# River Adjustment to Altered Hydrologic Regimen—Murrumbidgee River and Paleochannels, Australia

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# RIVER ADJUSTMENT TO ALTERED HYDROLOGIC REGIMEN—MURRUMBIDGEE RIVER AND PALEOCHANNELS, AUSTRALIA

By S. A. Schumm


## ABSTRACT

The Murrumbidgee River flows westward across the Riverine Plain of New South Wales, Australia. The river is sinuous, narrow, and deep and transports relatively small quantities of sediment. On the flood plain of the modern river and on the surface of the Riverine Plain are traces of old aggraded and abandoned river channels or paleochannels. The youngest set of channels has been termed "ancestral-river channels"; the older set has been referred to as prior-stream channels. In pattern, shape, and sediment characteristics, the ancestral-river channels resemble the channel of the modern river, but they are much larger. In contrast, the prior-stream channels are relatively straight, wide, and shallow and are filled with crossbedded sands. Geologic evidence indicates that the differences among these channels can be attributed to the effects of Quaternary climate changes on the hydrologic regimen of the drainage basin.

The morphologic and sediment characteristics of the channels indicate that although the modern Murrumbidgee River transports little sediment, the prior streams moved large quantities of sand onto and across the plain. The prior streams were undoubtedly characterized by high flood peaks, but the runoff from the headwaters was probably less than that at present, a condition reflecting a relatively drier climate than that of the present. The ancestral-river channels carried higher peak discharges and higher annual runoff than either the modern or prior-stream channels, which suggests that they existed during a time when the climate was more humid than at present.

The rivers adjusted to the changing hydrologic regimen by altering channel width, depth, gradient, meander wavelength, sinuosity, and width-depth ratio in a fashion that conflicts with previously developed regime equations but which can be predicted if both the change in discharge and the type of sediment load is known. For example, reductions in runoff and only a minor change in the sediment load transported through the ancestral-river channel caused a major reduction in channel width, depth, and meander wavelength; but gradient, sinuosity, and channel shape remained relatively unchanged. However, the increase in discharge and the decrease in sand load or bedload associated with the transformation of the prior stream to an ancestral river caused a major change in channel morphology; not only did channel width decrease and depth increase, thereby causing a major change in shape, but sinuosity increased and both gradient and meander wavelength decreased. Empirical equations have been developed for stable alluvial rivers of the Great Plains of the United States and for the channels of the Riverine Plain which demonstrate the influence of both discharge and type of sediment load on channel morphology.

Major changes in dimensions, pattern, and shape of modern river channels in response to man-induced alterations of hydrologic regimen have also occurred, and these are analogous to the changes which have occurred on the Riverine Plain. For example, destruction of vegetational cover and the subsequent increased erosion has caused higher flood peaks and larger sediment loads in many rivers. The result has been the conversion of Murrumbidgee-type channels to prior-stream-type channels. On the other hand, reduction of peak discharge and of sediment loads by river regulation has caused some modification of prior-stream-type channels toward channels of a Murrumbidgee type.

The present investigation supports the hypotheses that all aspects of river morphology are influenced by the type of sediment load moved through stream channels and that a classification of river channels based on this variable has validity. The Murrumbidgee River channel and the ancestral-river channels are of the suspended-load type, whereas the prior-streams channels are of the bedload type.

Documentation of the channel changes that have occurred on the Riverine Plain has provided the basis for some conclusions of general significance to river-control engineers, geologists, and geomorphologists. For example, the control of tributary runoff and sediment contribution to an alluvial channel will—if both runoff and the type of sediment load are significantly altered—induce a long-term adjustment of the river system. The induced changes may be difficult to recognize in a short span of time, but they will, nevertheless, be significant over very long reaches of alluvial rivers, especially in arid, semiarid, and subhumid climatic regions. Depending on the type of sediment load transported by the river, quite different types of adjustment can occur.

The greater length of the ancestral river and the modern river as compared with the length of the prior-stream channels demonstrates that, if possible, an adjustment of river gradient will be made by an increase or decrease of sinuosity—that is, an increase or decrease of river length. Deep incision of alluvial deposits in major river valleys may therefore occur only as a result of diastrophism or of lowering of base level. However, minor changes in base level may have little effect on the upstream reaches of a major river because adjustments of river length can steepen or lessen river gradient without incision. The above factors lead one to conclude that parallel river terraces which are composed of different types of sediments could have been formed by rivers that were morphologically very different.

Finally, the change in channel length can, in effect, shift the sediment-source area either toward or away from the site of deposition. Abrupt changes in sediment type in the stratigraphic record of fluvial sedimentation can reflect not only climatic and tectonic changes but also major river adjustments to these changes.

## INTRODUCTION

Numerous geomorphic, stratigraphic, and engineering investigations have been concerned with the response of rivers to changed volumes of runoff and sediment load. The problem has been approached in the past by the documentation of modern-river adjustment to regulation or to major floods by the study of model rivers or by the field investigation of sediments deposited by ancient rivers. As fruitful as these investigations have been, it has not been possible to recognize the long-term effects of a significant climatic or hydrologic change on the morphology of a major river system because of the brief span of time during which modern rivers and models have been studied, and because when major river adjustment occurs the original channel is either destroyed by erosion or buried by deposition. Therefore, the history of the natural adjustments of an Australian river, the Murrumbidgee, to Pleistocene and Holocene climatic changes should be relevant to the development of a better understanding of past river activity, as well as to the prediction of future behavior of rivers under the influence of man-induced modifications of river flow and climate.

The Murrumbidgee River flows westward across the alluvial Riverine Plain of southwestern New South Wales. The plain was constructed by Pleistocene and Holocene fluvial deposition, and on its surface the traces of ancient, aggraded, and abandoned stream channels are visible. Two sets of paleochannels of quite different appearance are apparent. Butler (1950) applied the term "prior streams" to the older channels (figs. 17, 23), and Pels (1964b) used the term "ancestral rivers" to designate the younger channels (figs. 10, 12).

The morphology of the present Murrumbidgee River differs greatly from that of the prior-stream channels, as observed on aerial photographs (fig. 9) and as described by Australian scientists (Butler, 1958; Langford-Smith, 1960b). However, the ancestral-river channels, although larger than the channel of the modern river, are otherwise morphologically similar.

The source area of sediment and runoff for the modern and ancient systems of river channels has not been modified by diastrophism either during the period of formation and abandonment of the ancient channels or during the development of the modern river (David and Browne, 1950, p. 642–643). Therefore, any difference in the morphology of the channels should reflect only the changes in sediment load and runoff from the catchment area of the upper Murrumbidgee River—that is, the hydrologic regimen of the drainage system.

The Riverine Plain, therefore, is a unique area in which to pursue an investigation of channel modification because not only can the modern Murrumbidgee River be studied but the aggraded and abandoned channels of the ancient river systems can also be investigated with relative ease. These paleochannels have been preserved because the modern river has established a course across the alluvial plain that left the ancient channels undisturbed, except locally where the two systems intersect.

Previous work on the morphology of stable alluvial rivers of Western United States has led the writer to conclude that several morphologic characteristics of these channels are largely dependent on the type of sediment load transported by the river, or, more specifically, on the ratio of suspended sediment load to bedload (Schumm, 1963a).

It was recognized that wide, shallow, relatively straight channels were sandy, whereas narrow, deep, sinuous channels contained appreciable amounts of fine sediments. The assumption was then made that the type of sediment forming the alluvial channel, expressed as the percentage of silt and clay forming the perimeter of the channel, was representative of the type of sediment load transported through the channels. On this basis, three classes of channels—bedload, mixed load, and suspended load—were identified (Schumm 1963a, table 6). The surface expression of the prior-stream channels of the Riverine Plain resembles that of the bedload channels studied in the United States, whereas the ancestral- and modern-river channels resemble suspended-load channels.

The recognition of the importance of sediment-load components to channel morphology permits an explanation of the significant differences that occur among alluvial rivers on the basis of their different sediment-source areas. Further, it can be suggested that if the sediment load of a river were altered drastically, a change in channel morphology would occur that is commensurate with the change in type of sediment load (Schumm, 1963b).

The study of the Murrumbidgee River and its associated paleochannels was begun (1) to obtain additional data that would be relevant to the hypothesis that the sediment load largely determines the shape and pattern of alluvial channels and would, in turn, support the proposed classification of alluvial channels (Schumm, 1963b), and (2) to document the changes in river morphology which reflect the effect of a climate change on the hydrologic regimen of the drainage basin. Such information should be useful in the interpretation of the erosional history of other areas, as well as in the prediction of the future channel changes which will result from man's regulation of modern rivers in subhumid, semiarid, and arid regions.

In this report the morphologic and sediment characteristics of the prior-, ancestral-, and modern-river channels are described and compared, and, finally, an attempt to establish the nature of the climate changes and to describe the mechanics of the river adjustment to these changes is made.

At least half of the report consists of descriptions of the Murrumbidgee River and its associated paleochannels; the climate, vegetation, and geology of the drainage basin and the Riverine Plain; and a review of the previous work of Australian scientists. This material, although necessary for a complete understanding of the problems can be avoided by the reader who may choose to move directly to the section entitled "Comparative Morphology and Hydrology of the Riverine Plain Channels."

## ACKNOWLEDGMENTS

The success of any investigation in a foreign land depends to a major extent on the assistance of the indigenous scientists who are laboring on related or similar problems; therefore, I am very grateful to all those Australians who were very generous with their encouragement, assistance, and information.

The Department of Geography, University of Sydney, served as headquarters during the study, and Professor G. H. Dury, chairman of that department, made available the departmental facilities as well as his generous advice and unbounded enthusiasm. Mr. W. G. Tuddenham, University of Sydney, and Brian Schumm assisted in the field during the surveying of cross sections and the sampling of sediments along the Murrumbidgee River. Dr. Trevor Langford-Smith, also of the Department of Geography, provided copies of his unpublished dissertation and maps of the Murrumbidgee drainage basin. Both Prof. Dury and Dr. Langford-Smith reviewed the initial draft of the report, and their criticisms provided a basis for revision of the report. Dr. C. V. G. Phipps, Department of Geology, University of Sydney, loaned the sampling device used to obtain sediment samples from the floor of the Murrumbidgee River.

Dr. Donald Walker, Department of Geography, Australian National University, provided suggestions on the methods of taking sediment samples for pollen analysis, and he then examined the samples for pollen content.

Officers of the Soils Division, Commonwealth Scientific and Industrial Research Organization, especially Drs. John Loveday and Tjeerd Talsma of the Irrigation Research Laboratory, Griffith, New South Wales, offered advice and guidance in the field and storage facilities at Griffith. Mr. Bruce Butler of the Soils Division at Canberra acquainted the writer with the field area and demonstrated that prior streams are not as easily identified on the ground as one might expect from the clarity with which they are displayed on aerial photographs. He also reviewed the first draft of the manuscript.

The officers of the New South Wales Water Conservation and Irrigation Commission in Sydney were exceedingly generous of their time and data. The staff of the Hydrographic Branch provided unpublished hydrologic data. Mr. John Poirrier of the Survey Department furnished aerial-photograph mosaics of the study area and reproductions of pertinent maps and plans. Mr. W. H. Williamson of the Geology Department provided information on maps of the area. Mr. Peter Van Lowenson of the Materials Laboratory supervised the grain-size analyses of the sediment samples. In the field, Mr. A. Stocklin, Griffith, New South Wales, made available a memorandum report on borings in the Murrumbidgee River flood plain at Tombullen Swamp. Mr. Mark Stannard of the Leeton office furnished data from his bore logs, and figures 19, 20, and 21 are based on the illustrations in one of his as yet unpublished manuscripts. Mr. Stannard also reviewed an early draft of the report. Mr. Simon Pels of the Deniliquin office offered suggestions in the field and provided maps and aerial photographs that simplified the investigation.

John Hewitt, New South Wales Main Roads Department, Wagga Wagga, loaned the writer his unpublished map that showed the locations of many sandpits, and Mr. S. Kaldor of the same organization located and produced copies of plans that show cross sections of the Murrumbidgee River at bridge construction sites. The shire engineers in the Murrumbidgee area also were most cooperative in providing information on pit locations.

To those Australians mentioned above, and to all those with whom I have had contact during the investigation, I proffer my thanks.

Carl F. Nordin, Jr., R. W. Lichty, G. P. Williams and W. W. Emmett of the U.S. Geological Survey reviewed the revised draft of the report.

## LOCATION AND TOPOGRAPHY

The Riverine Plain, as defined by Butler (1950), lies within the States of New South Wales and Victoria in southeastern Australia, and it is the alluvial plain across which the Murray and Murrumbidgee Rivers flow westward from the Eastern Highlands. These rivers enter the Riverine Plain at Albury and Narrandera. The Murrumbidgee River follows a sinuous course across the plain to the longitude of Balranald, where it turns to the south to join the Murray River (pl. 1).

The Murray River area was less suitable for study than the northern, or Murrumbidgee River, part of the Riverine Plain because the Murray River has developed a new course near Echuca, Victoria, as a result of Pleistocene(?) faulting in that area. The resultant disruption of the drainage pattern, although posing an interesting geomorphic problem (Harris, 1939; Bowler and Harford, 1966), renders an already complex problem more difficult. Therefore, this investigation was restricted to the northern, or Murrumbidgee River, part of the Riverine Plain between Narrandera on the east and Maude on the west (pl. 2).

Within the Murrumbidgee River drainage basin, three different topographic regions can be recognized: the mountainous, or high-country, section of the Eastern Highlands east of Wagga Wagga; the valley section of the Eastern Highlands between Wagga Wagga and Narrandera; and the Riverine Plain section west of Narrandera (pl. 1). The Eastern Highlands is one of the four major physiographic provinces of the Australian Continent (David and Browne, 1950), and the highest altitudes of the continent occur in the Kosciusko Plateau or Snowy Mountains, where Mount Kosciusko rises to an altitude of 7,308 feet. The Murrumbidgee River originates north of Mount Kosciusko and follows a rather unusual course to eventually join the Murray River near Balranald (pl. 1). Near Jugiong, below the canyon in which the Burrinjuck Dam was constructed (fig. 1*A*), the Murrumbidgee River leaves the true highland region and flows through an area of moderate relief (fig. 1*B*, 1*C*). The river valley is confined between bordering hills to near the city of Wagga Wagga. Below Wagga Wagga the valley becomes progressively wider, and at Narrandera, at the west edge of the Highlands belt, the valley ends, and the Murrumbidgee River debouches onto the Riverine Plain of the Central-eastern Lowlands (fig. 1*D*).

The Riverine Plain near the course of the Murrumbidgee River is, as its name suggests, a flat alluvial plain with a gradient about 1.5 feet per mile (pl. 2). The flood plain of the modern river lies at a slightly lower level, generally no more than 5 feet below the surface of the Riverine Plain. The modern river and the paleochannels with their levee systems and associated sand dunes form the major topographic relief of the Riverine Plain.

Farther west, between Maude and Balranald, is the Lowbidgee region—a low, very flat modern flood plain, where the surface expression of the paleochannels is obscured by recent deposition. Twenty-five miles west of Maude the river changes course from west to southwest, a direction it follows for about 50 miles to its junction with the Murray River.

## CLIMATE

The climatic conditions in the Murrumbidgee River drainage basin range between two extremes. Hot dry summers and cool moist winters occur on the Riverine Plain, and alpine climates with cool summers and cold wet winters occur at altitudes greater than 5,000 feet in the Snowy Mountains.

Storms move into the area from the west, but occasionally the weather is affected by a monsoon from the north. According to Morland (1958, p. 27), rainfall increases by about 10 inches for every 1,000 feet rise in altitude in the Murray River basin, and this relationship applies equally well to the Murrumbidgee River basin, for average precipitation increases from about 12 inches at Maude, at an altitude of 250 feet, to about 60 inches near Kiandra, at an altitude of 5,700 feet (pl. 1).

The eastern part of the drainage basin receives more precipitation in the summer than in the winter, whereas to the west of Burrinjuck Dam the winter precipitation is about 30 percent greater than summer precipitation (Commonwealth Bureau of Meteorology, 1948, map 38).

Snowfall increases with altitude. A few light falls occur each winter at 3,000 feet; frequent falls, which cover the ground for several weeks, occur at 4,000 feet; and heavy, frequent snowfalls occur above 5,000 feet. At the highest altitudes snow may remain on the ground for more than 6 months.

East of Narrandera is the 14,000 square miles of drainage basin that contributes sediment and runoff to the Riverine Plain. The annual temperature in much of this area is between 60°F and 65°F, with the 65°F isotherm located well to the north of the drainage divide. The 60°F isotherm crosses the basin between Wagga Wagga and Tumut (pl. 1). Only a small area in the high country of the southeast has an annual temperature less than 50°F (Commonwealth Bureau of Meteorology, 1945), and the average temperature for the basin above Narrandera is about 60°F.

Mean annual precipitation increases toward the east from about 16 inches at Narrandera to a maximum greater than 70 inches near Kiandra. However, this upstream increase of precipitation along the Murrumbidgee River valley is interrupted by a rainshadow effect in the Cooma area (pl. 1). Cooma, at an altitude of 2,600 feet, receives only 19 inches of precipitation. Toward the north, the blocking effect of the mountains that rise above 6,000 feet (between the Tumut and Murrumbidgee valleys) decreases, and precipitation increases in a downstream direction to 23 inches at Canberra, at an altitude of 1,800 feet, and to 34 inches at Burrinjuck Dam, at 1,000 feet. Only in the southeastern-

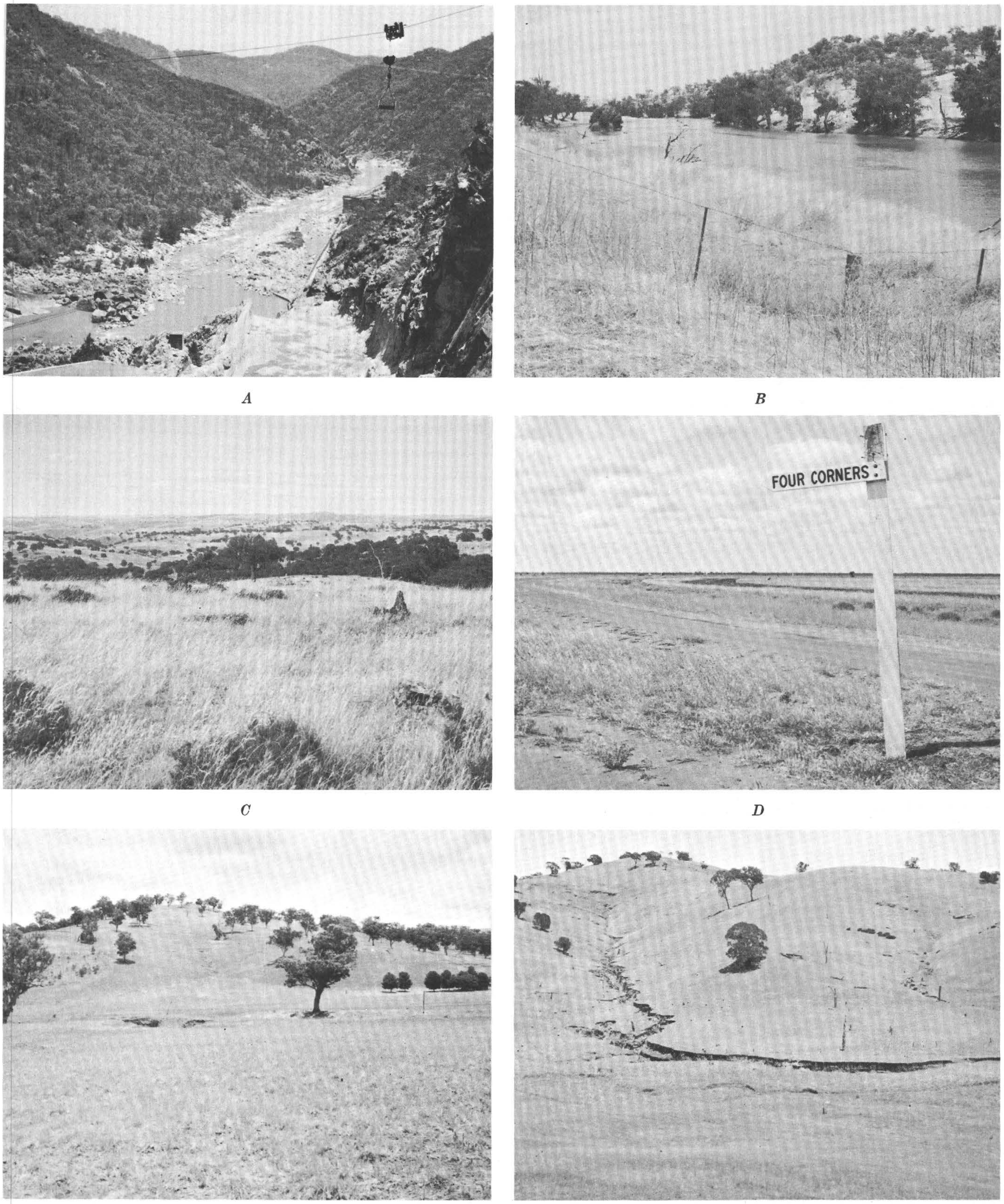


FIGURE 1.—Murrumbidgee River and its drainage basin. *A*. Murrumbigee River canyon below Burrinjuck Dam. *B*. Murrumbidgee River flowing through granitic terrain near Jugiong. *C*. Murrumbidgee River drainage basin south of Burrinjuck Reservoir. Scattered trees and grass cover the rolling hills composed of sedimentary rocks and volcanics of Devonian age. *D*. Riverine Plain near Four Corners. *E*. Murrumbidgee River drainage basin northwest of Gundagai (Kinovale Homestead). *F*. Gullying in soils formed on sedimentary rocks of Ordovician age north of Hume Highway and southeast of Wantabadgery.

