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RIVER METAMORPHOSIS^a

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INTRODUCTION

Engineers and geologists since the origin of their professions have been concerned with rivers, but they have approached their subject with quite different objectives. These are either the control of man's environment or the development of an understanding of earth history through the documentation of river changes through geologic time. Nevertheless, the interchange of information has been significant (8,13),² and this tendency will be reinforced as quantification of the geologist's observations becomes commonplace.

The engineer is only too well aware of the type of channel response that results from his efforts to control river behavior (1,8) and the engineering literature is replete with descriptions of local but rapid channel-response to man's influence. The geologist, on the other hand, recognizes in alluvial deposits and river terraces evidence of the long-term adjustment of entire river systems to the effects of climate change, mountain building processes, and sea level fluctuations (13).

Rivers adjust rapidly to altered hydrologic regimen in the geologic sense, but complete adjustment may not occur during the lifetime of one individual. For example, a comparison of the descriptions of the North Platte River during the last half of the 19th century with modern maps leads one to conclude that, during the last 100 yr, significant changes in the geometry of this channel have occurred from the Wyoming-Nebraska State line eastward through 8° of longitude. Therefore, one objective of this presentation is to demonstrate that, with time, a complete transformation (metamorphosis) of river morphology may be the consequence of river regulation. That is, although the imme-

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² Numerals in parentheses refer to corresponding items in the Appendix II.—References.

diated morphologic result of dam construction is local and is generally manifested by channel degradation, geologic evidence suggests that the influence of regulatory and diversion structures may cause a complete alteration of river channel morphology throughout the length of a river system.

The adjustment of channel gradient to changed water and sediment discharge has received thorough treatment by those concerned with river dynamics. However, both Mackin (13) and Rubey (16) have considered, in addition, possible changes of channel cross section, and Lane (8) was also aware of the need to investigate this aspect of river metamorphosis.

Leopold and Maddock (11) have shown the influence of mean annual discharge on channel width and depth, and Leopold and Wolman (12), Dury (4) and Carlston (3) have discussed the effect of discharge on meander dimensions. Further, Leopold and Maddock (11) have suggested how suspended sediment load and bedload affect channel dimensions, and they have concluded that rivers can adjust to changes in discharge of water and sediment, not only by a change in gradient but also by adjustments of channel width and depth.

Other studies have demonstrated that channel width, depth, and width-depth ratio are related to the nature of the bed and bank material (17,22). Further consideration of the nature of the bed and bank materials in stable, alluvial channels, that are transporting primarily clay, silt, and sand leads to the obvious conclusion that the sediment forming the perimeter of a stable alluvial channel reflects the type of sediment being moved through the channel (18,19).

Herein, empirical relationships between channel characteristics, water discharge, and the type of sediment load moved through a channel will be presented. These relations can then be used to deduce how channels will adjust to alterations of hydrologic regimen. Finally, field examples of both geologic and historic river metamorphosis will be cited in support of the postulated adjustments of rivers to altered hydrologic regimen.

CONTROLS OF CHANNEL MORPHOLOGY

The dimensions, shape, gradient, and pattern of stable alluvial rivers should be controlled by the quantity of water and quantity and type of sediment moved through their channels. To investigate these interrelations, information on the channel geometry and sediment characteristics of 36 stable alluvial rivers was collected in the field, and hydrologic data were obtained from the records of nearby gaging stations (20).

All of the channels are located in the semiarid to subhumid regions of the Great Plains of the United States of the Riverine Plain of New South Wales, Australia. Each is formed of sediments transported by the river itself and none of the channels contain more than about 10% gravel (see Appendix I.—Basic Data).

The channels are defined as stable because they have shown no progressive channel adjustment during the last 10 yr of record, and they are described as alluvial channels because their bed and banks are composed of sediment that is being transported by the river. Mean annual discharge, Q_m , and the mean annual flood, Q_{ma} , are used as indexes of the hydrology of each channel.

No relation between channel morphology and the size of the bed and bank sediments was obtained, and this may reflect the small range in bed-material size of these alluvial channels. However, although data on the total sediment

load was available for only five cross sections (20), the percentage of silt and clay (sediment finer than 0.074 mm.) in the sediments forming the perimeter of the channels, M , has been found to be inversely related to the percentage of the total sediment load that is sand or bed-material load, Qt , at mean annual discharge, $M = 55/Qt$. Therefore, this parameter, M , can be used as an index of the ratio of bed-material load to total sediment load, that is, of the type of sediment load moved through the channels. The percentage of silt and clay, M , can be the same for rivers of greatly diverse size and discharge, therefore, when more data on total sediment load becomes available, it may be found to be an index of the quantity of bed-material load, Qs , expressed in ppm or tons per ft of channel width, but only for rivers of comparable mean annual discharge.

Alluvial river channels have been classified according to the type of sediment load moved through them as bedload, mixed-load, and suspended-load channels (19). According to the limited data available, the bedload channels carry more than eleven percent of their total sediment load as sand or coarser sediment (less than 5% silt and clay in channel perimeter). The suspended load channels carry less than about 3% of the total load as sand or coarser sediment (greater than 20% silt-clay in channel perimeter) and the mixed-load channel carries between 3% and 11% of its total sediment load as sand or large sediment (20). The type of sediment load moved through these channels, although not readily measured, can be estimated by the nature of the bed and bank sediment, and type of sediment load is here expressed as the percentage of silt and clay exposed in the perimeter of a channel, M .

