of its existence (Schumm, 1968, p. 30–36). For example, on bends lateral migration of the channel occurred, planing away the heavy clay of the alluvial plain at a depth considerably less than the maximum thickness of the sand deposit. The sand body is composed of crossbedded sedimentary units which average about one foot thick. This implies that when the stream flowed near the surface of the plain its depth was only a few feet below the contact between overlying fine sediments and the fluvial sand (8 to 12 feet below the surface of the plain, Figure 6). Further, distributary systems related to the major stream are about 10 feet deep (Pels, 1964).

The Australian paleochannels were wide, shallow streams that transported relatively

FIG. 5.—Aerial photograph of paleochannel on the Riverine Plain of New South Wales, Australia. The width of the channel at the surface of the plain is about 500 feet. See figure 6 for cross section of this fluvial deposit. (Photograph courtesy of New South Wales Lands Dept.)

large quantities of sand. They were, therefore, bedload or mixed load channels, according to the classification of Table 1. Quantitative studies of channel morphology reveal that the Australian paleochannels conform to the relations developed between type of sediment load, hydrology, and morphology of rivers of the Great Plains of the western United States. These relations indicate that only a part of the width and a fraction of the depth of the valley-fill deposit can be related to the stream that transported the sediment (fig. 6). Therefore, in most cases the cross-sectional area, width, and depth of a lens-shaped sand body is greater than that of the stream that transported the sediment. If the surface of the paleochannel deposit is flat, then channel width could be that of the sand body, but if the upper surface is convex then the

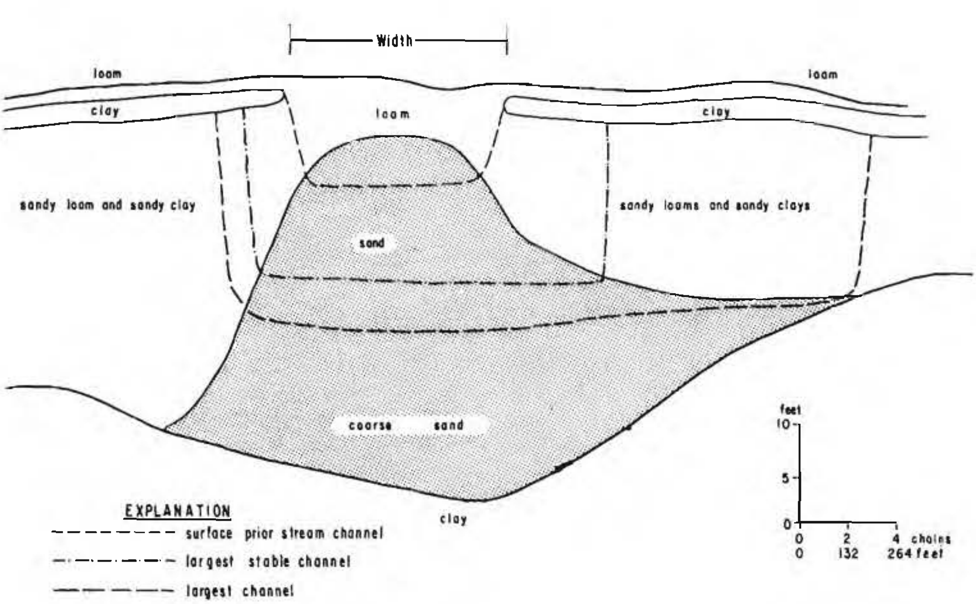

FIG. 6.—Generalized cross section of Australian paleochannel on Riverine Plain of New South Wales from bore data obtained by M. Stannard (from Schumm 1969). Location is just off of eastern edge (right side) of figure 5. Dashed lines show outline of three possible channel cross sections. The smallest is that associated with the channel visible on the surface of the plain. The intermediate and largest cross sections shown are the largest stable cross section and the largest possible cross section that could be associated with an alluvial channel. In each case the depth of the cross sections is considerably less than the depth of the sand body.

width of the channel is probably less than half that of the sand body (fig. 6). As the width-depth ratio of a bedload channel will usually be greater than 40, one may search for evidence of a channel floor at a depth about 1/40 the width of the sand body.

Perhaps other evidence may be found to assist in the delineation of a paleochannel. For example, a pebble layer may be evidence of a commonly achieved depth of scour (Livesey, 1963), or an abrupt change in the texture of the sediment at the top of the channel sand may be evidence of the onset of a final period of paleochannel aggradation (Schumm, 1968, p. 36).

It remains for the stratigrapher to recognize within a fluvial deposit the lateral and vertical extent of the channel. Once this is done then the equations can be used to estimate paleochannel hydrology, gradient, and meander characteristics.

DISCUSSION

Several problems associated with determining the third dimensional character and hydrology of paleochannels have been considered but an important aspect of the problem deserves mention. The apparent exactitude of equations 5 through 8 should not mislead an investigator into assuming that they provide anything but improved estimates of paleochannel character.

Geologists have frequently been intimidated when the apparently conclusive results of other disciplines have been applied to geologic problems with disconcerting results. A reasonable approach to the problems discussed here would be to use the equations to estimate paleochannel discharge, gradient and pattern, but if the estimates are at variance with other geologic evidence, then the geologic evidence should be considered to be of a higher order of significance.

Appendix 1—Definition of Symbols

A	channel cross-sectional area in square feet
d	channel maximum depth in feet
F	width-depth ratio
l	meander wavelength in feet
M	percentage of silt and clay in channel perimeter (sediment finer than 0.074 mm)
P	sinuosity, ratio of channel length to valley length
Qw	water discharge, Qm or Qma, in cubic feet per second
Qs	percentage of total mean sediment load that is sand size or larger (bedload)
Qma	mean annual flood in cubic feet per second
Qm	mean annual discharge in cubic feet per second
s	channel gradient in feet per mile
Sv	valley gradient in feet per mile
V	velocity in feet per second

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