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most extension of the basin is precipitation high (pl. 1). Perhaps 20 percent of the area above Narrandera receives less than 20 inches of precipitation annually, and 60 percent receives less than 25 inches. Thus, in spite of the high precipitation at high altitudes, mean annual precipitation for the basin above Narrandera is about 26 inches. On the Riverine Plain west of Narrandera, the mean annual temperature is between 60°F and 65°F, and the annual precipitation is less than 16 inches, decreasing to less than 12 inches west of Maude (pl. 1).

### VEGETATION, SOIL, AND EROSION CONDITIONS

As the Murrumbidgee flows from the highlands toward the plains, it proceeds through several vegetational and soil zones. The headwaters of the Murrumbidgee River and those of one of its major tributaries, the Tumut River, are in the Eastern Highlands at altitudes in excess of 4,500 feet. The highest altitude within the basin is about 6,000 feet. In these highland areas precipitation is abundant and a winter snow cover is usual. Tussock grass (*Poa caespitosa*) and snow gum (*Eucalyptus niphophila*) are the characteristic vegetation (Newman, 1955).

Below the geographically restricted alpine tracts, the climate is warmer and drier, and the vegetation is dominated by eucalypts (*E. robertsoni*, *E. dalrympleana*, *E. gigantea*, and *E. pauciflora*) which require between 40 and 60 inches of precipitation. A mesophytic undergrowth is characteristic, but clearing of the forest vegetation and undergrowth for grazing purposes is a common practice.

At about 1,500 feet the forest is of the dry schlerophyll type, which is dominated by hardy eucalypts such as red stringybark (*E. macrorhyncha*), white gum (*E. maculosa*), and others. Precipitation ranges between 30 and 40 inches, and snow is rare.

Between altitudes of 1,500 feet and 1,000 feet the rainfall varies between 30 and 35 inches, and the snowfall is negligible. The area is devoted to pastoral pursuits and some farming. The vegetation originally consisted of red gum (*Eucalyptus blakeleyi*), yellowbox (*E. melliodora*), kangaroo grass (*Themeda australis*), and *Danthonia* grasses among the trees. The native vegetation has been cleared over large areas and replaced by crops and introduced pasture species. At Wagga Wagga, at an altitude of about 600 feet, the valley widens, and farming becomes relatively more important. Precipitation decreases steadily toward the west to 16 inches at Narrandera, at about 450 feet, where the characteristic river red gum (*E. camaldulensis*) dominates the flood plain.

At Narrandera the river enters the Riverine Plain, and from there it flows westward to its junction with the Lachlan River, at an altitude of about 230 feet above sea level; in this distance, precipitation decreases from 16 to 10 inches. The plain is relatively flat, and trees are scattered and become fewer to the west. The Murray pine (*Callitris glauca*) is found on sandhills, and the river red gum and blackbox (*E. largiflorens*) are concentrated on the flood plain of the Murrumbidgee and on the alluvial soils of the prior rivers. The boree (*Acacia pendula*) is found on the plain, but farther west, saltbush (*Atriplex vesicaria* and *A. nummularium*) is dominant. The windmill and wallaby grasses (*Chloris* and *Danthonia*) are common and provide good grazing, particularly in the east.

From the head of the Murrumbidgee River to its junction with the Murray River, the increase in temperature and decrease in precipitation is reflected in the soils (Langford-Smith, 1958). In the mountains, alpine humus is replaced in a downstream direction by a brown podsolic soil association, which in turn becomes a gray-brown Podsol near Gundagai and Tumut. Red-brown earths occur from Wagga Wagga to the west. The Riverine Plain is composed of red-brown earths formed on sandy alluvium, gray and brown soils of heavy texture formed on clayey sediments, and relatively unweathered alluvial and eolian deposits. Both the distribution of these deposits and the soil types are controlled by the fluvial depositional pattern of the Riverine Plain (Dijk and Talsma, 1964).

In spite of extensive clearing of native vegetation, fires, and past rabbit infestations, erosion appears not to be a serious problem in the headwater area of the Murrumbidgee River (fig. 1*C*, *E*). Gullying occurs locally (fig. 1*F*), but throughout much of the basin a good grass cover protects the gentler slopes of the drier areas, and the steepest slopes are forested. For example, in the Tumut River basin evidence of advanced erosion is rare (Newman, 1955). In general, in the Eastern Highlands no appreciable erosion occurs on about 40 percent of the area; only moderate gully and sheet erosion occur over about 59 percent of the area; and severe gully erosion occurs on only about 1 percent of the area (Commonwealth Bureau of Meteorology, 1948, p. 156).

All the available information suggests that the volume of sediment being introduced into the Burrinjuck Reservoir on the Murrumbidgee River is very small; also, the few sediment samples collected from the Tumut River reveal that a very small amount of sediment is moving out of this major tributary into the Murrumbidgee River. These observations confirm that erosion is not a serious problem in the Murrumbidgee River basin.

## GEOLOGY

The geology of the Murrumbidgee River basin will not be discussed in any detail. For the purpose of this report, a brief review of the geologic history of the region and a discussion of the distribution and abundance of rock types will suffice. The following is based on the review by David and Browne (1950) and on the geologic map of New South Wales by Rose, Mathews, and others (1962).

### MURRUMBIDGEE CATCHMENT

The Murrumbidgee River rises about 30 miles north of Kiandra at an altitude of more than 4,500 feet in an area of sedimentary and extrusive igneous rocks of Silurian and Devonian age and granite intrusives of Middle Devonian age (David and Browne, 1950, p. 271). It then flows to the southeast across Ordovician shales, graywackes, and sandstones, as well as intrusive rocks and a granitic intrusion of Middle Devonian age. Near Cooma the river turns northward (pl. 1) and flows to the east of the Murrumbidgee batholith for about 50 miles in sedimentary rocks and volcanics of Silurian age. To the east is a belt of Ordovician sedimentary rocks. Southeast of Yass, the river turns to the west and crosses the geologic grain of the country. In sequence, the river crosses Middle and Lower Devonian sedimentary rocks and volcanics, Silurian volcanics east of Jugiong, granite of Middle Devonian age at Jugiong, Silurian rocks ranging from shales to conglomerates and volcanics near Gundagai, and Middle Devonian granitic rocks and Ordovician rocks ranging from limestone to sandstone near Wantabadgery. At Wagga Wagga the river flows on Quaternary alluvium, but Middle Devonian granitic rocks and Ordovician sedimentary rocks crop out to the north and south of the river. The river passes between outcrops of Upper Devonian lavas and clastic rocks near Narrandera, where it enters the Riverine Plain. It then flows across the Quaternary sediments of this alluvial plain to its junction with the Murray River.

Because the river traverses the north-south-trending geologic structure of the Eastern Highlands, it crosses rocks typical of those cropping out both to the north and to the south in its drainage basin, and the major tributaries follow the north-south trend of these outcrops.

The Goodradigbee River flows northward to join the Murrumbidgee between Yass and Jugiong. It drains a large area of Ordovician, Silurian, and Devonian sedimentary rocks and granitic intrusives. These rocks are also crossed by the Murrumbidgee as it follows a circuitous route around the south end of the Australian Capital Territory. The Yass River flows from the northeast to join the Murrumbidgee River above the Burrinjuck Dam and drains an area geologically similar to that drained by the Murrumbidgee River south of Yass. Other large tributaries, such as the Tumut, drain areas of similar rocks to the south.

To the east of Narrandera the important events of the Tertiary geologic history, which have determined the present topography, were Oligocene uplift and volcanic activity followed by Miocene planation. During the late Pliocene, uplift associated with the Kosciusko orogeny caused incision of the streams. Only minor and local faulting and folding occurred during the Pleistocene (David and Browne, 1950).

There were no glaciers in the Murrumbidgee River basin during the Pleistocene; however, glaciation did occur just to the south of the drainage divide in the Mount Kosciusko area within the Murray River basin. According to Galloway (1963), the maximum extent of glaciation in Australia was only about 20 square miles, and the glaciation was of Wisconsin age.

### RIVERINE PLAIN

The late Pliocene uplift in the eastern part of the Murrumbidgee River basin caused a major change in the type of sediments delivered to the area west of Narrandera. Deposition of marine and lacustrine sediments ceased, and fluvial sedimentation became dominant. For example, at a typical bore in the Murrumbidgee irrigation area near Leeton, 150 feet of fluvial sediments overlies about 400 feet of the Tertiary sediments (Pels, 1960).

The Quaternary alluvium on the Riverine Plain is composed of channel, levee, and flood-plain sediments. The channel sediments in the upper 40 feet of this complex deposit are of concern here primarily because they can be observed in prior-stream channels and because they allow an evaluation to be made of the type of sediment transported through the prior-stream channels.

Butler and his colleagues have mapped the soils over large areas of the Riverine Plain, and Butler (1958) has identified five depositional units in the upper part of the deposit. Three of these are fluvial deposits (riverine deposits), one is eolian, and one is a mixed fluvial-eolian layer.

The mixed fluvial-eolian deposit (Katandra riverine deposit) is the oldest of the five (fig. 2), and it was on the surface of the Katandra sediments that the major late Pleistocene and Holocene river adjustments occurred. The Katandra sediments seen during the fieldwork were gray clay, but they are actually a complex deposit consisting of both riverine (channel and flood-plain sediments) and eolian sediments (Butler, 1958, p. 24). The oldest prior-stream sediments (Quiamong riverine) were deposited in deep channels eroded into the Ka-

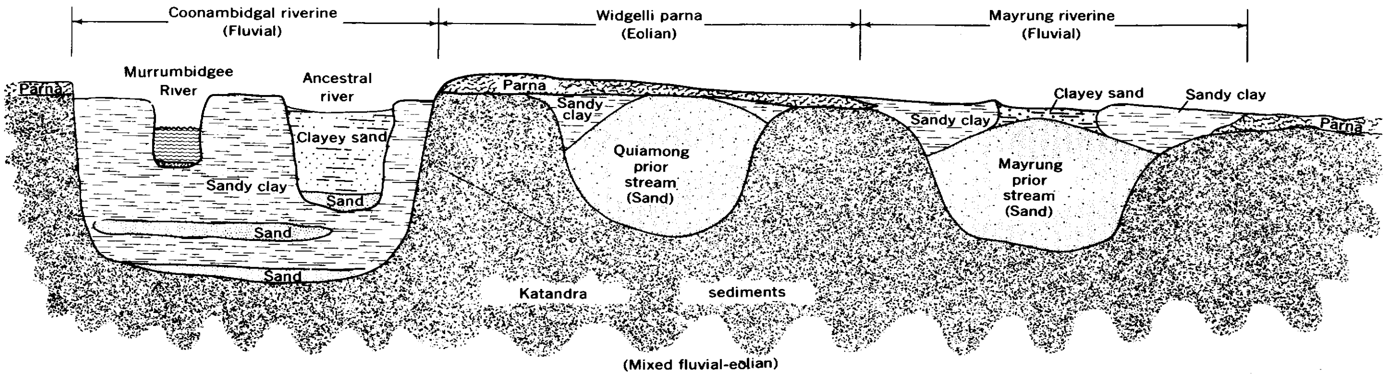


FIGURE 2.—Surficial stratigraphy of the Riverine Plain. (After Butler, 1958.)

tandra sediments. After the channel aggradation a blanket of eolian clay (Widgelli parna) was deposited over this Katandra and Quiamong landscape (Butler, 1956; Butler and Hutton, 1956). The youngest of the prior streams incised through the parna and into the older riverine sediments. These channels were subsequently filled with fluvial sediments (Mayrung riverine). The most recent fluvial sediments form the flood plain and channel of the Murrumbidgee River Coonambidgal riverine deposit).

The physical characteristics and distribution of some of these deposits are considered in more detail later in this report, and to avoid undue repetition they have only been identified here.

The available evidence and the current geologic opinion concerning the late Pleistocene and Recent geologic history of the Murrumbidgee River basin indicate that the source area of the sediments that now compose the surficial deposits of the Riverine Plain has not been modified by tectonic activity or glaciation, nor has it been reduced or enlarged by river capture. Therefore, these deposits reflect the late Pleistocene and Recent climate changes in the headwaters of the drainage system.

## PREVIOUS INVESTIGATIONS

Presentation of a reasonably comprehensive review of the Riverine Plain literature published since 1950 is necessary for the following two reasons:

First, for convenience to the reader, who may find that some of the publications to which reference is made later in the report are not readily available; and second, many of the data, observations, and conclusions presented in the works reviewed are necessary to the inferences drawn later in this report.

Soil mapping in the Riverine Plain, at least as late as 1942, was done without an understanding of the regional significance of the patterns that appeared during mapping. The linear patterns of soils and soil salinity and the distribution of microrelief landforms were attributed to modern flooding from the Murrumbidgee and Murray Rivers. However, when aerial photographs of the Riverine Plain first became available and were studied, it became clear that soil patterns and microtopography were actually related to another. earlier stream system, the prior streams. "The sedimentary pattern of the Riverine Plain of southwestern Australia was formed by a system of streams which traversed the Plain in a period prior to the present era. These are called prior streams * * *." These streams occur as a distributary system of channels on the alluvial plain (Butler, 1950, p. 236), and the sandy, well-drained depressions that have been traced across the plains by soil surveyors are prior-stream channels. Even the pattern of soil salinity on the plains could be related to the distribution of prior streams. Salinity, of course, was less near the paleochannels. Thus, the topography of the plain and the sediment characteristics, distribution, and chemistry of the alluvium are closely related, one to the other, and "the lack of correlation between the sedimentary pattern and the existing hydrologic system is proof that the latter was not the causal factor * * *" (Butler, 1950, p. 241).

After reviewing the geologic history of the region, Butler (1950, p. 249) concluded that the prior-stream sediments are the last of a series of alluvial sediments deposited on the plain during late Pleistocene time. Since the pattern of the channel deposits is so perfectly preserved (figs. 17, 23) he concluded that some of the prior streams could have been functional until very recent times. Butler also concluded that the flows during the last phase of stream activity were unable to cross the plain and were dissipated there. This could have been true only during a time when the climate was drier than at persent. Also, the salinity of the soils which border the prior-stream channels indicates that the channel sediments were deposited during a more arid climate than the present one. Butler inferred that the increased precipitation during the later Holocene (post-

Hypsithermal) allowed development of a channel which carried water to the sea by way of the Murray River.

The details of the prior-stream distribution have been obscured in the easternmost part of the Riverine Plain by the deposition and reworking of the eolian Widgelli parna (Butler, 1956). Parna is an Australian aboriginal word meaning sandy and dusty ground. It differs from loess, for parna was deposited as clay aggregates rather than as discrete mineral particles. The parna occurs on the east edge of the Riverine Plain as a sheet 3–6 feet thick. According to Butler (1950), the source of the parna was to the west, where the vegetational cover was weakened or destroyed during an arid climatic phase, and the parna is tentatively correlated with the Hypsithermal, or Great Australian, arid period (Gill, 1955). A more detailed study of the Widgelli parna sheet by Butler and Hutton (1956) demonstrated that the particle size of the parna decreases with distance from the sand dunes of the Mallee country to the west.

More than one parna deposit has been reported in the sediments of the Riverine Plain. The parna now mantling the surface is of most concern here, however, for it provides an important stratigraphic marker that can be used to differentiate between two systems of prior-stream channels (fig. 2), and according to Butler (1950) it is evidence of a period of severe aridity separating the last two phases of prior-stream activity.

Hawkins and Walker (1956) recognized that heavy gray calcareous clays alternate with coarser fluvial sediments on the plain. They attribute the cutting of the prior-stream channels to increased runoff during a wetter climate, and the filling of the channels to decreased runoff as the climate became more arid. They noted that sand dunes overlie parts of these channels and suggest that a phase of aridity followed, and perhaps accompanied, the filling of these prior-stream channels.

Butler (1958) in a summary of his previous research discussed in detail the five uppermost deposits of the Riverine Plain. These five deposits were mentioned in a preceding section, on the geology of the Riverine Plain (fig. 2), but some of Butler's evidence relating to the age of these deposits and to the climatic conditions that prevailed during and after their deposition requires review at this point.

Butler (1958) identified a paleosol which had formed on the surface of the Katandra riverine deposit, and because of the extent and nature of the weathering on this surface he concluded that it had formed during a long period of relatively humid climate. Following this, the Katandra surface was incised by channels to depths of 20 feet (Butler, 1958, p. 20). In these incisions river-channel sands of Quiamong age were deposited (fig. 2), and adjacent to the channels the Quiamong levee and flood-plain sediments were deposited. Butler described the distribution of the Quiamong prior-stream sediments as follows: "The Quiamong occurs in all parts of the Riverine Plain. It occurs as separate ribbon-like lobes in the upper section of the plain adjoining the foot hills, and some 40 to 70 miles out on the plains these lobes broaden and tend to become continuous laterally." These Quiamong sediments are mantled over much of the plain by the Widgelli parna, and where the Widgelli parna is absent, the Quiamong sediments are buried by more recent prior-stream deposits. The Quiamong sediments are unweathered, and Butler (1958, p. 20) concluded that the time interval between Quiamong prior-stream deposition and Widgelli eolian deposition was shore. As indicated above, the Widgelli parna was deposited during a relatively more arid climatic phase.