The width-depth ratio, F , and the sinuosity (P , ratio of channel length to valley length) have been found to be significantly related to the type of sediment load, M , as follows (17,18)

$$F = 255 M^{-1.08} \quad (1)$$

$$P = 0.94 M^{0.25} \quad (2)$$

The correlation coefficients for both equations are 0.91 and the standard error is 0.20 and 0.06 log units respectively, indicating that both channel shape and sinuosity are determined largely by the type of sediment load moved through the channels.

With data acquired in the field and from gaging station records (20, Appendix I) multiple regression equations were obtained for channel width, w ; depth, d ; width-depth ratio, F ; and meander wavelength, L , as a function of channel silt-clay, M ; and mean annual discharge, Qm ; or mean annual flood, Qma . These equations are presented below, as Eqs. 3 through 10, with their correlation coefficients, r , and standard errors, Se .

$$w = 2.3 \frac{Qma^{0.58}}{M^{0.37}} \quad (3)$$

$$r = 0.94$$

$$Se = 0.13 \text{ log unit}$$

$$w = 37 \frac{Qm^{0.38}}{M^{0.39}} \quad (4)$$

$$r = 0.93$$

$$Se = 0.14 \text{ log unit}$$

$$d = 0.09 M^{0.35} Qma^{0.42} \dots \dots \dots (5)$$

$$r = 0.86$$

$$Se = 0.13 \text{ log unit}$$

$$d = 0.6 M^{0.34} Qm^{0.29} \dots \dots \dots (6)$$

$$r = 0.89$$

$$Se = 0.13 \text{ log unit}$$

$$F = 21.4 \frac{Qma^{0.18}}{M^{0.74}} \dots \dots \dots (7)$$

$$r = 0.93$$

$$Se = 0.15 \text{ log unit}$$

$$F = 56 \frac{Qm^{0.10}}{M^{0.74}} \dots \dots \dots (8)$$

$$r = 0.93$$

$$Se = 0.15 \text{ log unit}$$

$$L = 234 \frac{Qma^{0.48}}{M^{0.74}} \dots \dots \dots (9)$$

$$r = 0.93$$

$$Se = 0.19 \text{ log unit}$$

$$L = 1890 \frac{Qm^{0.34}}{M^{0.74}} \dots \dots \dots (10)$$

$$r = 0.96$$

$$Se = 0.16 \text{ log unit}$$

The equations for channel width (Eqs. 3 and 4) indicate that a large proportion of the variability of width (88%) can be explained by discharge and type of sediment load with mean annual discharge and type of sediment load being about equally important. The relationship for channel depth is not quite as good; only about 81% of the variability of channel depth being explained by mean annual flood, Qma , and percent silt-clay, M .

Although type of sediment load is the major factor determining width-depth ratio, as indicated by Eq. 1, discharge does have a minor but significant influence as demonstrated by Eqs. 7 and 8.

The effect of type of sediment load, M , on channel width-depth ratio supports the observation of Leopold and Maddock (11, p. 24) that "decreasing width at a constant velocity . . . results in increased capacity for suspended load at constant discharge" and "At constant velocity and discharge, an increase in width is associated with a decrease of suspended load and an increase in bed load transport." Therefore, a high width-depth ratio is associated with large bedload.

The addition of a discharge parameter does not improve the significance of the relation between sinuosity and M , but Eqs. 9 and 10 show clearly that meander wavelength is significantly related to discharge and to type of sediment load, and meander wavelength can, in fact, vary 10-fold at a given discharge depending on type of sediment load.

Because meander amplitude has been shown to be related to channel width (12), then meander amplitude should be related to M and to discharge, as some multiple of Eqs. 3 and 4.

About 40% of the variability of channel gradient can be explained by either Qm or Qma , and with the addition of M , 79% of the variability is accounted for

$$S = 60 M^{-0.38} Qm^{-0.32} \dots \dots \dots (11)$$

$$r = 0.84$$

$$S = 0.15 \text{ log unit}$$

The empirical equations presented above tell several things of general interest. The shape (width-depth ratio) and sinuosity of an alluvial channel are primarily determined by the type of sediment load or the ratio of bed-material load to total load moved through the channels, whereas channel width, depth, gradient, wavelength, and amplitude are significantly influenced by both discharge and type of sediment load. The equations demonstrate that for most changes of hydrologic regimen, which involve both a change in discharge and type of sediment load, many aspects of channel morphology will change. In addition, the reaction of a channel to a change of discharge and type of load may result in changes of channel dimensions contrary to those indicated by the standard regime equations. That is, it is conceivable that under certain circumstances with a decrease of discharge depth will decrease and width will increase.