Incised through the Widgelli parna and into the underlying Quiamong and Katandra riverine sediments is another system of prior-stream channels. These channels are filled with the riverine sediments termed "Mayrung" (fig. 2) by Butler (1958, p. 11). The stream that eroded the Mayrung channels entered the Riverine Plain at Narrandera, as does the modern Murrumbidgee River. These Mayrung channels are not easily recognized east of Darlington Point—that is, on the first 30 miles of the plain, where the channels have been obscured by eolian activity and flooding. Nevertheless, they are well exposed on the Riverine Plain farther to the west (pl. 2).

Where the Widgelli parna was buried by overbank flooding from the Mayrung channels, the buried soil developed on the parna indicates that the period between Widgelli and Mayrung depositions was of "low leaching activity (i.e., arid) or short or both" (Butler, 1958, p. 11). Natural-levee sediments were deposited near the channels, and these are transitional with flood-plain sediments. Sand dunes are found along the Mayrung stream channels, indicating that eolian activity accompanied or followed Mayrung deposition.

The most recent fluvial deposit that Butler recognized is associated with, and forms the flood plain of, the Murrumbidgee River. These modern sediments compose the Coonambidgal riverine deposit (fig. 2), and they fill the incision scoured into the plain by the ancestral Murrumbidgee River.

In a review of the evidence, Butler (1958, p. 29) concluded that the "Quiamong and Mayrung periods were respectively the semiarid lead into, and lead out of, the main peak of aridity." The deposition of the Widgelli parna marks the maximum period of dryness. Butler (1958, p. 26, 28) stated, "There is evidence of three main intervals of deposition: The Katandra, the Quiamong plus Mayrung, and lastly the Coonambidgal. These depositions were separated by more or less long periods when no deposition occurred and during which the rivers entrenched their beds." The Quiamong and Mayrung "were closely related in time to deposition of the parna sheet, and hence to general open desert conditions to the west." When Mayrung deposition came to an end, the old Katandra landscape had been completely covered. Then a long period of nondeposition ensued (Butler, 1958, p. 28). During this period "the rivers underwent a change from their 'prior' to their present position and incised their beds more deeply and widely than at present obtains" (Butler, 1958, p. 28–29). Butler concluded that the changes in river activity on the plain were the result of changed hydrologic conditions accompanying the climate changes of late Pleistocene and Holocene time. In his opinion the evidence from soil investigations indicated that a climate more arid than that of the present prevailed during the time of Quiamong, Widgelli, and Mayrung deposition.

In a lively series of exchanges, Butler (1950) and Langford-Smith (1959, 1960a, b) differed regarding the climatic conditions that existed during prior-stream deposition and, in addition, elicited comments from Stannard (1962), Dury (1963), and Cotton (1963). The pertinent items of these discussions are as follows: Langford-Smith (1959) pointed out that to explain the numerous prior-stream channels and the width of their meander belts, as measured near Maude, it is necessary to conclude that the prior-stream channels carried discharges greatly in excess of those moving through the channel of the Murrumbidgee River at the present time. In rebuttal, Butler (1960) drew attention to the very large meander scars preserved in the Coonambidgal sediments near Darlington Point (figs. 10, 11). These scars appear to be the result of major stream activity during a time when discharge was greater than at present, and they suggest that between prior-stream activity of Mayrung age and the establishment of the present Murrumbidgee River a major river of large dimensions flowed where the present Murrumbidgee flood plain now exists. Butler also suggested that there apparently is no simple relationship between meander width and discharge on the Riverine Plain.

Stannard (1962) presented data to demonstrate that the prior-stream channel deposits may be almost 30 feet deep and almost 1,800 feet wide, far in excess of the 20-foot depth and 200-foot width of the Murrumbidgee River channel. Nevertheless, he suggested that although the incision which formed the channel may have occurred during higher runoff, the filling of the channels probably occurred when the ratio of sediment load to runoff increased—that is, during a time of aridity.

In his final statement, Langford-Smith (1962) modified his earlier conclusions and suggested that although the onset of a pluvial period, if sudden, could cause aggradation on the plains, channel incision probably would result from increased precipitation and runoff. He inferred that during a waning pluvial period—that is, during a time of climate change—progressive aggradation of the prior-stream channels occurred. This statement suggests that Butler and Langford-Smith approached agreement (Cotton, 1963). However, Langford-Smith (oral commun., 1965) still considered that most of the prior-stream aggradation occurred during a time when the climate was more humid than at present over the Murrumbidgee River basin because the wavelength of prior-stream meanders is greater than that of meanders of the modern Murrumbidgee River (Langford-Smith, 1962; Dury, 1963).

More recent studies indicate that the erosional and depositional history of the last system of prior-stream channels is more complex than has previously been recognized. For example, Simon Pels (1960), during one part of a ground-water investigation of the Murrumbidgee Irrigation Area near Leeton, noted that in the approximately 150 feet of fluvial sediment in this area three main sand deposits were identified. These deposits are separated by clayey sediments, and Pels (1960) suggested that the sandy layers represent sediment carried to the plains by high-discharge Pleistocene streams. He was of the opinion that the prior streams that have surface expression are post-Pleistocene in age. Pels (1964a) reported on his detailed stratigraphic studies of Quiamong and Mayrung prior-stream deposits in the Benerembah Irrigation District near Darlington Point where he distinguished five phases of filling and distributary formation along a major 45-foot-deep channel of Mayrung age. Crevassing through the levees of the stream at four different levels formed distributary channels 32, 21, 17, and 11 feet deep. Pels (1964a, p. 113) considered the sediments to represent a phase of deposition that was "a period of continuous and gradually waning stream activity by streams which were frequently diverted." He concluded that the climate changed gradually and culminated in a period of relative aridity, when sand dunes were formed. These dunes overlie the prior-stream channels at some locations.

Charcoal found in one of the channels was dated as "in excess of 36,000 years," and Pels (1964a) concluded that the prior streams are Pleistocene in age and that sediments of Holocene age are associated with Murrumbidgee River deposition.

An important idea advanced in Pel's paper (1964a) is that the several prior-stream courses visible on the plain, could not have been active contemporaneously. Rather, the flow was probably confined to a major channel that had distributary channels which were active at different times. Mark Stannard (unpub. data) presents additional proof that the major surface prior-stream channels were functional at different times. He identified three major prior-stream channels of Mayrung age south of the Murrumbidgee River and designated them as the northern, central, and southern prior streams (pl. 2). He concluded that the differences among them are such that they could not have been functional concurrently. For example, the northern prior stream has no significant levee development but is characterized by associated sand dunes, whereas the southern stream has well-developed levees but has virtually no associated sand dunes. One may conclude from the difference in the intensity of eolian activity that the channels were functional at different times.

Pels' (1964b, 1966) most recent contribution was to recognize the existence of paleochannels in the Murray River area that are more recent than the prior-stream channels. These he termed "ancestral rivers." Unlike the prior-stream channels, which are aggraded to the level of the plain (fig. 18*C*), the ancestral-river channels are characterized by a linear surface depression and are partly filled with sediments identified as of Coonambidgal age by Pels. Gum Creek and the traces of older channels on the Murrumbidgee flood plain are ancestral rivers, according to Pels' definition (figs. 10, 11, 12). These channels have carried water during modern periods of major flooding on the plain.

The paucity of datable materials in the channels prevents the establishment of a history or chronology of prior-stream activity. The age of more than 36,000 years given by Pels suggests a Pleistocene age for some of the channels. The five ages given by Langford-Smith (1963) for the Riverine Plain prior streams (samples Y861–Y866) show a considerable range; however, the first two dates (samples Y861–Y862) now are thought to be for samples collected from eolian deposits (Langford-Smith, oral commun., 1965). Two of the remaining three dates are in reasonable agreement (4,700 and 4,090 B.P.) and suggests that at least the near-surface deposits of Mayrung channels are of Holocene age. The final date, in excess of 28,000 years B.P. was obtained from a sample taken from an older Quiamong prior-stream channel (Y866).

On the surface of the northern Riverine Plain (Murrumbidgee area), three types of river channels can be identified. First is the channel of the modern Murrumbidgee River, for which the present climatic and hydrologic controls are known. Less recent are Pel's ancestral-river channels, which now function only to carry intermittent floodwaters. The prior-stream channels have been aggraded and no longer carry any surface flows; however, at least two phases of near-surface prior-stream activity occurred on the Riverine Plain during the late Quaternary.

These three types of channels—prior, ancestral, and modern—have distinctive morphologic properties and clearly were formed under different climatic conditions. The obvious differences among these channels reflect the effect of climate on the type and volumes of sediment and the amount of runoff delivered to the Riverine Plain from the catchment area in the Eastern Highlands.

Current work on the stratigraphy of the Riverine Plain undoubtedly will considerably modify the conclusions derived from previous investigations. The problem of the ages of the channels will not be resolved until many more dates have been determined. Nevertheless, the lack of certainty regarding the age of the events, the significance of parna, and other matters should not prevent comparison of the channels and documentation of the changes that have occurred. Thus, the limited goals of this investigation can be achieved, although many other details of the geology and hydrology of the Riverine Plain remain unresolved.

## METHODS OF INVESTIGATION

In the effort to obtain data pertaining to the dimensions and sediment characteristics of the range of channels on the Riverine Plain, standard methods were used. For example, 10 readily accessible representative reaches of the Murrumbidgee River were selected for study (table 1). Five of these reaches are at or near existing gaging stations, and information on the discharge at these stations was furnished by the Water Conservation and Irrigation Commission of New South Wales. At each location a cross section was surveyed, and bed- and bank-sediment samples were collected. At all the sections the depth of water precluded wading, and soundings were made from a boat.

Fortunately, the prior-stream channels have been exploited during the past 15 years as a source of sand and gravel for the road-building program of the State of New South Wales and the local shires. Numerous pits have been opened in these channels, and several extend to the base of the deposit—the Mayrung-Katandra contact. These exposures facilitated the collection of sediment samples and the measurement of prior-stream dimensions. Information from bores into prior-stream channels was generously supplied by Mark Stannard and Simon Pels of the Water Conservation and Irrigation Commission of New South Wales, and these data were supplemented by sediment samples obtained by hand augering. Although most of the information obtained on the sediment and morphologic character of the prior streams was obtained at locations where the channels had been exposed in the pits, there appears to be no reason why data collected at these locations should not be representative of the prior streams.

Because the Quiamong sediments are not exposed continuously on the surface of the plain in the study area, the dimensions of the Quiamong channels could not have been obtained without initiating an extensive boring program. Therefore, in the investigation, attention is concentrated on the fluvial sediments that are younger than the Widgelli parna.

Good aerial photographs are available for the entire area. Survey data and maps, prepared by the Water Conservation and Irrigation Commission of New South Wales for the development of irrigation areas near the Murrumbidgee River, provided information on the gradient of the rivers and the slope of the Riverine Plain surface.

Sediment samples along the perimeter of the Murrumbidgee River channel were obtained by hand sampling and by use of a drag bucket. The grain-size characteristics of the sediment samples were obtained by sieving and by hydrometer analysis. The fact that the percentage of silt-clay exposed in the perimeter of a stable, alluvial channel is significantly related to the width-depth ratio and the sinuosity of the channel had previously been determined (Schumm, 1960b). Therefore, the silt-clay in the perimeter of the Murrumbidgee and prior-stream channels was calculated in this same manner as in the previous study. The percentage of sediment smaller than 0.074 mm in the perimeter is designated $M$, and

$$M=\frac{(Mc\times W)+(Mb\times 2D)}{W+2D}.$$

$Mc$ is the percentage of silt-clay in the samples taken from the floor of the channel, $Mb$ is the percentage of silt-clay in the bank samples, $W$ is the bankfull width of the channel, and $D$ is the maximum bankfull depth. This weighting procedure yields the percentage of silt and clay exposed in the bed and banks of the channel. A comparison of this calculated weighted mean percentage of silt-clay with the measured percentage of silt-clay in composite samples of bed and bank sediments for some Great Plains rivers is given in figure 3. The close agreement between the two sets of values demonstrates that the weighting procedure produces a parameter representative of the silt-clay in the channel perimeter.

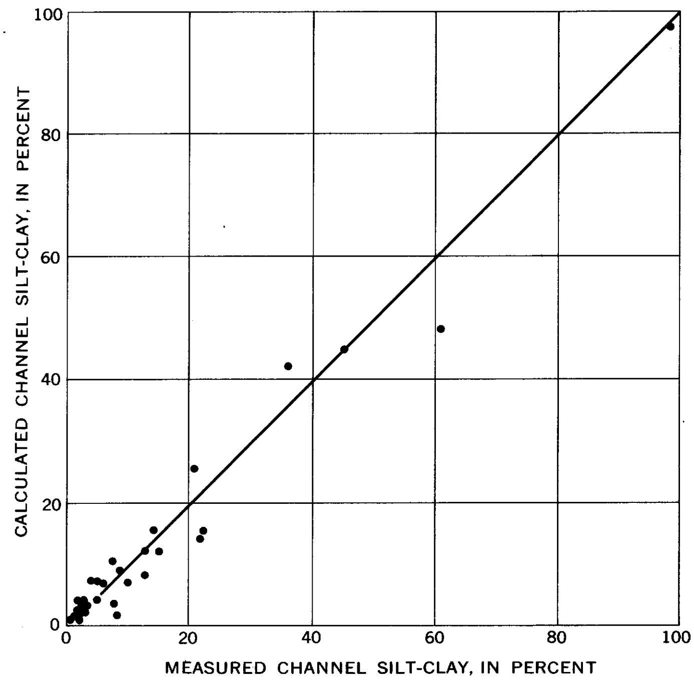


FIGURE 3.—Relation between calculated percentage of silt-clay (weighting procedure) and measured percentage of silt-clay (one composite sample) in the perimeter of alluvial stream channels.

Snags near the bank at several of the cross sections made taking samples from across the entire width of channel impossible. Nevertheless, it could be determined that the channel floor in these places is composed of fine sediments. Elsewhere, the cohesive bank sediments extend out into the channel, and the samples obtained by drag bucket were not considered to be representative. Thus, although the part of the channel composed of sand could be sampled, at some sections as much as one-third of the width of the channel floor is composed of fine sediment. At the Narrandera section the fine channel sediment contained about one-third less silt and clay than did the bank sediments. When the percentage of silt-clay in the channel perimeter at these locations was calculated, an adjustment was made to allow for that part of the channel floor that contained cohesive sediments.

## CHANNEL MORPHOLOGY AND HYDROLOGY

### MURRUMBIDGEE RIVER

The characteristics of the Murrumbidgee River and its drainage basin have been described in general terms above, and only the information collected at the representative reaches is presented here. Ten cross sections were surveyed across the Murrumbidgee River between Wantabadgery to the east and Maude to the west. The data acquired at each section are given in table 1, and the location of the sections is shown on plates 1 and 2. The channel sections studied on the Riverine Plain are the most pertinent to the discussions that follow. Nevertheless, information is also presented for three cross sections surveyed east of Narrandera.

At the Wantabadgery section the river is confined within a valley about 1 mile wide, but downstream the valley broadens, and at the Wagga Wagga and the Currawarna sections the river meanders freely on a wide flood plain. At Narrandera the river crosses the last outcrop of resistant rock and enters the Riverine Plain. The six sections surveyed west of Narrandera can be compared with the prior-stream channels of the Riverine Plain.

The photographs in figure 4 illustrate the type of river to be discussed, and the surveyed cross sections are plotted in figure 5.

TABLE 1.—*Data from Murrumbidgee River cross sections*

| Section No. | Location | Distance from Burrinjuck Dam (miles) | Channel | | | Gradient | | Width-depth ratio | Sinuosity | Median grain-size in channel (mm) | Silt-clay (percent) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Width (ft) | Depth (ft) | Area (sq ft) | Channel (ft per mile) | Valley (ft per mile) | | | | Bank | Channel |
| 1 | Wantabadgery | 107 | 241 | 17 | 3,300 | 1.5 | 1.8 | 14 | 1.6 | 0.88 | 50 | 0.07 |
| 2 | Wagga Wagga | 149 | 273 | 27 | 6,030 | .9 | 2.1 | 10 | 2.3 | .40 | 60 | 15 |
| 3 | Currawarna | 191 | 252 | 21 | 4,690 | .6 | 2.1 | 12 | 2.0 | .63 | 85 | 17 |
| 4 | Narrandera | 274 | 246 | 25 | 4,730 | 1.1 | 1.9 | 10 | 1.7 | .90 | 82 | 27 |
| 5 | Darlington Point | 338 | 220 | 23 | 3,680 | .7 | 1.3 | 10 | 1.9 | .71 | 70 | 23 |
| 6 | Yarrada Lagoon | 353 | 230 | 20 | 3,520 | .7 | 1.4 | 11 | 2.0 | .52 | 40 | 8.0 |
| 7 | Bringagee | 364 | 195 | 19 | 3,090 | .7 | 1.6 | 10 | 2.3 | .47 | 64 | .12 |
| 8 | Carrathool | 408 | 213 | 31 | 4,580 | .7 | 1.6 | 7 | 2.3 | 1.30 | 55 | 18 |
| 9 | Hay | 493 | 245 | 29 | 5,360 | .6 | 1.3 | 8 | 2.1 | .95 | 69 | 23 |
| 10 | Maude | 557 | 165 | 24 | 3,420 | .4 | .7 | 7 | 1.9 | .57 | 87 | 40 |

| Section No. | Location | Proportion of bed composed of bank sediment | Silt-clay in channel (*M*) (percent) | Mean annual discharge (cfs) | Mean annual discharge adjusted for diversion (cfs) | Mean annual flood, (cfs) | Bankfull velocity (ft per sec) | Bankfull discharge (cfs) | Terrace height above flood plain (ft) | Meander wavelength (ft) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Wantabadgery | 0 | 6.3 | | | | 4.0 | 13,000 | 15 | |
| 2 | Wagga Wagga | 1/4 | 19 | 4,560 | | 26,000 | 4.3 | 25,000 | 8 | 4,400 |
| 3 | Currawarna | 1/5 | 19 | | | | 2.9 | 14,000 | 5 | |
| 4 | Narrandera | 1/3+ | 29 | 3,661 | 4,081 | 15,000 | 4.2 | 20,000 | 3 | 3,100 |
| 5 | Darlington Point | 1/3 | 25 | 3,050 | 3,762 | 11,000 | 3.1 | 11,000 | 3 | 2,800 |
| 6 | Yarrada Lagoon | 1/5 | 11 | | | | 2.9 | 10,000 | | |
| 7 | Bringagee | 0 | 11 | | | | 2.9 | 9,000 | 5 | |
| 8 | Carrathool | 1/3 | 22 | | | | 3.6 | 16,000 | | |
| 9 | Hay | 1/3 | 25 | 3,116 | | | 3.5 | 20,000 | 5 | |
| 10 | Maude | 1/2 | 41 | 2,412 | | | 2.7 | 9,000 | 5 | |

#### MORPHOLOGIC AND SEDIMENT CHARACTERISTICS

The graphs in figure 6 illustrate the downstream changes in discharge, width, depth, width-depth ratio, gradient, sinuosity, median grain size, and silt-clay content of the Murrumbidgee River (table 1).

Channel width is the bankfull width, and channel depth is the maximum depth as measured from the top of the bank, indicated by the solid line in figure 5, to the deepest part of the channel. The width-depth ratio was calculated from these maximum values. Channel gradient was obtained from the longitudinal profile of the river, as surveyed by the Water Conservation and Irrigation Commission (fig. 7). Sinuosity is the ratio of channel to valley length, as measured over a valley length of about 5 miles near the cross section. The median grain size was obtained from the size-frequency curves of sediment samples, and the silt-clay content of the perimeter of the channel was obtained from the amount of sediment smaller than 0.074 mm in samples from the channel perimeter, as described previously.

The Murrumbidgee River differs from most rivers in that mean annual discharge decreases in a downstream direction (fig. 6). In the downstream direction, there is an overall decrease in width, width-depth ratio, and gradient. No progressive downstream change in channel sinuosity occurs, but there is an overall increase in channel depth. These changes are accompanied by a general increase in the amount of fine sediment exposed in the channel perimeter, but there is no progressive change in the median grain size of the channel sediment.

In figure 6 the marked decrease in channel depth, median grain size, and percentage of silt-clay at the Yarrada Lagoon and Bringagee sections (6 and 7) reflects the introduction of sand into the Murrumbidgee River where it intersects a major prior-stream channel near Darlington Point (pl. 2). The larger median grain size at the Carrathool section (8) reflects the introduction of coarser sediment into the channel where the river cuts into the older sediments of the Riverine Plain a short distance upstream.

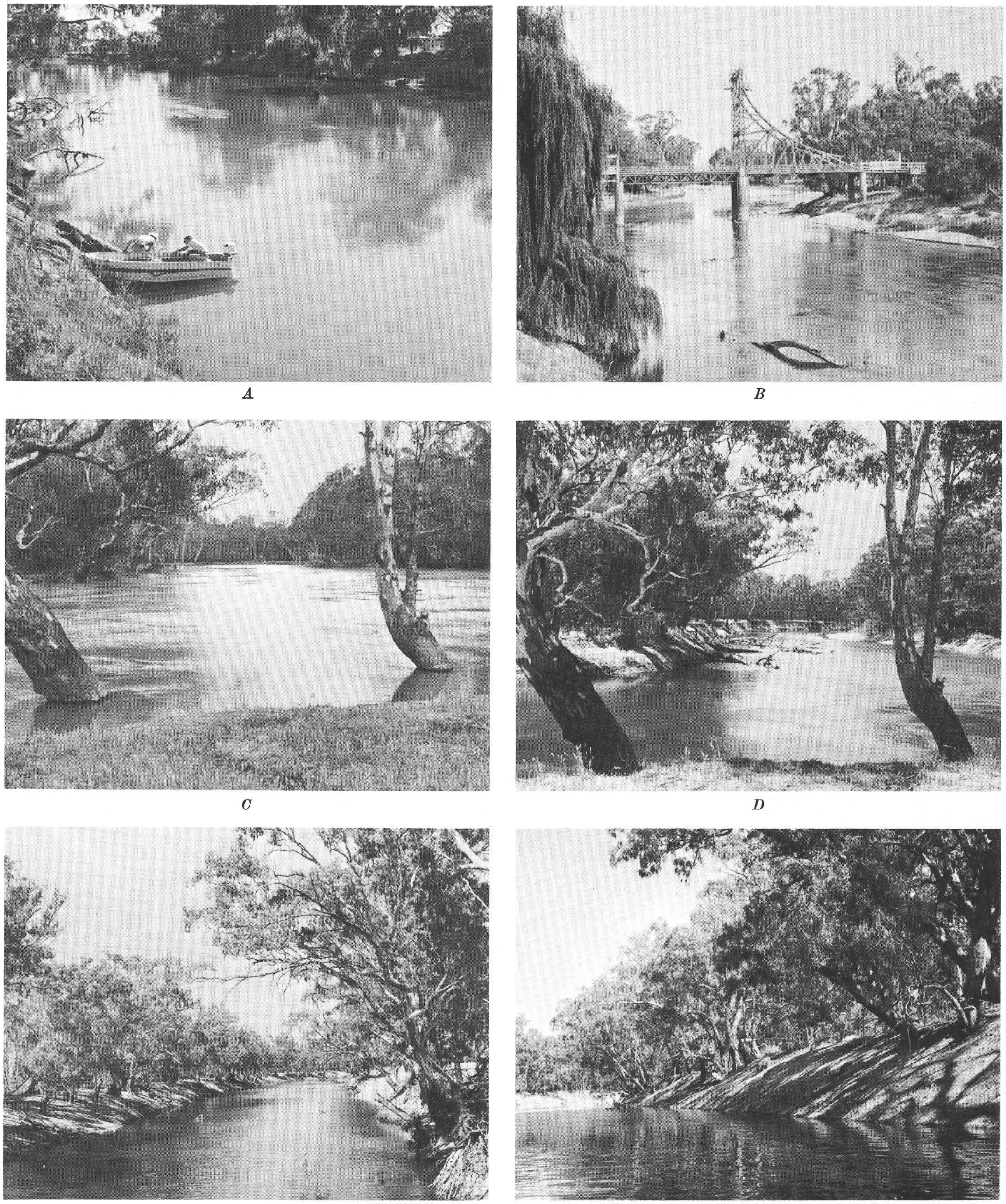


FIGURE 4.—Murrumbidgee River. *A*, Near Narrandera. *B*, At Darlington Point. *C*, Near 57 milepost on Sturt Highway about 20 miles west of Darlington Point, during high water, October 1964. *D*, Near 57 milepost on Sturt Highway during low water, March 1965. *E*, Near Carrathool bridge. *F*, Below Maude.

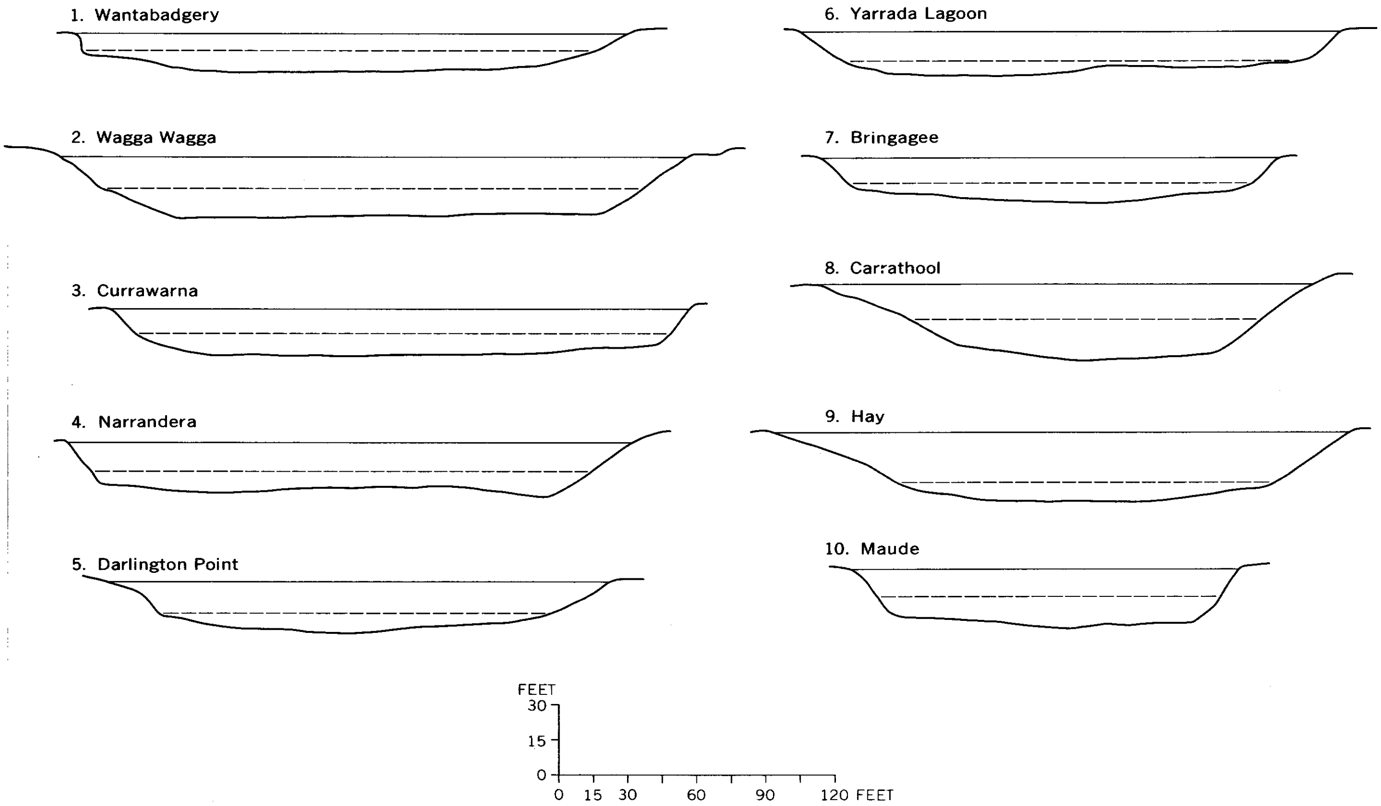


FIGURE 5.—Cross sections surveyed along Murrumbidgee River. Dashed line shows water level when survey was made, February 1965, and solid horizontal line designates bankfull stage.

Described simply, the Murrumbidgee River is a relatively narrow, deep (low width-depth ratio) sinuous river of low gradient.

#### EFFECT OF REGULATION ON MURRUMBIDGEE RIVER DIMENSIONS

Discharge in the Murrumbidgee River has been diverted and regulated; therefore, it is necessary to determine whether any major morphologic changes have resulted from these modern modifications in natural flow.

The earliest recorded statement concerning the dimensions of the channel is in the journal of Capt. Charles Sturt (1833), who followed the river to its mouth in 1829. According to Sturt (p. 34), the river was 70–80 yards wide near Wantabadgery. This width is very near the present width of 241 feet, as measured at the Wantabadgery cross section. Sturt stated that the river at Hamilton Plains) which, according to Cumpston (1951, p. 34), is somewhere between Narrandera and Darlington Point) was uniformly about 150–170 feet wide and a maximum of 20 feet deep. The widths given by Sturt are considerably less than those measured during the present study at the Narrandera and Darlington Point cross sections (table 1). However, Sturt may have been commenting on the width of the water surface rather than the bankfull width of the river, which, at the measured sections, is 30 feet wider than the water surface at low water. Nevertheless, the Narrandera section may be about 50 feet wider now than it was in 1829, and the Darlington Point section may be about 20 feet wider.

Along the Riverine Plain part of the river course, Sturt (1833, p. 61) noted that the Murrumbidgee was deeper than it was near the mountains, but that its width was "about the same." The increase in depth is in agreement with modern observations.

Some data on the past dimensions of the river were obtained from the Water Conservation and Irrigation Commission and the Main Roads Department of New South Wales. Bankfull widths and depths, as measured from old surveys, are given in table 2 for comparison with the dimensions measured during this investigation. Three of the seven locations for which data are available show little or no change in width and depth: Narrandera, 1902 and 1965; Darlington Point, 1954 and 1965; and Hay, 1873 and 1965 (table 2). The channel is smaller at present at Wagga Wagga, Carrathool, and Maude, but at the Currawarna section the width has increased and the depth has decreased. Several of the modern measurements were taken near, though not at, the exact locations of the early surveys; as a result, some lack of correspondence can be anticipated.

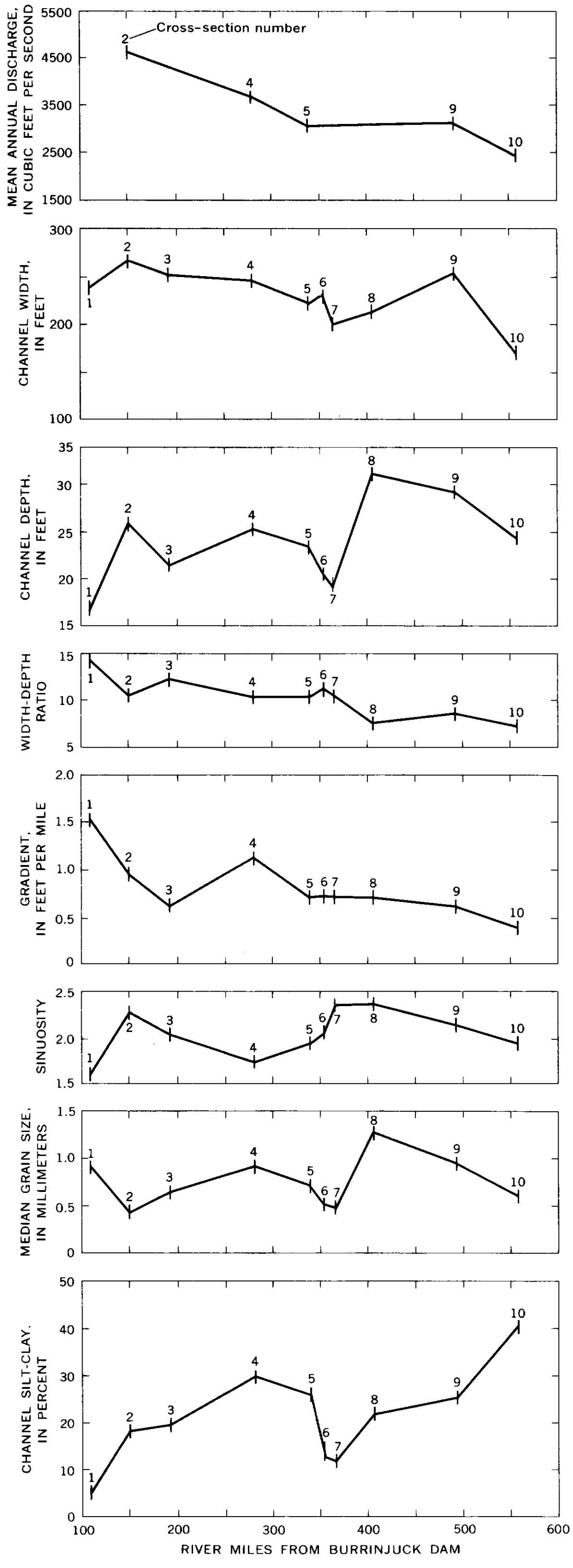


FIGURE 6.—Downstream changes in channel character, sediment size, and discharge at the Murrumbidgee River cross sections.

Although some changes have occurred along the river, as might be expected, neither progressive or systematic enlargement nor decrease in size of the channel has occurred during historic times. This lack of change suggests that the Murrumbidgee has a stable channel; that is, it is not progressively eroding or depositing as a result of changes in sediment loads or discharge. The modern channel of the Murrumbidgee River, though no doubt influenced somewhat by diversion and control, apparently reflects the modern climatic and erosional conditions in its drainage basin.

TABLE 2.—*Dimensions of the Murrumbidgee River channel*

| Location | Year | Width (ft) | Depth (ft) |
|---|---|---|---|
| Wagga Wagga | 1893 | 295 | 39 |
| | 1965 | 273 | 27 |
| Currawarna | 1938 | 228 | 25 |
| | 1965 | 321 | 21 |
| Narrandera | 1890 | 220 | 22 |
| | 1902 | 248 | 23 |
| | 1902 | 253 | 28 |
| | 1902 | 246 | 28 |
| | 1953 | 240 | 28 |
| | 1965 | 246 | 25 |
| Darlington Point Whitton weir | 1954 | 218 | 24 |
| | 1965 | 220 | 23 |
| Carrathool | 1920 | 243 | 34 |
| | 1965 | 213 | 31 |
| Hay | 1873 | 225 | 30 |
| | 1873 | 240 | 28 |
| | 1902 | 230 | 37 |
| | 1965 | 245 | 29 |
| Maude | 1902 | 200 | 27 |
| | 1930 | 200 | 19 |
| | 1952 | 246 | 21 |
| | 1965 | 165 | 24 |

## HYDROLOGY

A distinguishing characteristic of the Murrumbidgee River, as noted above, is a downstream decrease in discharge (fig. 6). This decrease in discharge is primarily the result of a decrease in precipitation toward the west, but the natural decrease in discharge is emphasized by diversion of water for irrigation at several locations. Diversion of water from the Murrumbidgee River was begun in 1879 when a canal was cut to connect the Murrumbidgee River and its former distributary channel, Yanko Creek (pl. 2). However, no information is available for Murrumbidgee River discharge prior to 1885.

The values of mean annual discharge given in table 1 are for 19 years of record—1937–39; 1942–51; 1954–56; 1958–60—common to the five gaging stations (Water Conservation and Irrigation Comm., 1956; B. Beck, written commun., 1965) near the surveyed cross sections. These data include the effects of the control of discharge since 1913 at Burrinjuck Dam, the diversion of 420 cfs (cubic feet per second) mean annual discharge into the main canal at Berembed weir above Narrandera since

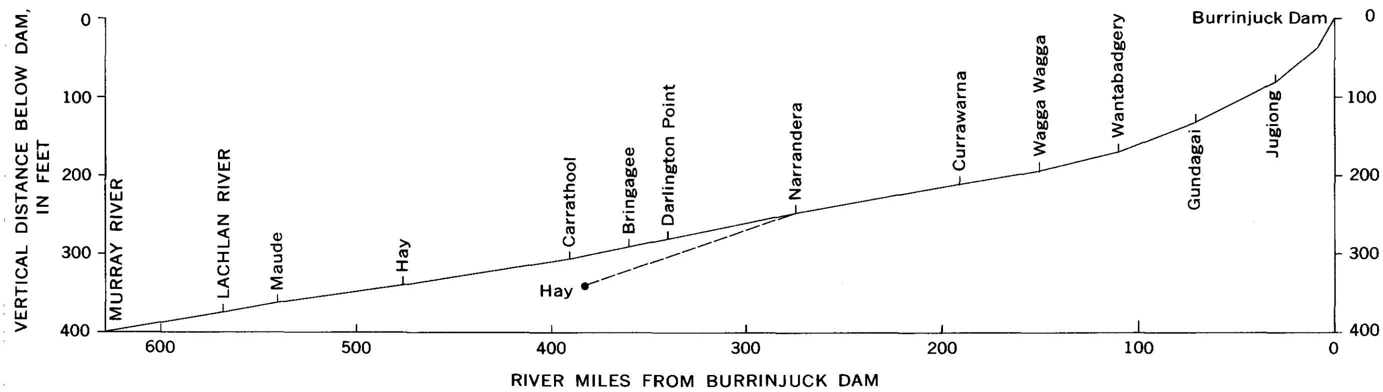


FIGURE 7.—Longitudinal profile of Murrumbidgee River from Burrinjuck Dam to the Murray River (based on New South Wales Water Conservation and Irrigation Comm. plans). Dashed line indicates longitudinal profile of prior stream between Narrandera and Hay.

1912, and a diversion of about 292 cfs mean annual discharge into Yanko Creek at the Yanko Creek weir since 1924.

Since 1940, water has been diverted from the river at the Maude weir to induce artificial flooding of the Lowbidgee area, but no estimate of the amount of diversion from the channel can be made. Diversions at the Golgeldrie weir began in 1960, and since 1961 the annual average diversion at the weir has been 220 cfs.