CHANNEL METAMORPHOSIS

Lane (8) in his important paper presented a qualitative relation between bed-material load, Qs ; water discharge, Qw ; sediment size, D ; and gradient, S , as follows

$$QsD \approx QwS \dots \dots \dots (12)$$

He concluded that a channel could be maintained in dynamic equilibrium by balancing changes in sediment load and sediment size by compensating changes in water discharge and river gradient. It is known, of course, that in many cases sediment and water discharge can be independent of each other and that only in a completely controlled canal system can water and sediment discharge be so balanced as to maintain a constant gradient. For example, in natural river systems, climatic fluctuations, changing agricultural practices, river regulation, and diversions can significantly modify the balance between water discharge and sediment load.

As suggested by Eqs. 1 through 11, the change from one stable morphology to another may involve changes in all aspects of a channel, and the initial response of a river to altered hydrologic regimen may not necessarily indicate the type of final adjustment that will occur. Therefore, an attempt will be made to discuss river metamorphosis within the framework of these empirical equations. First, however, it should be emphasized that Eqs. 1 through 11 result from an analysis of stable alluvial rivers that transport only small quantities of gravel and that are, for the most part, located in subhumid and semiarid regions. Even if the equations are shown to have a wider application, the constants and exponents of these equations would be expected to change as more data from a wider range of geologic and hydrologic conditions are accumulated. Therefore, the following treatment will stress directions of change rather than magnitudes.

Eqs. 3, 4, 5, 6, 9, and 10 indicate that channel width, w ; depth, d ; and meander wavelength, L , are directly related to discharge, whereas Eq. 11 demonstrates that gradient is inversely related to discharge. From these equations the generalized relation of Eq. 13 is obtained

$$Qw \approx \frac{w, d, L}{S} \quad (13)$$

Either mean annual discharge, Qm , or mean annual flood, Qma , can be substituted for Lane's water discharge, Qw , in this and subsequent equations. Considerable independent information is available to demonstrate that the relations expressed by Eq. 13 are valid.

Eqs. 3, 4, 9, 10, and 11 demonstrate that channel width, meander wavelength, and gradient are inversely related to the type of sediment load, M , whereas Eqs. 2, 5, and 6 indicate a direct relationship between channel depth, sinuosity and type of sediment load, M . The percentage of silt-clay in the perimeter of a channel reflects the nature of the sediment load moving through that channel expressed as the percentage of bed-material load in total load, Qt , but for a given channel or for channels of equal discharge, M probably can be related inversely to the quantity of bed-material load that moves through the channel; therefore, $1/Qs$ can be substituted for M in Eqs. 1 through 11 if discharge is constant. From these equations the generalized relation of Eq. 14 is developed

$$Qs \approx \frac{w, L, S}{d, P} \quad (14)$$

Width-depth ratio, F , is not included in Eq. 14, although it is highly dependent on M , because both width and depth appear separately in the equation; nevertheless the relation between width-depth ratio and M in Eq. 1 will prove useful for interpreting changes of channel width and depth in subsequent relations.

To discuss in more detail the effects of changing discharge and sediment load on channel morphology, a plus or minus exponent will be used to indicate how, with an increase or decrease of discharge or bed-material load, the various aspects of channel morphology will change. For the relatively straightforward cases of an increase or decrease in discharge or bed-material load alone, Eqs. 15 through 18 are obtained.

$$Qw^+ \approx \frac{w^+ d^+ L^+}{S^-} \quad (15)$$

$$Qw^- \approx \frac{w^- d^- L^-}{S^+} \quad (16)$$

$$Qs^+ \approx \frac{w^+ L^+ S^+}{d^- P^-} \quad (17)$$

$$Qs^- \approx \frac{w^- L^- S^-}{d^+ P^+} \quad (18)$$

An increase or decrease of discharge Qw alone could be caused by diversion of water into or out of a river system. An increase of Qs can result from increased erosion in the catchment area which can be induced by deforestation or by an increase in the area under cultivation. A decrease of Qs could result from improved land use or a program of soil conservation.

An increase or decrease of discharge changes the dimensions of the channel and its gradient, but an increase or decrease of bed-material load at constant mean annual discharge changes not only channel dimensions but also the shape of the channel (width-depth ratio) and its sinuosity.

In nature, however, it would be rare that a change in discharge or sediment load could occur alone. Generally, any change in discharge will be accompanied by a change in the type of sediment load and vice versa. This is because these two variables are dependent on other factors which influence both runoff and sediment yield.

When, however, the effects of changing water discharge and sediment load are combined, we can no longer assume that M is related to $1/Q_s$ because discharge is changing. Therefore, M can be used only as an index of the ratio of bed-material load to total sediment load or of the percentage of bed-material load Qt in the equations that follow.