When the values of annual discharge are adjusted for the diversions at Berembed and Yanko Creek weirs, a decrease in discharge still occurs between Wagga Wagga and Darlington Point (table 1). The marked decrease in mean annual discharge between Hay and Maude can perhaps be attributed to the diversion of flow at the Maude weir. However, before the weir was constructed, some water was lost from the channel by overflow of floodwaters southward across the Riverine Plain.

Note that the double-mass curves in figure 8 do not show a decrease in discharge since 1913, when storage began behind the Burrinjuck Dam; rather, the curves indicate that discharge has increased since 1915. Perhaps the recurrence of major floods has been prevented by the regulation of flow. Such flow control may cause a greater amount of water to move through the Murrumbidgee River channel for a longer period of time than was possible previously, when channel overflow flooded the valley above Narrandera and the plain west of Narrandera. The increased flow for a longer period of time would also explain why the channel has not adjusted significantly to the effects of the regulatory structures, because despite the reduction in overbank flooding, bankfull floods still move through the channel.

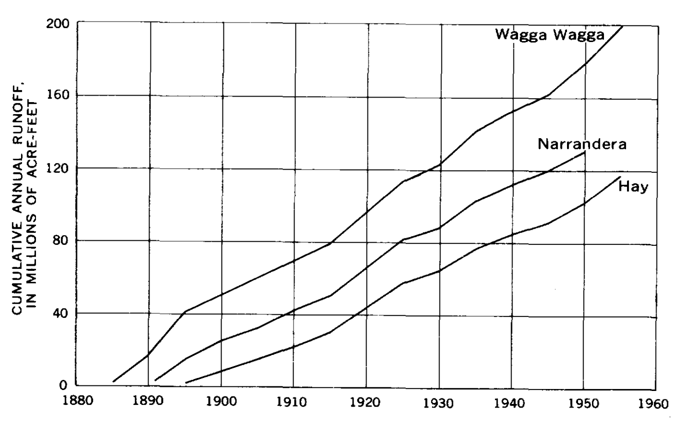


FIGURE 8.—Cumulative runoff at three gaging stations as plotted against time to demonstrate that no significant change in the annual discharge of the Murrumbidgee River has occurred during this century.

Information on the sediment discharge of the Murrumbidgee River is, unfortunately, lacking. No suspended-sediment samples have been collected along the Murrumbidgee River, probably for the simple reason that the Murrumbidgee River does not have a sediment problem. That is, sediment does not accumulate behind the weirs or in irrigation canals to the extent that remedial measures are required. Therefore, information on the sediment loads of the Murrumbidgee River is necessarily qualitative. During the low flow of summer the water is relatively clear, and swimming is a popular sport on the river. During the floods of winter the river water is turbid, which indicates a moderate concentration of suspended sediment.

During 1964, 24 suspended-sediment samples were collected at Oddy's Bridge on the Tumut River (data from files of Water Conservation and Irrigation Comm., Sydney). The Tumut River is a major tributary of the Murrumbidgee (pl. 1), and the samples were collected about 7 miles south of Tumut. Although the runoff is derived from the steep headwater parts of that basin, the maximum concentration of sediment in the water samples was 92 ppm (parts per million), a very low concentration.

In 1964 the sediment accumulation behind Berembed weir was removed, and it was established that only a few hundred cubic yards of sediment had accumulated since 1912 (Mr. Middleton, Principal Maintenance Engineer, Water Conservation and Irrigation Comm., oral commun., 1965). Of course, the weir gates are open during floods, and accumulated sediment may be flushed out of the slack-water area each year. Nevertheless, the accumulation of sand behind these structures could be a serious problem if the river were transporting large amounts of sediment.

Sediment surveys and sampling behind Burrinjuck Dam revealed that the amount of sediment being introduced into the reservoir is small. For example, the average suspended load introduced during the 6-year period ending June 30, 1916, was 416 ppm, and the total sediment accumulation in the reservoir was less than 5,000 acre-feet during the 24-year period 1938–62 (from files on siltation surveys, Water Conservation and Irrigation Comm., Sydney). If the figure of 5,000 acre-feet is used as the total sediment accumulation, the rate of sediment accumulation in this reservoir would be 210 acre-feet per year, or 0.042 acre-foot per square mile per year. The specific weight of a clay-silt mixture is about 75 pounds per cubic foot (Gottschalk, 1964, p. 17–18); therefore, the sediment yield is about 70 tons per square mile per year, a relatively low sediment yield.

For comparison, sediment accumulates in Lake Mead on the Colorado River at a rate of 877 tons per square mile per year and in Elephant Butte Reservoir on the Rio Grande River at a rate of 798 tons per square mile per year (Gottschalk, 1964, p. 17–29). In the Hume Reservoir on the Murray River, sediment accumulation rates are also very low (0.08 acre-ft, or 130 tons per sq mi). Sampling in this reservoir reveals that little or no bedload is present, that fine silts are being deposited, and that no delta building is indicated (E. Martin, written commun. in files of Dept. of Works, 1945). At the present rate of deposition, it would take 8,000 years to fill the Hume Reservoir with sediment (Craft, 1935, p. 142). The catchment area above the Hume Reservoir is geologically similar to that above the Burrinjuck Reservoir, but the relief is greater; therefore, one would expect higher sediment loads in the Murray River than in the Murrumbidgee. Nevertheless, the sediment load of the Murray River is low.

Along the Murrumbidgee River west of Narrandera, sand is exposed at low water at river bends (figs. 4*B*, 9, 10), but it is not likely that large amounts of sand can be moved through this sinuous channel (Brush, 1959).

Perhaps the most convincing evidence of the low rate of sand transport through the Murrumbidgee River is that based on the calculations of the velocity of bankfull discharge through the channel. Bankfull velocity, calculated by use of the Manning equation, at the cross sections on the Riverine Plain (table 1) is about 3 feet per second (roughness, $n$, was estimated at 0.035).

The calculated velocity of bankfull discharge can be compared with the traveltimes of approximately bankfull flood crests between the gaging stations. Data on the date and time of arrival of flood crests at Wagga Wagga, Narrandera, Hay, and Maude were obtained from the Water Conservation and Irrigation Commission (chart 145/287, sheet 1) for floods arriving at Wagga Wagga on July 5, 1942; October 28, 1949; July 26, 1950; July 26, 1951; August 11, 1952; October 4, 1953; March 17, 1956; and April 4, 1956. The average traveltime between Wagga Wagga and Narrandera, a distance of 125 miles, was 5 days, or 1.5 ft per sec; between Narrandera and Hay, a distance of 219 miles, 12 days, or 1.1 ft per sec; and between Hay and Maude, a distance of 64 miles, 2 days, or 1.9 ft per sec. The calculated velocities for the cross sections are higher than the average values. This difference can be expected because the average channel roughness, for example, is probably greater than that estimated for the individual channel cross sections, which were surveyed at straight reaches of the channel.

The sand load transported through a channel can be calculated by the method developed by Colby (1964, fig. 26), if the mean depth of the channel, the median grain size of the bed sediment, and the mean velocity of flow are known. For the three cross sections on the Riverine Plain between Narrandera and Carrathool (5, 6, 7), mean depth is about 16 feet, median grain size is 0.6 mm, and average velocity about 3 feet per second. On the basis of these values, the estimated discharge of sand per foot of width of the Murrumbidgee River channel is about 9 tons per day per foot of width, or, at a width of 220 feet, about 2,000 tons per day. If channel width were reduced by one-third to adjust for that part of the bed not covered with sand (table 1), the sand load at bankfull discharge would be about 1,400 tons per day. For a river with a bankfull discharge of 10,000 cfs, this is a low rate of sand transport, and at low flows the movement of sand would be negligible. Indeed, if the average velocity of the flood crests between Narrandera and Hay of 1.1 ft per sec is used in the calculation, a sand load of only about 0.004 ton per day per foot of width, or about 1 ton per day, results.

In summary, the limited information available suggests that the Murrumbidgee River is not transporting large amounts of sediment and that the greater part of the sediment load being transported is in suspension. The velocity data provide strong evidence for this conclusion because large volumes of sand cannot be moved at such low flow velocities.

## ANCESTRAL RIVERS

A system of river channels intermediate in age between that of the modern river and that of the prior-stream channels was recognized by Butler (1960) and described and termed "ancestral-river channels" by Pels (1964b, 1966). These channels are associated with the Coonambidgal sediments and occur as depressions (fig. 18*A*) on the Riverine Plain and on the flood plain of the Murrumbidgee River. They commonly carry water during floods, and they are obviously remnants of channels that were much larger than the modern river channel (Pels, 1964b, p. 113). Pels' description of these channels specifically refers to those associated with the Murray River south of the Murrumbidgee River area, but his inferences can be applied to the features of the Murrumbidgee River area as well.

### MORPHOLOGIC AND SEDIMENT CHARACTERISTICS

Along the course of the Murrumbidgee River between Narrandera and Gum Creek, numerous traces of the ancestral-river channels can be recognized on the flood plain. The flood plain of the Murrumbidgee River has a very irregular contact with the sediments of the Riverine Plain (fig. 9). The margins of the flood plain were formed by large meander loops of the older, ancestral river. At three locations the traces of this old channel are preserved as oxbow lakes (figs. 9, 10, 11).

The width of the ancestral-river channel at these locations ranges from 420 to 530 feet and averages about 460 feet. The ancestral-river channel followed by Gum Creek (fig. 12) is only about 375 feet wide, however, because it was a distributary channel of the main river and probably carried only about half the total river flow. Below the point where Gum Creek leaves the Murrumbidgee flood plain, the width of the flood plain and the dimensions of the meander scars are considerably reduced in size, as would be expected in any channel in which discharge has been reduced (figs. 13, 14, 15). Apparently in the recent past the discharge of the Murrumbidgee River was considerably larger than at present, and at that time both the wide ancestral-river channels and the two major distributary channels—those of Yanko Creek and Gum Creek—were formed.

Some information on the depth of the ancestral-river channels was obtained from drilling records of the New South Wales Water Conservation and Irrigation Commission. For example, boring into the ancestral-river channel at Tombullen Swamp (pl. 2) revealed that the ancestral river incised into the sands of a buried prior-stream channel and removed these sands to a depth of 32 feet below the surface of the Riverine Plain, or to about 20 feet below the surface of Tombullen Swamp.[1]

[1] A. Stocklin, 1963, unpub. Water Conservation and Irrigation Comm. Misc. Rept. 631C2394.

Borings into the Murrumbidgee River channel at weir site 8 and at the Whitton weir site (pl. 2) provided further information on the ancestral-river channel (fig. 16), and the data suggest that the depositional history of the Murrumbidgee River flood plain is more complex than the surface evidence indicates (Pels, 1966).

The greatest depths measured in the Murrumbidgee River were 22 feet at the Whitton weir site and 26 feet at weir site 8. At the Whitton weir site (fig. 16*A*) the channel is underlain by sand to a depth of about 8 feet. Farther downstream, at weir site 8 (fig. 16*B*), sand extends to about 15 feet below the floor of the channel, or 40 feet below the level of the flood plain. However, a lens of fine sediment underlies the channel on the left side at a depth of 6 feet, so that probably only about the upper 6 feet of this sand layer can be associated with scour by the modern channel.

Underlying the sand is a layer of finer sediment that extends to a depth of 35 feet below the flood plain at the Whitton weir site and to a depth of 48 feet at weir site 8. Below the fine sediment is another deposit of sand, about 10 feet thick. The top of this second, or lower, sand deposit probably represents the approximate depth at which the ancestral-river channel was stable, if one assumes that this lower sand deposit had the same relation to the ancestral-river channel as the upper sand now has to the modern river channel. Also, the depths of 35 and 48 feet below the flood plain are similar to the depth of the channel at Tombullen Swamp, and if used with an average width of 460 feet to calculate the width-depth ratio, they yield a width-depth ratio of between 10 and 13 for the ancestral river. These width-depth ratios are similar to those obtained for the channel of the modern river.

Beneath the second sand deposit is an additional layer of finer sediment and, finally, a third sand deposit, all of which indicate past river activity at a depth of 45–60 feet below the present flood plain. This third sand deposit overlies a dense clay, presumably the Katandra.

The sequence of sedimentary deposits that lies beneath the modern channel suggests a complex depositional history for the flood plain, and provides evidence for at least two earlier phases of river activity and scour to a depth of 55–64 feet.

Much less information is available for Gum Creek (fig. 12), but as suggested above, it was probably a distributary of the ancestral Murrumbidgee River. Gum Creek is about 350 feet wide, and the floor of the depression lies 5 feet below the Riverine Plain (fig. 18*A*). In a shallow hole augered into the floor of the channel, 11 feet of clayey sediment was penetrated before sand


FIGURE 9.—Murrumbidgee River and Riverine Plain 10 miles west of Darlington Point. The ancestral-river channel which forms Yarrada Lagoon can be seen in the center of the figure. (See also fig. 11*A*.) The Sturt Highway borders the larger ancestral-river meander scars south of the flood plain. The northern prior-stream (arrow) channel parallels the highway (bottom of figure). (Photograph courtesy of the New South Wales Lands Dept.)


FIGURE 10.—Murrumbidgee River and a large ancestral-river channel preserved on the flood plain as an oxbow lake, southeast of Carrathool. (See also fig. 11*B*.) (Photograph courtesy of the New South Wales Lands Dept.)

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FIGURE 11.—Ancestral-river channels. *A*, Yarrada Lagoon, November 1964. (See also fig. 9.) *B*, Carrathool oxbow lake, February 1965. (See also fig. 10.)

was reached at a depth of 16 feet below the surface of the plain. If this depth is taken as the depth of the channel, the width-depth ratio of the channel was 22, and the sinuosity 1.7. The sinuosity of the ancestral river in the flood plain of the modern river is about 1.7, as estimated from the fragmentary pattern visible on aerial photographs.

The bed and bank sediments of the ancestral-river channel were not sampled, but if previously developed relationships are applicable (Schumm, 1963a), a channel having a sinuosity of 1.7 and a width-depth ratio of 13 can be expected to have about 16 percent silt-clay along the channel perimeter.

In summary, the width and depth of the ancestral-river channel and the amplitude and wavelength of its meander pattern were much greater than the same dimensions of the modern river; nevertheless, the slope, sinuosity, and sediment characteristics of the ancestral-river channel were not greatly different from those of the modern river channel.

### PALEOHYDROLOGY

The volume of water that passed through the ancestral-river channels was undoubtedly considerably greater than that passing through the channel of the modern river, but the concentration and type of sediment transported by the ancestral river was not greatly different.

Perhaps the most significant information obtained from the Tombullen Swamp bores is that the ancestral stream apparently transported large quantities of fine sediment. The bores revealed that this ancestral-river channel is filled with clayey sediment.[2] Also, the upper 20–40 feet of the Murrumbidgee River flood plain (Coonambidgal riverine) is composed of fine-grained alluvium (fig. 16), which indicates that both the modern river and the ancestral rivers were characterized by low sand loads.

Only very crude estimates of the volumes of water and sediment that passed through the ancestral-river channels can be made. If channel roughness and gradient are assumed to have been the same as in the Murrumbidgee River ($n=0.035$ and $S=0.0013$), and the hydraulic radius was 26 feet for a maximum depth of 35 feet, then bankfull mean velocity, as calculated by the Manning equation, would have been 4.2 feet per second, or somewhat greater than that of the modern Murrumbidgee. Bankfull discharge would have been on the order of 51,000 cfs, or about five times that in the Murrumbidgee River. Another means of estimating bankfull discharge is by the relation between meander wavelength and bankfull discharge, as developed by Dury (1965, fig. 6). Meander wavelength, as measured on aerial photographs, for the ancestral-stream channel is about 7,000 feet. Using this value, bankfull discharge, as estimated from Dury's regression line, is about 60,000 cfs.

[2] A Stocklin, 1963, unpub. Water Conservation and Irrigation Comm. Misc. Rept. 631C2394.


FIGURE 12.—Gum Creek ancestral-river channel meanders across upper half of photograph. Northern prior-stream channel (arrow) crosses from east to west (right to left) in lower half of photograph. Tree-covered sand dunes border the prior-stream channel. (Photograph courtesy of the New South Wales Lands Dept.)


FIGURE 13.—Murrumbidgee River and Riverine Plain about 12 miles northeast of Hay. Flood-plain width is considerably narrower here. Prior-stream channel crosses photograph from southeast to northwest (lower right to upper left). (Photograph courtesy of the New South Wales Lands Dept.)


FIGURE 14.—Murrumbidgee River and Riverine Plain at Hay. Hay pit is in the prior-stream channel south of the airport (arrow). (Photograph courtesy of the New South Wales Lands Dept.)