Using the plus or minus exponents to indicate an increase or decrease in a variable, four combinations of changing discharge and sediment load can be considered. For example, if both discharge and the percentage of bed-material load increase, perhaps as the result of diversion of water from a bedload channel into a suspended-load channel, Eq. 19 suggests the nature of the resulting channel changes

$$Qw^+ Qt^+ \approx \frac{w^+ L^+ F^+}{P^-} S^+ d^+ \dots \dots \dots (19)$$

Eq. 19 indicates that, with an increase in both discharge and percentage of bed-material load, width, meander wavelength, and width-depth ratio should increase and sinuosity should decrease. The influences of increasing discharge and percentage of bed-material load on channel depth and gradient are in opposite directions, and it is not clear in what manner gradient and depth should change. However, by including width-depth ratio in Eq. 19 an estimate of the direction of change of depth can be obtained. Width-depth ratio is predominantly influenced by type of load (Eqs. 1, 7, and 8) and, therefore, it increases in Eq. 19. This suggests that depth will remain constant or decrease because both width and width-depth ratio increase. Channel gradient will probably increase because sinuosity decreases, thereby straightening the channel and increasing its slope.

When both Qt and Qw decrease, as could result from dam construction, the reverse of Eq. 19 pertains as follows

$$Qw^- Qt^- \approx \frac{w^- L^- F^-}{P^+} S^- d^- \dots \dots \dots (20)$$

When, as common in nature, the changes in Qw and Qs are in opposite directions, the following relations are obtained

$$Qw^+ Qt^- \approx \frac{d^+ P^+}{S^- F^-} w^+ L^+ \dots \dots \dots (21)$$

$$Qw^- Qt^+ \approx \frac{d^- P^-}{S^+ F^+} w^- L^- \dots \dots \dots (22)$$

The situation expressed in Eq. 21 could result from a combination of controls. For example, dam construction with impoundment of sediment and diversion of water into the channel from another source. The situation of Eq. 22 could result from increased water use and increased land use, thereby, decreasing discharge but increasing the percentage of bed-material load.

Eq. 21 shows that with an increase in discharge but a decrease in the percentage of bed-material load the channel depth and sinuosity will increase,

but gradient and width-depth ratio will decrease. With an increase in depth and a decrease in width-depth ratio, channel width will probably decrease. Meander wavelength will remain unchanged or will either increase or decrease, depending on the magnitude of the changes or discharge and bed-material load. As sinuosity increases, it seems likely that meander wavelength might decrease.

The situation portrayed by Eq. 22 is the reverse of that for Eq. 21.

The above relations suggest in a qualitative way how channel metamorphosis will occur with changes of discharge and the type of sediment load. The magnitude of the changes of channel characteristics could be estimated through the use of Eqs. 1 through 11 if the magnitudes of the changes of discharge and the percentage bed-material load in the total sediment load are known.

The significantly different channel dimensions, shapes, and patterns that are associated with different quantities of discharge and types of sediment load indicate that, as these independent variables change, major adjustments of channel morphology can be anticipated. Further, if changes in not only channel width and depth but also an adjustment of sinuosity and meander wavelength are required to compensate for a hydrologic change, then a long period of channel instability can be envisioned with considerable bank erosion and lateral shifting of the channel before channel stability is restored.

GEOLOGIC EXAMPLE OF RIVER METAMORPHOSIS

Although based on equations that were obtained by analysis of modern river data, the relationships of Eqs. 20 through 22 may not agree with changes of channel morphology to be deduced from regime equations or from observed effects of river regulation. For example, Eq. 19 indicates that with increased discharge channel depths will probably decrease. In fact, degradation and deepening of a channel may be the first phase of channel metamorphosis, although the long-term result may be a decrease in channel depth. Documentation of long-term channel changes are required for support of these relations. However, most studies of river channel changes are inhibited by the channel change itself. That is, the old river channel is either destroyed or buried by the adjustment of the channel to the change of hydrologic regimen, and, therefore, without prior documentation only indirect evidence concerning the old river channel characteristics can be found. Fortunately, at least one example exists where the channels have not been destroyed by the change, and they can be studied in the field on the Riverine Plain of New South Wales, Australia.

The sinuous Murrumbidgee River (Fig. 1) drains from the highlands of southeastern New South Wales toward the west (left on photograph). It crosses the Riverine Plain, an alluvial plain that slopes at about 1.5 ft per mile to join the Murray River at the New South Wales-Victoria border. The channel is about 200 feet wide, and it is confined to an irregular flood-plain on which are preserved large oxbow lakes which are evidence of a past time of high discharge (paleochannel 1, middle arrow). The trace of an older low sinuosity stream channel (paleochannel 2) crosses the lower quarter of the photograph (lower arrow). In the upper half of the drainage basin the river is confined within a valley, and no evidence pertaining to the past condition of the Murrumbidgee River is apparent because the old channels have been destroyed, where-

as on the alluvial plain the position of the channel has shifted through time, and portions of older channels (paleochannel 2, lower arrow) have been preserved (Fig. 1). Three different types of channels are visible, and these re-



FIG. 1.—PART OF THE RIVERINE PLAIN NEAR DARLINGTON POINT, NEW SOUTH WALES

flect the hydrologic regimen of the time when each channel was functioning. In Table 1 the dimensions and other form characteristics of these three channels are presented with data on sediment characteristics and hydrology. Pe-

TABLE 1.—MORPHOLOGY OF

Location (1)	Channel width, in feet (2)	Channel depth, d , in feet (3)	Width-depth ratio, F (4)	Sinuosity, S (5)	Gradient, S , in feet per mile (6)
Murrumbidgee River (Upper arrow, Fig. 1)	220	21	10	2.0	0.7
Paleochannel 1 (middle arrow, Fig. 1)	460	35	13	1.7	0.8
Paleochannel 2 (lower arrow, Fig. 1)	600	9	67	1.1	2.0

^a Calculated by use of Manning equation and channel area.