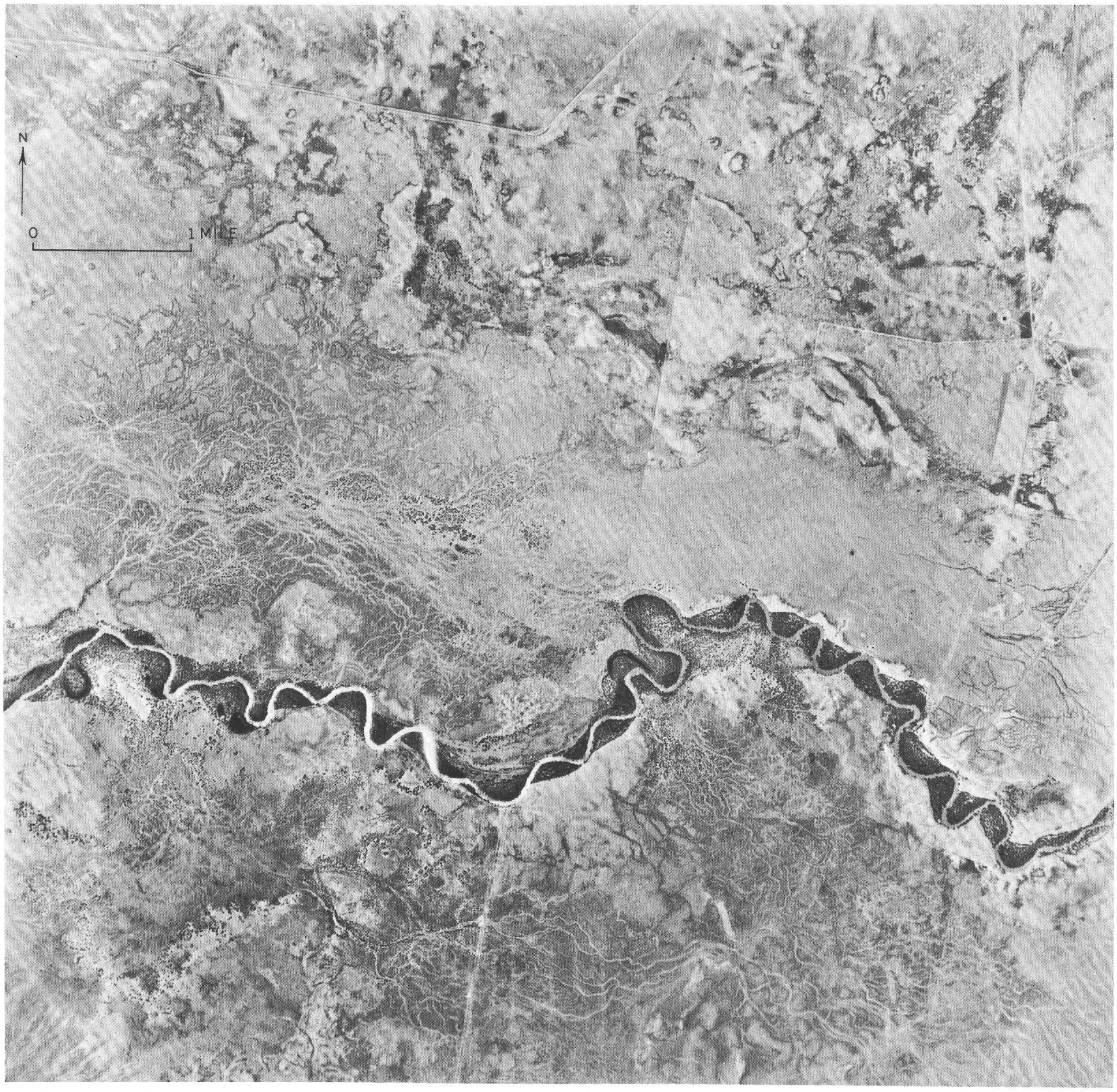
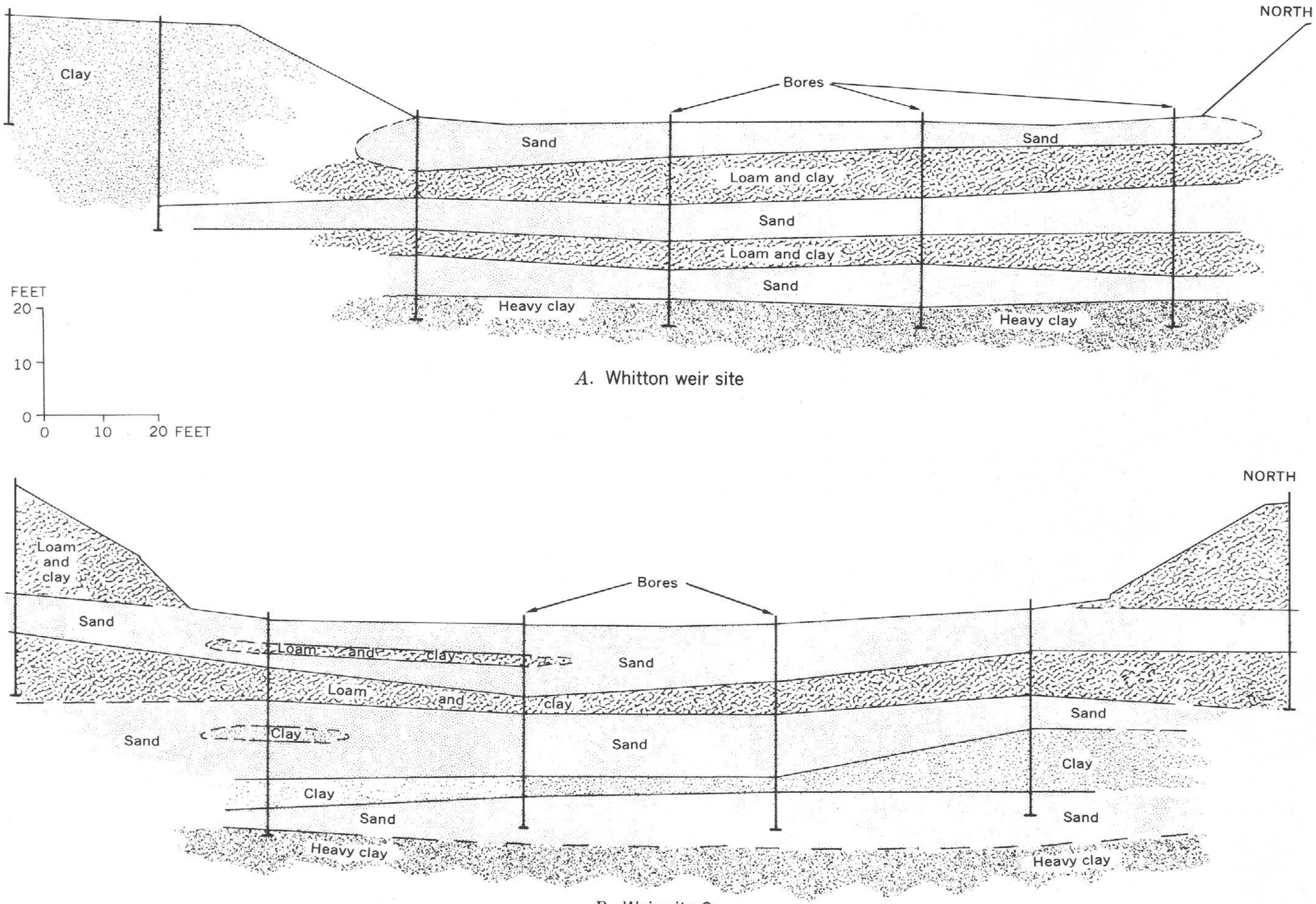



FIGURE 15.—Murrumbidgee River and Riverine Plain near Maude. (Photograph courtesy of the New South Wales Lands Dept.)




*A.* Whitton weir site

*B.* Weir site 8

**FIGURE 16.—Channel of Murrumbidgee River and associated flood-plain sediments at the Whitton weir site and at weir site 8. (From New South Wales Water Conservation and Irrigation Comm. Plans cat. Nos. 145–101, 145–103.)**

If one assumes that the sand transported through the ancestral-river channels was approximately the same size as that which moves through the modern channel, Colby's (1964, fig. 26) graph indicates that at bankfull discharge the sand load transported per foot of channel width would have been 45 tons per day, or 21,000 tons per day at bankfull discharge. Bankfull discharge and sand load per foot of channel width at bankfull discharge were about five times greater in the ancestral-river channel than in the Murrumbidgee River.

The ancestral rivers transported larger quantities of water and sediment through their larger channels than does the modern river, but the percentage of the total sediment load that was transported as sand probably did not differ greatly from that of the modern river.

## PRIOR STREAMS

Data on morphologic and sediment characteristics were somewhat easier to obtain for the prior-stream channels than for the ancestral-river channels because sand pits had been excavated into the prior-stream channels during construction of the Sturt Highway (pl. 2). In addition, data from Water Conservation and Irrigation Commission bores were used to determine the form and stratigraphy of the channels, and aerial photographs were used to establish the location of the prior streams in the field and to obtain information on their width and sinuosity (table 3).

The prior-stream channels that were studied are of two types: the major channels south of the Murrumbidgee River, and the distributary channels both north and south of the Murrumbidgee River (pl. 2). All the prior-stream channels investigated are probably of Mayrung age, according to Butler's (1958) classification, because they are all visible on the surface of the Riverine Plain.

### MORPHOLOGIC AND SEDIMENT CHARACTERISTICS

Three large pits have been excavated into prior-stream channels (Kulki, Kearbury, and Smith pits), and information from bores is also available. At the three pits (pl. 2), an understanding of the dimensions and shape of the prior-stream channels can be acquired.

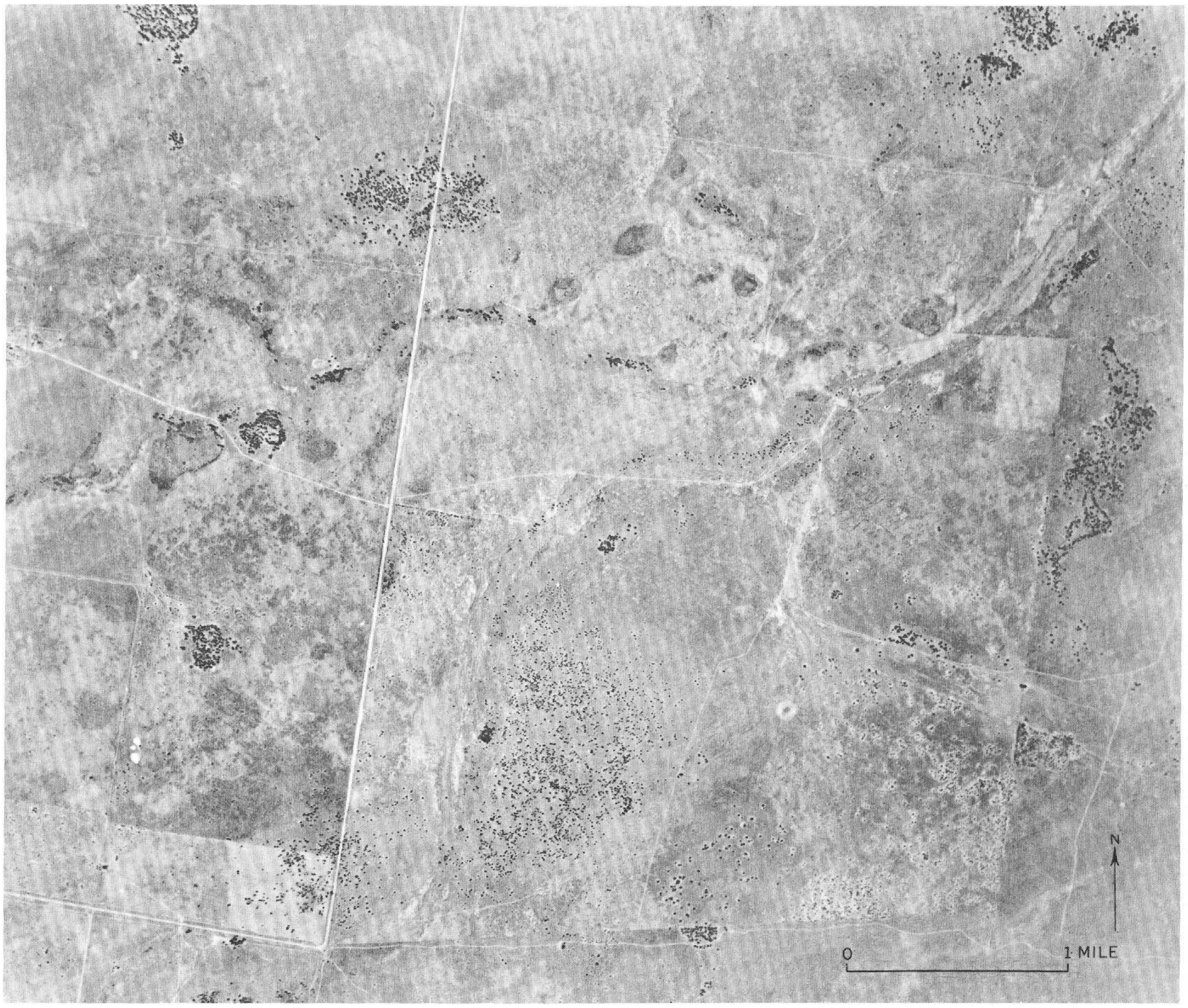



FIGURE 17.—Central prior-stream channel. Kulki pit is just west of area shown in photograph. Position of Stannard's (1962) bores can be estimated from locations shown on plate 2. (Photograph courtesy of the New South Wales Lands Dept.)

For example, the Kulki sand pit on Stannard's (1962) central prior stream (fig. 17) exposes the prior-stream sediments (fig. 18*B*) in a 30-foot-deep excavation. Also, cross sections of the prior-stream deposit, as interpreted from bore data, show the subsurface distribution of sediment types at the Kulki pit and at several other locations (fig. 19) along this prior stream.

The channel sediments were sampled with relative ease in the pits, but the measurement of channel dimensions was much more complicated. Although the pits were generally dug in the center of a prior-stream channel, the excavations were too small to reveal the full dimensions of the channels. For example, the central prior-stream channel, east of the Kulki pit, is about 400 feet wide, as measured on the aerial photograph (fig. 17). However, the cross sections (fig. 19) show that the deposit of crossbedded sand is much larger than is indicated by the channel surface expression.

All the sand deposits are roughly lenticular in cross section; the lower part of the deposit fills a channel scoured into the Katandra clay, and the upper part tapers upward toward the center of the channel that is visible on the aerial photograph (fig. 17). The form of the upper part of these accumulations, as delineated in Stannard's profiles, resembles that of deposits formed by an aggrading stream that transports appreciable bed load and suspended-sediment load (Schumm, 1960a, fig. 2*B*)—that is, as sand is deposited on the channel floor, fine sediments are deposited on the banks, and

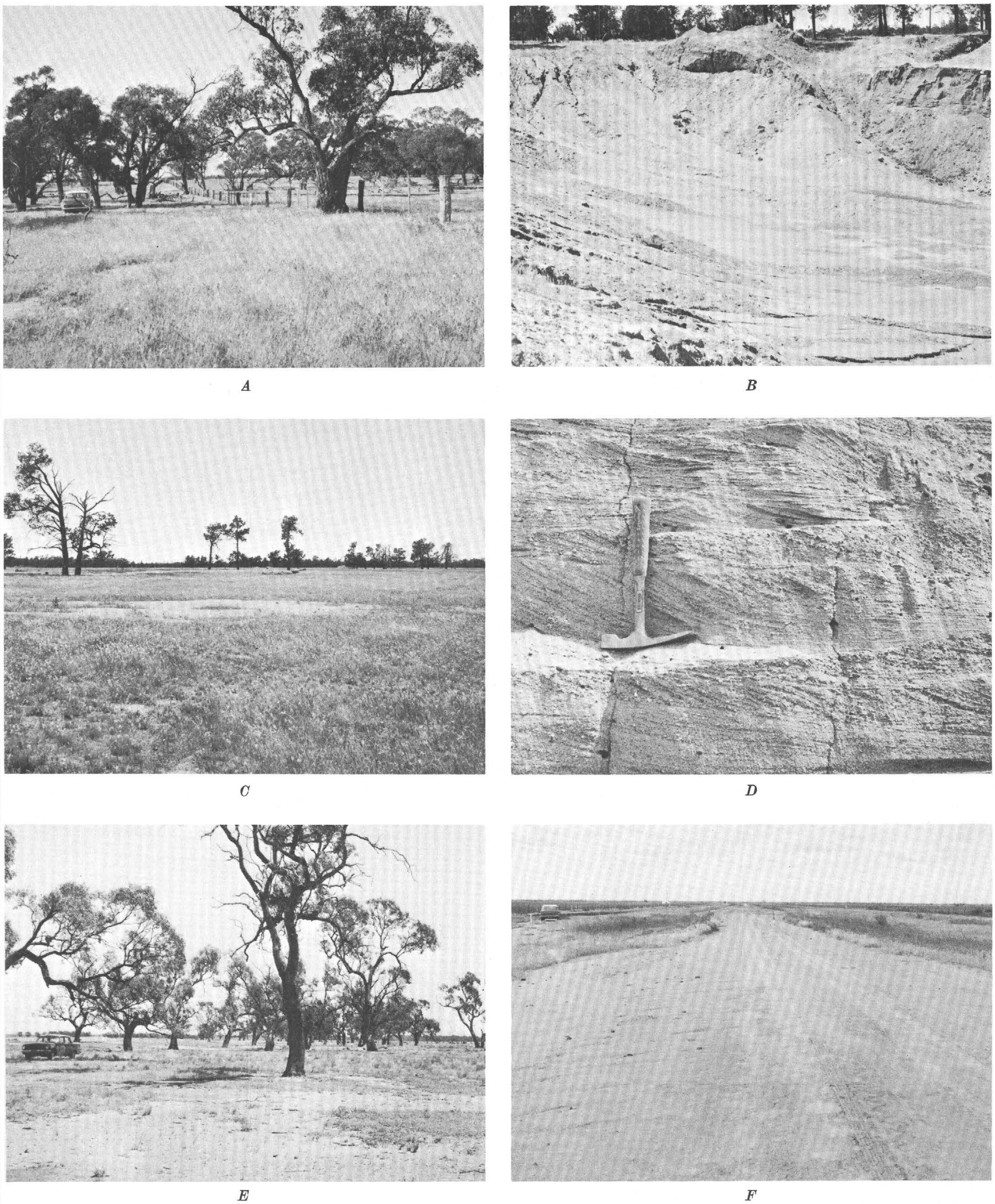



FIGURE 18.—Paleochannels. *A*, Gum Creek ancestral-stream channel. *B*, Kulki pit in central prior-stream channel. *C*, Northern prior stream, as viewed facing upstream from Kearbury pit. *D*, Crossbedded channel sands exposed in Smith pit. *E*, Prior-stream channel occupied by eucalypts south of Hay Airport. (See also fig. 14.) *F*, Road crossing Benerembah prior streams. (See also fig. 23.)

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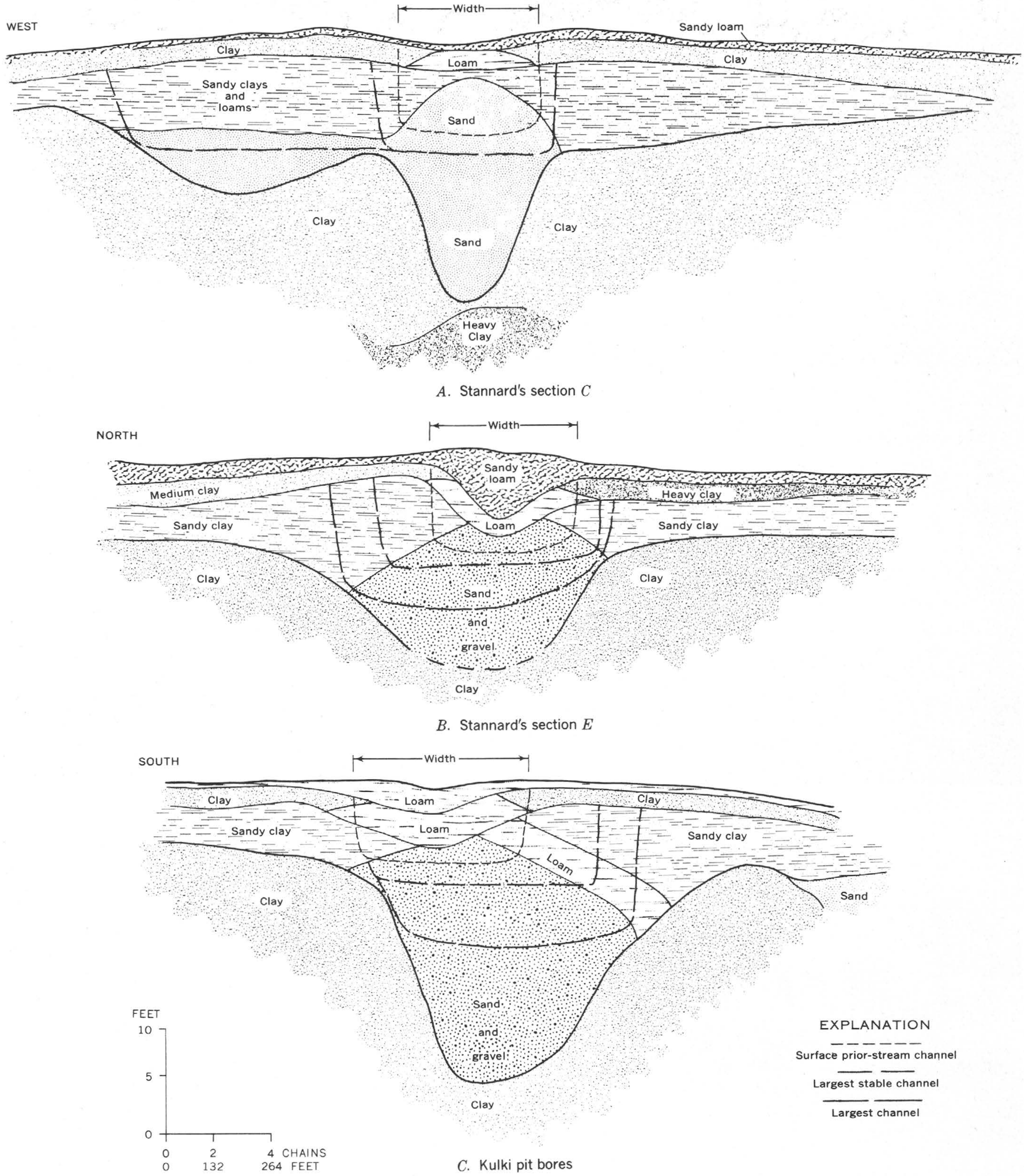


FIGURE 19.—Generalized cross sections of central prior-stream channel, based on unpublished data compiled by Mark Stannard. *A*, Stannard's bore section *C* (pl. 2). *B*, Stannard's bore section *E* (pl. 2). *C*, Stannard's bore section near Kulki pit (pl. 2).

both shallowing and narrowing of the channel occur concurrently.