^b Calculated by Colby's technique.

dologic (2) and geomorphic (20) evidence from the Riverine Plain indicate that the oldest of the paleochannels (Fig. 1 paleochannel 2) was functioning during a climate drier than that of the present and that the youngest (paleochannel 1) was functioning during a climate more humid than that of the present.

Further information on the Murrumbidgee River drainage basin and the Riverine Plain can be obtained from the work of Butler (2) and Langford-Smith (10) as summarized by Schumm (20).

The channel changes occurred not only because the water discharge increased or decreased, but also because climatic changes significantly altered the type of sediment load moved from the headwaters across the alluvial plain. At present, erosion is not a problem in the Murrumbidgee drainage basin. A good cover of vegetation protects the source area, and the river transports small quantities of sand, silt, and clay. An increase in precipitation will further improve the vegetation and although runoff will increase the sediment yield will decrease (9,20). On the other hand, a decrease in precipitation will decrease the amount of runoff, but greatly increase the yield of sediment from the drainage basin. Calculations of the quantity of sand that could be moved through these channels at bankfull discharge show that paleochannel 2 was competent to move large quantities of sand (Table 1). The abandoned channel of paleochannel 2 is filled with sand, whereas the abandoned channel of paleochannel 1 is filled largely with silts and clays. This suggests that, although paleochannel 1 could have transported relatively large quantities of sand, this type of sediment was available in large quantities only during the existence of paleochannel 2.

As fascinating as the paleochannels of the Riverine Plain may be, they are of concern here only as an illustration of the types of river changes that can occur naturally. If, for simplicity, it is considered that the paleochannels represent changes from a channel which initially was like that of the modern Murrumbidgee River (Fig. 1) then we can discuss the channel changes which will occur if the present climate of southeastern Australia becomes wetter (paleochannel 1) or drier (paleochannel 2). An increase in precipitation in the Murrumbidgee River headwaters will result in increased annual discharge and

RIVERINE PLAINS CHANNELS

Meander wavelength, L , in feet (7)	Median grain size in millimeters (8)	Channel silt-clay, M , in percent (9)	Bed-load, Q_t , in percent (10)	Bankfull discharge, in cubic feet per second (11)	Sand discharge at bankfull in tons per day ^b (12)
2,800	0.57	25	2.2	10,000	2,000
7,000	—	16	3.4	51,000 ^a	21,000
18,000	0.55	1.6	34	23,000 ^a	54,000

increased mean annual flood, but only a small change in sediment concentrations and in the type of sediment load moved through the channel. In response to this hydrologic change, which is similar in effect to that described by Eq. 15, the gradient and shape of the channel will not change, but it will become wider, deeper, and meander wavelength and amplitude will increase. The initial response will undoubtedly be severe channel erosion until the new dimensions are established. The result will be a relatively stable channel, but one larger than the modern river. On the Riverine Plain it is significant that although deepening of the channel did occur the increased discharge did not cause major incision. Gradient remained essentially constant.

On the other hand, a decrease in precipitation in the headwaters of the Murrumbidgee River will not only cause a decrease in annual discharge, but through reduction of vegetation density it will increase peak discharges and greatly increase the amount of sand moved through the channels. The result will be a complete transformation of the river system. To transport the increased sand load with less water, the channel will adjust its shape to move the large quantities of bed-material load by becoming wider and shallower. The greater slope required to transport this load will not be developed by deposition and steepening of the Riverine Plain, which would require immense quantities of sediment. Rather, the channel pattern will be changed. The gradient of the channel will be doubled without significant deposition by a reduction of the sinuosity from about 2 to about 1. These changes are in complete accord with Eq. 22.

As noted above, the events that occurred on the surface of the Riverine Plain were the reverse of the above sequence with the wide, straight, steep channel changing under the influence of altered hydrologic conditions to a relatively deep and sinuous channel (Fig. 1). In fact, the documented changes are in accord with those suggested by Eq. 21.

It is significant that, although the decrease in sediment load and increase of runoff dispensed with the need for the steep gradient of paleochannel 2 (Fig. 1), important incision did not occur. Although the modern river flows at a level about 5 ft below the surface of the Riverine Plain, the major decrease in

channel gradient was accomplished by a lengthening of the channel through the development of a sinuous course. The gradient was decreased by half due to the development of a sinuous course.

The example of the Riverine Plain paleochannels is instructive because they demonstrate that, although channel deepening and widening occurred in response to increased discharge, the adjustment of gradient was accomplished by a major change of channel pattern. This suggests that, if unconfined, modern rivers could decrease their gradient by the development of a sinuous course, rather than major degradation. Modern bank erosion problems may be only the initial stage of river metamorphosis if a reduction of river gradient is required by man-induced changes of river regimen. Further, the greater width of the oldest paleochannel, which was associated with relatively low discharge, is contrary to regime equations, but as Eqs. 3 and 22 indicate, the effects of a change in discharge can be counter-balanced by a change in type of sediment load, Qt .

HISTORIC EXAMPLES OF RIVER METAMORPHOSIS

If the conclusion that significant alteration of the hydrologic regimen of a river system will cause river metamorphosis is correct, then the effects of man's activities on the landscape should be recognized in river channel adjustment. Some evidence for such changes are available. For example, it is known that the great influx of sand and gravel into the Sacramento Valley from the western slopes of the Sierra Nevada as a result of hydraulic mining caused major deposition in the valley and destruction of the existing channels (5). The entire valley floor of many of these valleys became bedload channels. The transformation of the channels can confidently be attributed to the great increase of sediment load with probably minor changes in runoff (Eq. 14). The destruction of native forest vegetation in the North Island of New Zealand and its replacement on steep slopes by grasses, plus the introduction of grazing animals, precipitated a flood of coarse sediments into the rivers. However, it is unlikely that the runoff regimen remained unchanged. High peak discharges must have occurred and these, of necessity, increased the mean annual flood (Qma) and the movement of coarse sediment (6). The present major flood problems existing along these rivers are the result of both aggradation caused by greater sediment loads and higher flood peaks (Eq. 19).

The Cimarron River in southwestern Kansas greatly increased its width and decreased its sinuosity, thereby increasing gradient, as a result of increased flood peaks (21). The increased gradient, straight course, and greater width was ideal for the movement of large quantities of sand through the system. Thus, the river was transformed from what was apparently a suspended-load channel to a bedload channel of high peak discharge and mean annual flood. In these three cases, the river channels were greatly widened, the sinuous patterns were destroyed, and gradients were increased in accordance with Eqs. 17 and 19.

On the other hand, the reduction by regulation of flood peaks and annual discharge (Qm) along the North Platte River has caused a pronounced narrowing of the river. Because of tributary contribution, the main channel, as yet, is not meandering and braided reaches still occur. However, it has become more sinuous. The magnitude of the channel changes can be illustrated

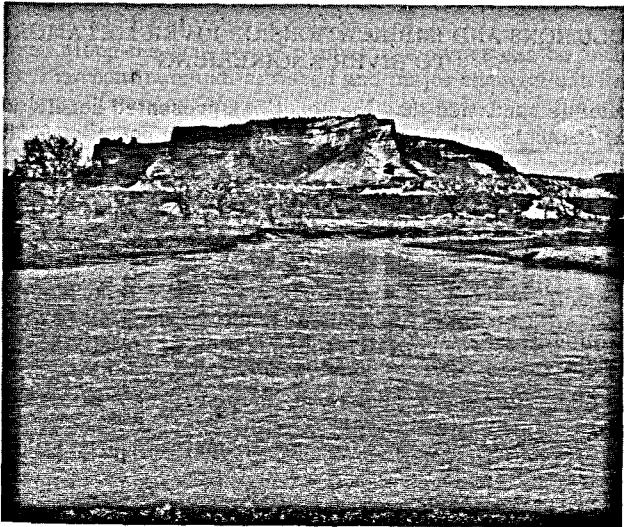
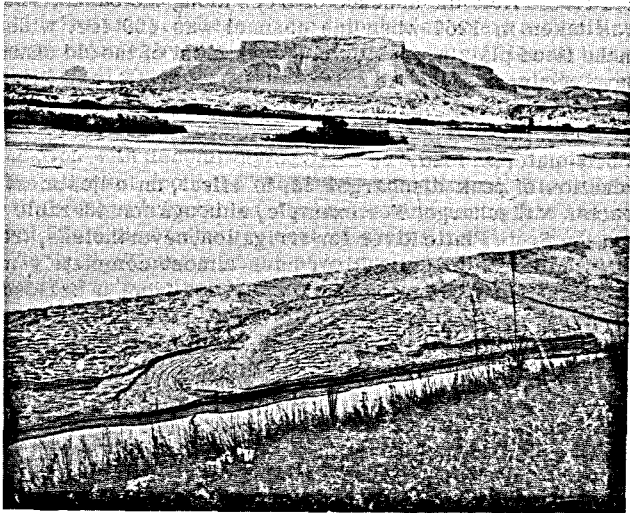


FIG. 2.—NORTH PLATTE RIVER AT SCOTTSBLUFF, NEBRASKA

by the photographs of Fig. 2. The upper photograph was taken in 1895, when the river was about three quarters of a mile wide and was a classic example of a braided river. Note the absence of trees along the banks. The lower photograph was taken in 1967 when the channel was 150 feet wide. Trees are growing on the flood plain which now occupies most of the old channel. Similar changes have occurred along the Arkansas (14), Red (21), and Gila Rivers, and they are in accord with the changes predicted by Eqs. 18 and 20. This suggests that the reduction in flood peaks and mean annual discharge has caused a reduction in bed-material load.

The reduction of peak discharges is, in effect, an adjustment of the seasonal character of discharge. For example, although considerable water is diverted from the South Platte River for irrigation, nevertheless, transmountain diversions into the South Platte River have almost completely made up this loss (20). In this case, the major channel change from a braided to a single channel stream is due almost entirely to the reduction of spring floods and the resulting decrease in bedload movement through the channel.