The widths of the prior-stream channels, as measured on aerial photographs, can probably be taken as the actual channel widths during the last phase of flow on the Riverine Plain. These channels are possibly analogous to those of modern rivers that flow over considerable thicknesses of fluvial deposits beneath their flood plains. The cross sections (fig. 19) show that a layer of clay overlies much of the deep prior-stream sand deposit, and this fine-grained sediment is probably analogous to the flood-plain sediments of modern rivers.

An estimate of the depth of the prior streams is less easily obtained, for intuitively one would not take the maximum depth of scour into the Katandra riverine sediment to be the depth of a stable channel. For example, at one of Stannard's sections (*A*), which was surveyed at a bend near Kulki pit (fig. 20), lateral shifting of the channel occurred 25 feet below the surface of the plain. Apparently the deepest scours, now filled with sand, were not maintained for any appreciable time, for they extend 35–40 feet below the present surface of the plain, whereas the surface of lateral planation is at the shallower depth.

At this cross section (fig. 20) the depth of the stable alluvial channel can be estimated to have been no greater than about 15 feet. This estimate is based on the conclusion that about 10 feet of deposition occurred above the level of the well-defined bank of this channel after it ceased to be functional. This deposition raised the level of both the channel floor and the surface of the Riverine Plain at this site with concurrent narrowing of the channel. A final phase of channel stability, prior to the complete filling of the channel, established the dimensions of the prior-stream channel still visible on the surface of the plain.

Additional evidence for the relative shallowness of the prior-stream channels was obtained at Lone Gum pit (pl. 2), which is also on a bend of a prior stream. Sand occurs in this pit at 8.5 feet below the surface, and clay at 12.5 feet below the surface. Lateral shifting of the channel at this bend has occurred and lateral planation of the clay at a depth of 12.5 feet was the result. The depth of the prior-stream channel at the Lone Gum pit was not greater than 9–10 feet.

Pels (1964a), in a study of the prior-stream deposits southwest of Griffith in the Benerembah Irrigation District, concluded that the depth of these channels during their last phase of activity was about 10 feet. Again, the evidence suggests that, although the maximum depth of the sand deposit is considerable, the depth of the channel during the final stable phase was not great.

Three channel cross sections have been sketched on the cross sections of the central prior stream (fig. 19). The smallest of the three is associated with the surface expression of the prior streams and the loamy channel fill, whereas the largest designates the largest channel that can be related to the deposit. The top, or bank level, of the smallest channel was drawn at the top of the clay layer (fig. 19), now 1–2 feet below the surface of the plain and overlain by fluvial and eolian sediments.

Channel depths were obtained by measuring from the top of the banks to the level at which the downward projections of the banks intersect channel sands (fig. 19). The stable channels could not have been significantly deeper than this point of intersection—about 8 feet in these sections—because exposure of sand beneath the fine bank sediments at a greater channel depth would have caused bank caving and channel widening. Where scour by the modern Cimarron River in Kansas exposed sand beneath finer bank sediments, significant channel widening occurred, as the banks were undercut (Schumm and Lichty, 1963). Therefore, to maintain a stable alluvial channel of the width measured on the surface of the plain, the depth of the channel could not have been greater than about 10 feet.

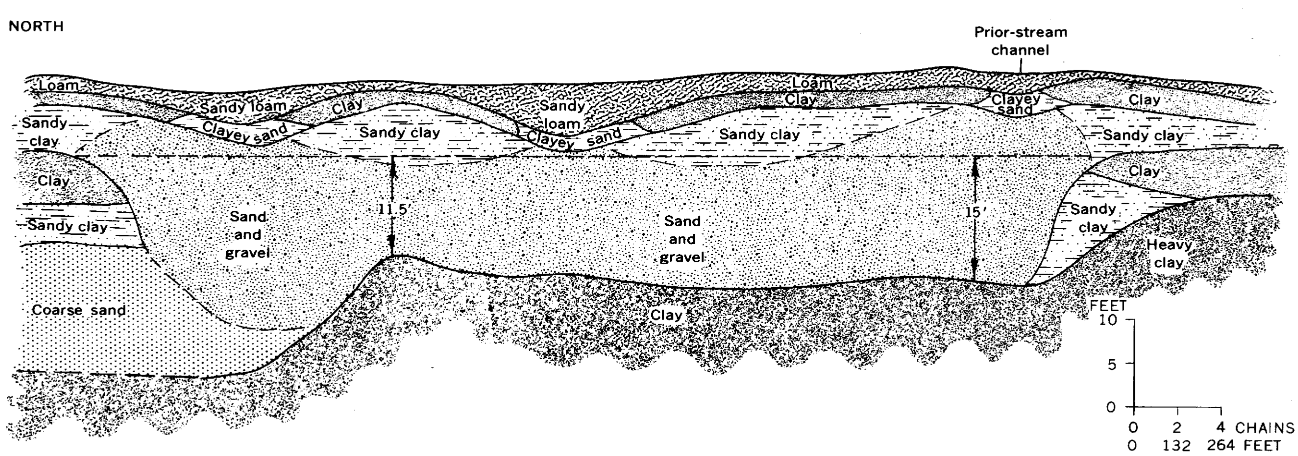


FIGURE 20.—Generalized cross section of central prior-stream channel at a bend (Stannard's bore section *A*, pl. 2).

The width of the largest channel that could have been associated with the deposit was taken as the maximum width of the deposit of crossbedded sand, which did not permit the older, underlying riverine sediment to crop out in the floor of the channel (fig. 19). The width of this channel might have been as much as 1,200 feet (fig. 19*A*) where some lateral shifting of the channel occurred, but it was more likely to have been about 800 feet (fig. 19*B*, *C*). The depth of the large channel was obtained by measuring from the bottom of the clay layer, which overlies much of the channel, to the deepest point at which crossbedded sand was reached. On this basis the depth of the largest channel would have been about 14 feet (fig. 19*B*, *C*). However, at this depth the base of at least one bank would probably have been stabilized by the older riverine sediment.

A channel of intermediate dimensions is also sketched on the sections in figure 19, and it is assumed that a channel of this size is the largest that could have been stable during the time that the prior streams were functioning—that is, the largest channel formed of river-transported alluvium. When depth is measured to a position where the older sediments could not influence channel stability, channel depth and width decrease by about one-third from those of the largest channel. The dimensions of the small, medium, and large prior-stream channels are given in table 3 and are summarized in table 4.

The data obtained from these sections indicate that the central prior stream was on the order of 500 feet wide during the last phase of flow, when its banks were near the surface of the plain. It probably was never wider than about 800 feet (table 3). The depth was about 8 feet. Thus, the width-depth ratio was about 63.

TABLE 3.—*Data for prior-stream channels*

| | Width (ft) | Depth (ft) | Width-depth ratio | Sinuosity | Gradient (ft per mi) | Channel median grain size (mm) | Silt-clay | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Bed (percent) | Bank (percent) | Channel perimeter (percent) | Adjusted channel (percent) |
| **Central prior streams** | | | | | | | | | | |
| Kulki pit | 400 | 10 | 40 | 1. 2 | 2 | 0. 60 | 0. 3 | 66 | 3. 4 | |
| Bores Kulki: [1] | | | | | | | | | | |
| Small | 500 | 8 | 63 | 1. 2 | 2 | | | | 3. 4 | |
| Medium | 660 | 9 | 74 | | | | | | | |
| Large | 800 | 14 | 57 | | | | | | | |
| Bores *C*: [2] | | | | | | | | | | |
| Small | 400 | 9 | 44 | | | | | | 3. 4 | |
| Medium | 530 | 20 | 26 | | | | | | | |
| Large | 1, 300 | 20 | 65 | | | | | | | |
| Bores *E*: [3] | | | | | | | | | | |
| Small | 420 | 8 | 53 | | | | | | 3. 4 | |
| Medium | 660 | 9 | 73 | | | | | | | |
| Large | 770 | 12 | 64 | | | | | | | |
| Gala Vale pit | 400 | 10 | 40 | 1. 2 | 2. 0 | . 63 | . 7 | 66 | 3. 8 | |
| **Northern prior stream** | | | | | | | | | | |
| Kearbury pit | 650 | 7 | 93 | 1. 05 | 2. 1 | 0. 55 | 0. 3 | 36 | 1. 1 | 1. 6 |
| Bores Kearbury: [4] | | | | | | | | | | |
| Small | 600 | 9 | 67 | | | | | | | |
| Medium | 1, 000 | 12 | 83 | | | | | | | |
| Large | 1, 700 | 20 | 90 | | | | | | | |
| "S" pit | 650 | 8 | 81 | 1. 0 | 1. 9 | . 61 | . 4 | 36 | 1. 3 | 2. 0 |
| Conargo Road pit | 425 | 9 | 47 | 1. 1 | 1. 7 | . 60 | . 3 | 36 | 1. 8 | 3. 1 |
| Lone Gum pit | 525 | 8 | 66 | 1. 1 | 1. 0 | . 80 | 1. 1 | 58 | 2. 8 | |
| Hay pit | 525 | 9 | 58 | 1. 1 | 1. 0 | . 40 | 1. 0 | 59 | 3. 0 | |
| **Distributaries** | | | | | | | | | | |
| Wahwoon pit | 525 | 9 | 65 | 1. 1 | 1. 0 | 0. 43 | 0. 3 | 88 | 2. 9 | |
| Kangaroo pit | 525 | 9 | 58 | 1. 1 | 1. 0 | . 83 | 3. 4 | 30 | 4. 5 | 5. 4 |
| Elginbah pit | 475 | 7 | 68 | 1. 2 | 1. 3 | . 45 | . 3 | 33 | 1. 2 | 2. 2 |
| Smith pit | 420 | 7 | 60 | 1. 1 | | . 43 | 1. 2 | 66 | 3. 7 | |
| Bores Smith: [5] | | | | | | | | | | |
| Small | 420 | 8 | 53 | 1. 1 | | | | | | |
| Medium | 740 | 111 | 67 | | | | | | | |
| Large | 800 | 14 | 57 | | | | | | | |
| Warrawidgee | 400 | 10 | 40 | 1. 1 | 1. 0 | . 60 | . 6 | 85 | 4. 6 | |
| Benerembah (*A–A′*) | 607 | 7 | 87 | 1. 1 | | | | | | |

[1] From fig. 19*C*. [2] From fig. 19*A*. [3] From fig. 19*B*. [4] From fig. 21. [5] From fig. 22.

The sinuosity of the channel was 1.2. The dimensions, shape, and pattern of all three sizes of possible central prior-stream channels are wholly different from those of the modern Murrumbidgee River (table 4).

A series of sediment samples was collected in the Kulki pit to determine changes with depth and whether the estimated channel depth is related to a change in sediment type. Some characteristics of these sediments are listed below:

| Depth (ft) | Sediment type | Median grain size $d_{50}$ (mm) | Silt and clay (percent <0.074 mm size) | Gravel (percent >2 mm size) |
|---|---|---|---|---|
| 1–3 | Loam | 0.35 | 14 | 3 |
| 3–9 | Gray clay | .02 | 89 | 0 |
| 9–10 | Silty sand | .36 | 17 | 6 |
| 10–14 | Crossbedded sand | .61 | .3 | 6 |
| 14–17 | do | .61 | .2 | 2 |
| 17–24 | do | .62 | .1 | 4 |
| 24–32 | Sediments covered by workings. | | | |
| 32 | Gray clay, Katandra clay. | | | |

A few pebbles were found in the samples of well-sorted channel sands; the largest pebble was 0.8 inch in diameter. The sharp contrast between the overlying channel-fill sediments and the crossbedded sands of the prior-stream channel is apparent at a depth of 10 feet.

Studies of aggrading ephemeral-stream channels in the Western United States have shown that an abrupt increase in the silt-clay content of the channel sediments occurs when aggradation begins (Schumm, 1961, p. 44). Thus, the bed of a prior-stream channel was probably only a short distance below the level where the marked change from fine sediment to channel sand occurs. Both the data from the bores and the vertical distribution of sediment in the Kulki pit support the conclusion that the depth of the last stable central prior-stream channel was about 10 feet.

Another deep pit has been excavated in the northern prior-stream channel near the Kearbury woolshed (pl. 2). Bore data are available for this channel (fig. 21) at the Jerilderie Highway crossing, about 9 miles east of the pit (pl. 2). The surface character of the channel is relatively unchanged over this distance (fig. 18*C*); therefore, the information obtained from the bores is believed to be representative of the channel at the Kearbury sand pit (table 3).

At the pit, width of the small surface prior-stream channel is about 650 feet, and at the highway cross section it is 600 feet (table 3). On the basis of the criterion that no sand can be exposed at the base of the banks of a stable channel, the depth at the highway section was 9 feet (fig. 21). The sinuosity of this channel is 1.1, and again the morphology of the three sizes of prior-stream channels differ significantly from that of the modern and ancestral rivers (table 4).

Some characteristics of the sediments exposed in the Kearbury pit are listed as follows:

| Depth (ft) | Sediment type | Median grain size $d_{50}$ (mm) | Silt and clay (percent <0.074 mm size) | Gravel (percent >2 mm size) |
|---|---|---|---|---|
| 2 | Red sandy clay | 0.33 | 36 | 4 |
| 3–5 | do | .60 | 14 | 10 |
| 5–7 | Silty sand to sand | .55 | .3 | 8 |
| 7–10 | Sand and ¼-inch gravel. | .55 | .2 | 18 |
| 13–18 | Sand, gravel | .45 | .1 | 2 |
| 20–22 | Sand | .35 | .2 | 9 |
| 29.5 | Gray clay | | | |

Additional data on prior-stream morphology and sediment characteristics were collected at shallow pits along the main northern prior-stream channel at "S" pit, Lone Gum pit, and the Hay pit (fig. 18*E*). Sand was penetrated in these pits at depths comparable to depths at which it was found in the Kearbury pit (table 3).

Comparison of bore data with data from exposures in a pit was also possible at Smith pit (fig. 19*D*), which was excavated in a distributary channel north of the river. A cross section of this prior-stream channel (fig. 22) was compiled from bore data by Pels (1964a). At Smith pit the width of the small surface channel was estimated to have been 420 feet, and the depth, 8 feet (table 3).

In the pit, clean sand occurs at a depth of 7 feet. Information on the sediment sampled in Smith pit is listed as follows:

| Depth (ft) | Sediment type | Median grain size $d_{50}$ (mm) | Silt and clay (percent 0.074 mm size) | Gravel (percent >2 mm size) |
|---|---|---|---|---|
| 0– 2 | Red clay | 0.007 | 72 | 0 |
| 2– 4 | Sandy clay | .033 | 73 | 0 |
| 4– 7 | Clayey sand | .42 | 64 | 2 |
| 7– 9 | Sand | .43 | 1.2 | 8 |
| 9–15 | do | .55 | .5 | 8 |
| 15–18 | do | .70 | .2 | 1.2 |
| 18–20 | do | .91 | 2.9 | |
| 23 | do | .95 | .2 | |
| 24 | Gray clay | | | |

For the other shallow sand pits located on distributary channels (Wahwoon, Kangaroo, and Elginbah pits, pl. 2), no bore data were available, and the widths of the channels were obtained in the field and checked on aerial photographs (table 3). Channel depths were taken as those depths at which clean crossbedded sand was encountered during augering. Although the floor of

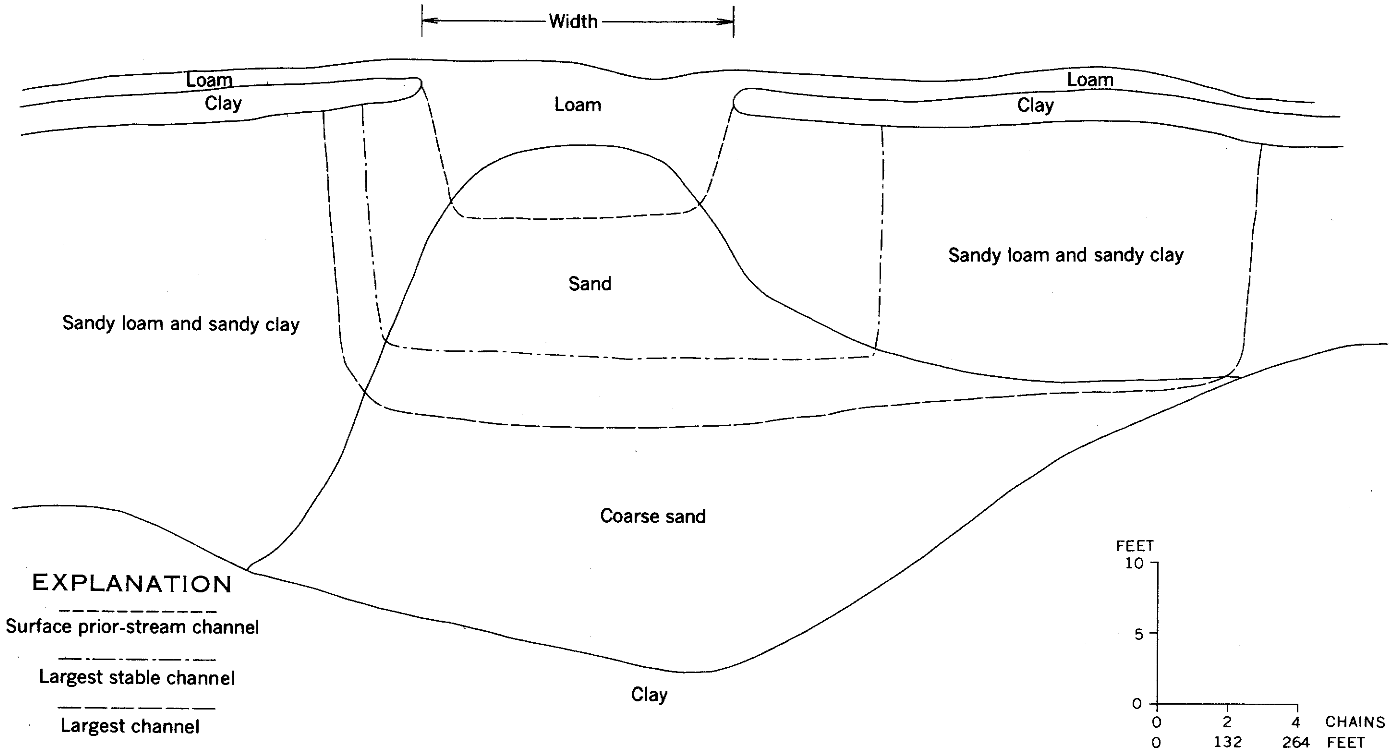


FIGURE 21.—Generalized cross section of northern prior-stream channel at Jerilderie Highway crossing, about 9 miles east of Kearbury pit (pl. 2). From bore data obtained by M. Stannard.