Major floods in semiarid regions tend to maintain wide, shallow, straight channels and, in fact, floods of unusual magnitude will transform a narrow sinuous channel to a wide, straight channel as the Cimarron River example demonstrates (7,23). Large releases of water from reservoirs may have the same effect on channels that have adjusted to reduced flood peaks. For example, the channel of the Republican River below the Harlan County and Trenton Dams in Nebraska narrowed significantly after water storage began, and the damage from local flooding has increased as a result of reduction of channel size (15).

CONCLUSIONS AND IMPLICATIONS OF RIVER METAMORPHOSIS TO RIVER ENGINEERING

The reader is cautioned that the equations presented herein do not pertain to artificial channels with bank materials that are not representative of the sediment load moved through the channel. Secondly, as most of the examples of rapid natural river changes have occurred in semiarid regions, the examples support the assumption that the greatest changes in sediment loads will occur in arid and semiarid climates with almost complete transformation of river morphology. In humid regions changes of runoff need not involve major changes of sediment load and, therefore, only changes in channel dimensions may be expected. Certainly, higher bank stability, a result of greater vegetational density, will not permit the enormous flood effects that can occur in drier regions (24).

The examples cited show long-term metamorphosis of entire rivers. The short-term adjustment of a river to regulation may, in fact, be only the initial changes which precede a complete change of river morphology, and the Riverine Plain examples indicate the magnitude and nature of the changes that can occur naturally along rivers.

River regulation for irrigation generally reduces peak discharge and prolongs the flow, in effect transforming an ephemeral or intermittent channel to a perennial one of low discharge. The result is a reduction in the size of the channel. The accompanying reduction of the ratio of bedload to total sediment load will cause a decrease in channel width-depth ratio and an increase in sinuosity (Eq. 20). The eventual result should be a very stable channel. There-

fore, many of the wide, sandy, "unstable" rivers of the Western United States could be transformed to stable channels by reducing flood peaks and bedload transport. This can be done in two ways either by control of the main stream or by control of tributaries. Where major tributaries exert a significant influence on the main channel by introduction of large quantities of bed-material load, upstream control along the main channel may allow the tributary to dominate the system with deleterious results. For example, where high discharges are required to clear the channel of sediment contributed from tributaries, serious aggradation with accompanying flood problems may arise if periodic flushing of the sediment from the channel is not allowed. The alternative is regulation of the bedload tributaries, those draining areas that are sources of sand and gravel. Selective tributary control seems mandatory if river transformation is desired. Thus, a basin-wide evaluation of tributary sediment loads and discharge is required before the effects of main stream regulation can be determined.

Flood control structures can cause downstream flood damage to be greater at reduced flows if the average hydrologic regimen is changed to the extent that channel metamorphosis occurs. In many areas the channel and floodplain should remain under Federal or State control for a period of time great enough for the effects of channel adjustment and floodplain formation to be evaluated.

A further concern might be the effectiveness of weather modification. The fluvial results of weather changes would be greatest in semiarid and arid regions, that is, exactly where more precipitation is desired. The nature of weather modification may be such that an increase in annual runoff will occur as a result of increased flood peaks, and as we have seen increased flood peaks can be very damaging. Geologic studies of the effects of climate changes on the landscape should be of value in this regard.

Great changes along the courses of many more rivers can be anticipated if the activities of man continue undiminished and major changes can be expected to occur over long distances downstream. Much depends on the climate and geology of each system, but a major change in hydrologic regimen should trigger a response that, if large enough, will completely transform the channel morphology. Therefore, it is not safe to assume that adjustment of channel slope by degradation will be the only response of a river. The equations have shown that, in fact, all aspects of river morphology may respond depending on the magnitude of the change of discharge and sediment load.

Much remains to be done both in the field and in the laboratory. It is hoped that this review of geomorphic investigations of river channels may provide suggestions for further experimentation in hydraulic laboratories as well as the incentive for detailed study of natural river metamorphosis during the recent geologic past.

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APPENDIX I.—BASIC DATA 1

Number	Location	Width, <i>w</i> , in feet	Depth, <i>d</i> , in feet	Width- depth ratio, <i>F</i>	Channel silt-clay, <i>M</i> , in percent
1.	Nowood Cr. near Tensleep, Wyo.	59	5.0	12	16.0
2.	Tongue River near Miles City, Montana	198	5.0	40	3.7
3.	M. F. Powder R. near Kaycee, Wyo.	37	4.0	9	14.8
4.	Powder R. near Locate, Mont.	325	6.1	53	2.5
5.	Little Missouri R. near Alzada, Mont.	46	5.7	8	44.6
6.	Lance Cr. near Spencer, Wyo.	105	4.9	21	8.0
7.	Cheyenne R. near Spencer, Wyo.	258	4.0	65	5.0
8.	Cheyenne R. at Edgemont, South Dakota	280	3.8	75	3.8
9.	White R. near Whitney, Nebr.	27	5.7	5	38.8
10.	S. F. White R. at White River, Nebr.	98	2.5	39	3.8
11.	Niobrara R. near Hay Springs, Nebr.	66	2.4	28	1.3
12.	So. Loup R. at St. Michael, Nebr.	123	4.0	31	6.7
13.	No. Loup R. at Taylor, Nebr.	153	2.9	53	2.8
14.	Calamus near Burwell, Nebr.	151	3.7	41	2.0
15.	No. Loup at Scotia, Nebr.	410	5.5	75	1.5
16.	No. Loup near St. Paul, Nebr.	431	5.7	75	1.8
17.	Elkhorn R. at Norfolk, Nebr.	192	4.3	45	7.3
18.	Republican R. at Benkelman, Nebr.	104	3.8	27	2.3
19.	So. Republican near Benkelman, Nebr.	207	3.0	69	2.2
20.	Frenchman Cr. at Palisade, Nebr.	30	5.4	6	27.8
21.	Frenchman Cr. at Culbertson, Nebr.	74	4.5	16	14.9
22.	Republican R. at McCook, Nebr.	115	4.5	26	6.8
23.	Red Willow Cr. near Red Willow, Nebr.	45	7.1	6	44.4
24.	Republican R. at Cambridge, Nebr.	320	3.5	93	2.9
25.	Republican R. near Orleans, Nebr.	146	6.0	24	6.7
26.	Beaver Cr. near Beaver City, Nebr.	55	10	6	22
27.	Beaver Cr. at Ludell, Kansas	28	8.0	4	36
28.	Sappa Cr. near Stamford, Nebr.	60	10	6	28
29.	Prairie Dog Cr. at Norton, Kans.	50	10	5	15
30.	Republican at Concordia, Kans.	251	7.1	35	4
31.	Solomon R. at Niles, Kans.	126	7.6	17	16
32.	Kansas R. at Wamego, Kans.	636	10	64	3.8
33.	Kansas R. at Topeka, Kans.	800	18	44	3.0
34.	Murrumbidgee R. at Wagga Wagga	273	27	10	19
35.	Murrumbidgee R. at Narrandera	246	25	10	29
36.	Murrumbidgee R. at Darlington Point	220	23	10	25

APPENDIX I.—BASIC DATA 2

Number	Mean annual discharge, Q_m , in cubic feet per second	Mean annual flood, $Q_m a$, in cubic feet per second	Meander wavelength, L , in feet	Channel gradient, S , in feet per foot	Sinuosity, P
1.	100	1,540	500	.00045	2.1
2.	357	4,400	3,400	.0019	1.7
3.	60	1,450	1,000	.0016	2.1
4.	592	11,000	6,000	.0011	1.2
5.	82	2,750	650	.0009	2.5
6.	24	2,700	1,300	.0012	1.9
7.	48	3,200	2,600	.0014	1.3
8.	102	4,300	5,800	.0014	1.2
9.	21	900	600	.0012	2.4
10.	136	2,300	4,500	.0020	1.1
11.	28	1,100	5,800	.0018	1.1
12.	250	4,300	5,500	.0009	1.4
13.	454	1,500	5,300	.0013	1.1
14.	293	580	8,000	.0011	1.1
15.	838	6,400	11,000	.0012	1.05
16.	982	8,700	8,000	.0012	1.2
17.	570	5,200	5,500	.0008	1.2
18.	96	4,400	5,300	.0020	1.3
19.	56	5,000	5,300	.0022	1.2
20.	91	1,030	600	.0016	1.6
21.	123	1,450	850	.0013	1.5
22.	248	3,500	5,000	.0015	1.3
23.	42	2,250	500	.00077	2.1
24.	407	7,800	5,300	.0012	1.2
25.	385	6,600	6,500	.00083	1.6
26.	34	1,050	500	.0010	1.8
27.	20	635	500	.0012	2.3
28.	88	2,100	500	.0007	1.8
29.	45	3,200	500	.0011	1.6
30.	904	9,300	5,300	.0006	1.5
31.	595	8,000	2,000	.00026	1.9
32.	4,400	39,000	19,200	.0008	1.2
33.	5,155	48,000	23,200	.0005	1.1
34.	4,560	26,000	4,400	.00017	2.3
35.	4,081	15,000	3,100	.00021	1.7
36.	3,762	11,000	2,800	.00013	1.9

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APPENDIX III.—NOTATION

The following symbols are used in this paper:

- d = maximum channel depth, in feet;
 D = sediment size (Lane's equation);
 F = width-depth ratio;
 L = meander wavelength, in feet;
 M = silt-clay in perimeter of stream channel, in percent;
 P = sinuosity (ratio of channel length to valley length);
 Q_w = water discharge (Lane's equation);
 Q_m = mean annual discharge, in cubic feet per second;
 Q_{ma} = mean annual flood discharge, in cubic feet per second;
 Q_s = bed-material load (Lane's equation);
 Qt = percentage of total sediment load that is bed-load or ratio of bedload (sand size and larger) to total sediment load $\times 100$ at mean annual discharge;
 S = gradient, in feet per mile; and
 w = bankfull width, in feet.