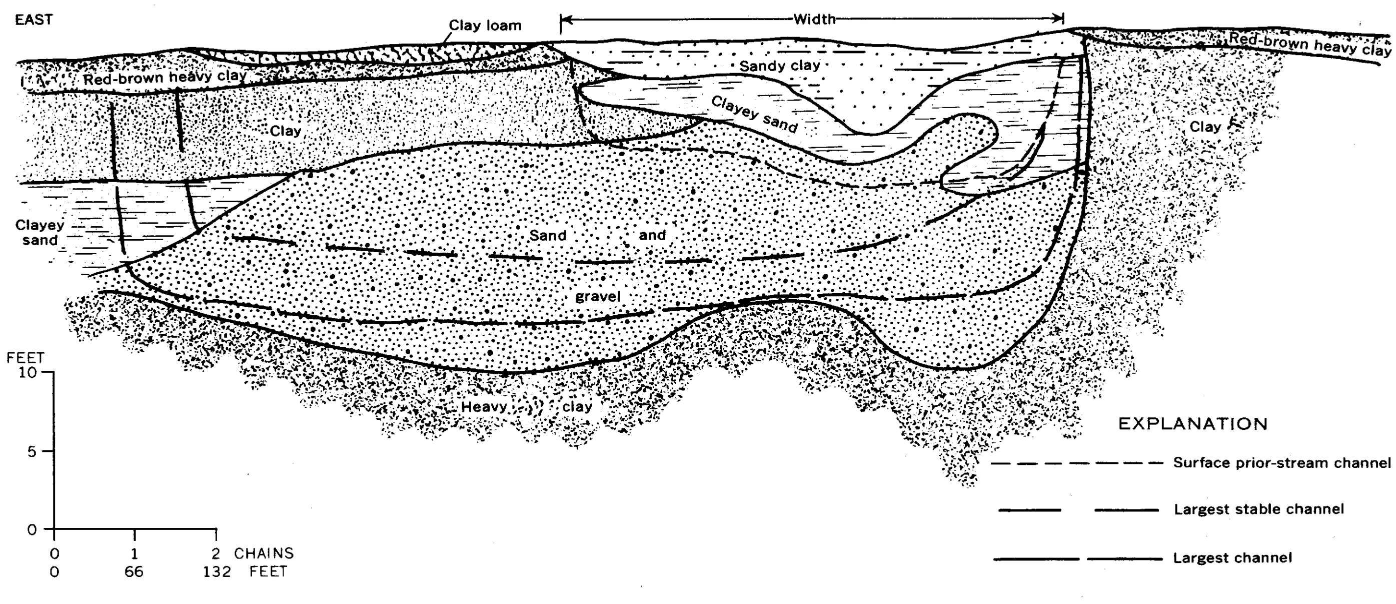


FIGURE 22.—Generalized cross section of prior-stream channel near Smith pit. (After Pels, 1964a, fig. 2, section *C–C′*.)

the channel would actually have been somewhat deeper, the postchannel surface deposition has probably raised the surface of the plain a comparable amount.

Borings made by Pels (1964a) into prior-stream distributary channels north of the river yielded information on channel widths and depths where there were no pits from which samples could be taken. Under these circumstances, samples of the prior-stream bed and bank sediments were obtained by hand augering. Cross sections of the prior-stream deposits, as constructed from Pels' bores at two locations (Warrawidgee site, from Pels' unpub. data; Benerembah site, from Pels, 1964a, fig. 27, section *A–A′*), provided data on a large


**FIGURE 23.—Distributary prior-stream channels in Benerembah Irrigation Area. Pels' section *A–A′* follows north trending road (on left of figure). Photograph (view facing south) in figure 18*F* was taken from a position just north of the northernmost prior-stream channel. Note that although the channels are clearly visible in the aerial photograph, their surface expression is slight. (Photograph courtesy of the New South Wales Lands Dept.)**

distributary prior-stream channel (figs. 18*F*, 23; table 3).

Despite difficulty in obtaining data on prior-stream morphology, the data given in table 3 shows that the width-depth ratios of the prior-stream channels range from 40 to 93 for the channels visible on the surface. Sinuosity was very low, about 1.1, and the gradient, therefore, was approximately that of the Riverine Plain surface, about 1.5 feet per mile. Although the median grain size of the sediment is not very different from that of the modern river sediment, the calculated silt-clay content of the channels is very low.

At pits in five prior-stream channels (the Kearbury, "S," Conargo Road, Kangaroo, and Elginbah pits) the silt-clay content of the bank samples is only about half that at pits in the remaining seven channels. Samples from these five pits are not considered to be representative bank sediments; rather, the sample locations now indicate that a coarser channel-fill sediment was sampled. Therefore, an adjusted value of $M$ was calculated for these channels using a value of bank silt-clay of 65 percent, which approximates the percentage in bank samples from the other channels (table 3).

All the data, although subject to some error, indicate that the prior-stream channels were relatively wide, shallow, and straight in comparison with the sinuous, relatively narrow, deep Murrumbidgee and the ancestral-river channels.

#### PALEOHYDROLOGY

Obviously no data are available for the discharge and sediment load transported through the prior-stream channels, but some estimates of water discharge and sediment load can be made (table 4) by using the techniques discussed in the preceding sections on the hydrologic characteristics of the ancestral and modern channels.

For the northern prior-stream channel near Darlington Point, depth is 9 feet, width 600 feet, and gradient, 2 feet per mile or 0.00037. Roughness, $n$, is estimated as 0.025 (Chow, 1959, p. 109; Howard Matthai, oral commun., 1966). Velocity, as calculated by the Manning equation, would have been about 5 feet per second in this channel, and bankfull discharge would have been 23,000 cfs. Sand transport, as estimated from Colby's (1964, fig. 26) graph, would have been 90 tons per day per foot of width, or 54,000 tons per day at bankfull discharge (table 4).

For the channel of intermediate size, or the largest stable channel, bankfull discharge would have been 73,000 cfs, and sand discharge 140,000 tons per day at bankfull discharge. If the maximum possible dimensions of the largest possible channel—1,700 feet and 20 feet—are used, velocity would have been about 9 feet per second at bankfull discharge, and bankfull discharge would have been on the order of 290,000 cfs. For these dimensions, the sand transport would have been 300 tons per foot of width per day, or 500,000 tons per day at bankfull discharge.

For the central prior stream near the Kulki pit, the smaller dimensions of the surface channel yield smaller values of bankfull discharge (19,000 cfs) and sand load (35,000 tons per day at bankfull discharge). Bankfull discharge and sand load, as calculated for the intermediate size and the largest prior-stream channels, are also less than the values obtained for the northern prior streams (table 4).

The bankfull discharge of the prior streams was much greater than that of the modern river, but except for the largest channels, it was of the same order of magnitude as that calculated for the ancestral river. However, the amount of sand transported through the prior-stream channels was considerably greater than that transported in either the ancestral-or the modern-river channels at bankfull discharge.

## COMPARATIVE MORPHOLOGY AND HYDROLOGY OF THE RIVERINE PLAIN CHANNELS

The descriptive data presented in the preceding sections provide a basis for comparison of the three types of Riverine Plain channels and for an explanation of the morphologic differences noted (table 4).

### COMPARISON OF CHANNEL DIFFERENCES

Although the source area of the sediment and runoff that was delivered to the Riverine Plain channels has remained the same, the channels are markedly different. The modern Murrumbidgee River channel has a low width-depth ratio, a low gradient, and a moderately high sinuosity. The ancestral river, as exemplified by the Yarrada Lagoon channel, was similar in its width-depth ratio, gradient, and sinuosity, but the greater

TABLE 4.—*Comparative data, Riverine Plain channels*

| | Median grain size (mm) | Channel silt-clay percent ($M$) | Width (ft) | Depth (ft) | Width-depth ratio | Sinuosity | Gradient (ft per mi) | Bankfull velocity (ft per sec) | Bankfull discharge (cfs) | Sand discharge (tons per ft per day) | Sand discharge (tons per day) | Meander wavelength (ft) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Murrumbidgee River near Darlington Point | 0.57 | 25 | 220 | 21 | 10 | 2.0 | 0.7 | 3.0 | 10,000 | 9 | 2,000 | 2,800 |
| Ancestral River (Yarrada Lagoon) | | 16 | 460 | 35 | 13 | 1.7 | .8 | 4.2 | 51,000 | 45 | 21,000 | 7,000 |
| *Prior streams* | | | | | | | | | | | | |
| Northern (Kearbury pit): | | | | | | | | | | | | |
| Small | .55 | 1.6 | 600 | 9 | 67 | 1.1 | 2.0 | 5.2 | 23,000 | 90 | 54,000 | 18,000 |
| Medium | | | 1,000 | 12 | 83 | | | 6.3 | 73,000 | 140 | 140,000 | |
| Large | | | 1,700 | 20 | 90 | | | 8.8 | 290,000 | 300 | 510,000 | |
| Central (Kulki pit): | | | | | | | | | | | | |
| Small | .60 | 3.4 | 500 | 8 | 63 | 1.1 | 2.0 | 4.8 | 19,000 | 70 | 35,000 | 15,000 |
| Medium | | | 800 | 9 | 90 | | | 5.2 | 35,000 | 80 | 64,000 | |
| Large | | | 800 | 14 | 57 | | | 7.0 | 77,000 | 210 | 178,000 | |

size of its channel indicates that it had a higher discharge. The sediment associated with these two channels is fine grained. The sediment load transported by the Murrumbidgee River is small, and on the basis of the similarity in channel morphology and sediment characteristics of the two channels, it is concluded that the sediment load transported by the ancestral river was also small. In contrast, the channels of the prior streams were relatively wide and shallow, the width-depth ratio was high, and the sinuosity was low. The crossbedded sands and loams filling these channels indicate that the sand load transported through the prior-stream channels was relatively high the average gradient was about twice that of the modern river.

A quantitative comparison of the shape and pattern of the Murrumbidgee and prior-stream channels is presented in figure 24, where sinuosity ($P$) is plotted against the width-depth ratio ($F$). The regression line for this figure was established from data obtained from rivers of the Great Plains of the Western United States (Schumm, 1963a), and it is described by the equation $P=3.5F^{-0.27}$. The data from the modern Murrumbidgee and the prior-stream channels conform to this relationship and demonstrate that for these rivers a sinuous channel has a relatively low width-depth ratio, whereas a straight channel has a high width-depth ratio.

In figure 25, sinuosity ($P$) of the channels is plotted against the silt-clay content ($M$) of the channel perimeter. Again, the regression line was established from the data from the Great Plains rivers, and the Australian data shown a similar relationship, described by the equation $P=0.94M^{0.25}$. The sandy channels are straight, whereas the high silt-clay channels are sinuous.

In figure 26 the width-depth ratios ($F$) of the Australian channels are plotted against the silt-clay content in the perimeter of the channels ($M$). The data from the Murrumbidgee River cross sections plot near the regression line established for the rivers of the Great Plains, described by the equation $F=255M^{-1.08}$. The prior-stream data plot below the regression line but are within the scatter of the data from which the regression line was established. Only the width-depth ratios of the surface prior streams were plotted in figure 26, but the width-depth ratios of all three sizes of prior-stream channels are comparable (table 3).

Previously, it was stated that the silt-clay content of five prior-streambank samples was increased to 65 percent, a value in agreement with that for other prior-stream channels. The adjusted values of $M$ are also plotted in figure 26 for these five channels, and the two points plotted for each of the five channels are connected by a line parallel to the abscissa. The adjustment brings the four points that plot well below the regression line much closer to, but still below, the regression line. The data show clearly that the width-depth ratio of the sandy prior-stream channels is significantly larger than that of the modern Murrumbidgee River.

As is common with plots of river data, the scatter is appreciable, but the plotted values for width-depth ratio, sinuosity, and channel silt-clay fall near the regression lines and demonstrate that the surface prior-stream channels were similar in form, pattern, and sediment character to the sandy or bedload rivers of the Great Plains. The Murrumbidgee River, however, is morphologically very different. Although no attempt has been made to locate the ancestral-river channel in figures 24–26, it is apparent, because of the low width-depth ratio (13) and the relatively high sinuosity (1.7) of this channel, that the channel is morphologically similar to that of the modern Murrumbidgee River. The dimensions and the discharge of the ancestral river were much greater, however, than those of the modern channel.

Although the differences between the width-depth ratios and the sinuosities of the channels may be explained by a change in the type of sediment load transported through the channels (Schumm, 1963a), the change in channel dimensions (meander wavelength, channel width and depth) requires a change in discharge. Therefore, a major change in the hydrologic regimen of the system has, no doubt occurred. The calculations of bankfull discharge for the three channels suggest that large floods moved down the ancestral- and prior-stream channels (table 4), and yet the great difference in the sediment characteristics, shape, and sinuosity of the ancestral-river and the prior-stream channels indicates that climatic and hydrologic conditions in the basin could not have been the same when each of the channels was functional. Therefore, the hydrologic regimens of the prior-stream and the ancestral-river systems differed from one another and were different from that of the modern Murrumbidgee.

## CLASSIFICATION OF ALLUVIAL RIVER CHANNELS

One of the stated objectives of this study was to obtain data to support the assumption that the silt-clay content of an alluvial river channel is dependent largely on the type of sediment load moved through the channel. Before proceeding with a detailed discussion of the adjustment of river channels to altered hydrologic regimen, it may be well to consider the validity of this assumption.

Three types of channels were previously defined (Schumm, 1963a) according to the amount of silt-clay ($M$) present in the bed and bank sediment and were designated as suspended-load, mixed-load, and bedload

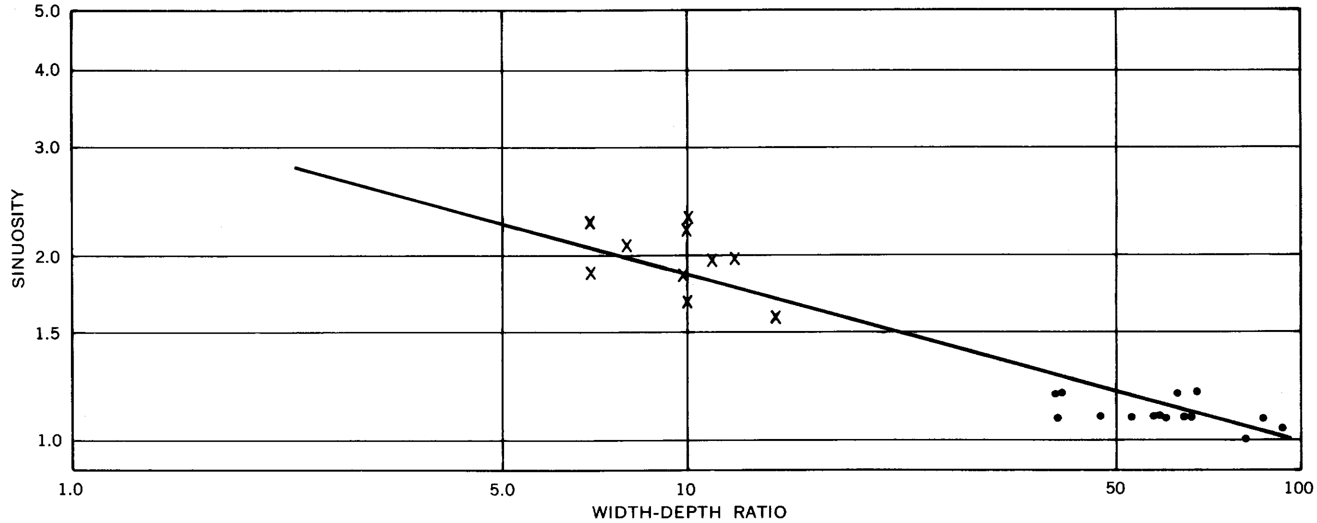


FIGURE 24.—Relation between width-depth ratio and sinuosity. Regression line established from data from Great Plains rivers (Schumm, 1963b). X, Murrumbidgee River data; dots, prior-stream data.

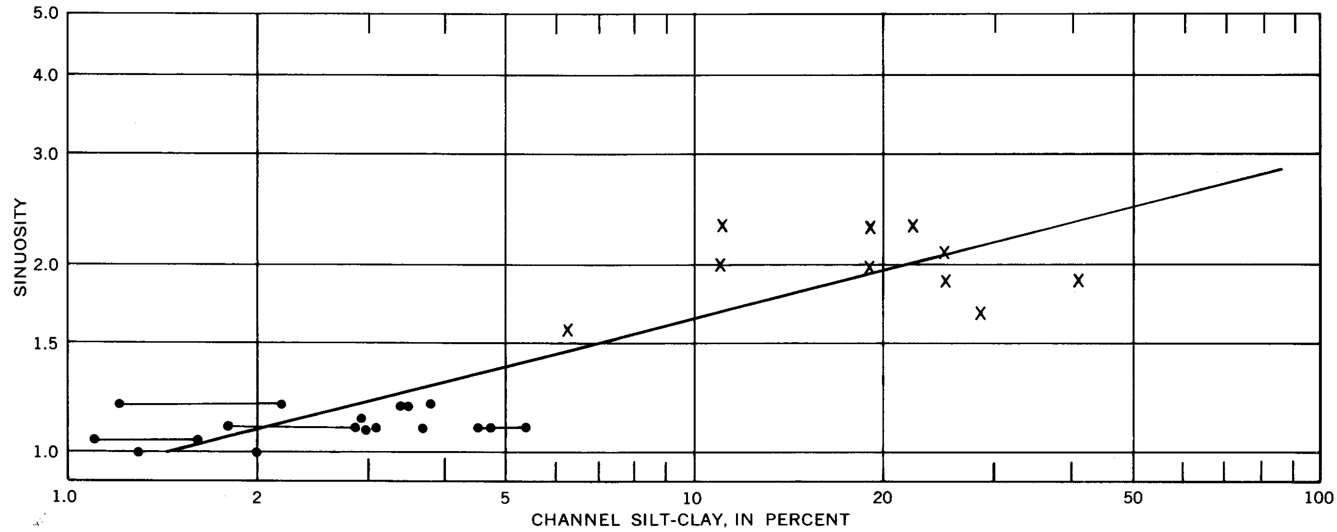


FIGURE 25.—Relation between channel silt-clay (*M*) and sinuosity. Regression line established from data from Great Plains rivers (Schumm, 1963b). Horizontal lines connect five pairs of points for which adjustment of the bank silt-clay has been made (table 3). In each adjustment the channel silt-clay content was increased. X, Murrumbidgee River data; dots, prior-stream data.

channels. The percentage of silt and clay (sediment smaller than 0.074 mm) in the channel perimeter, as determined by a size analysis of a composite sediment sample of both bed and bank sediments, was assumed to be an index of the ratio of suspended load to bedload transported through the channels.

Explanation for the physical relation between channel sediment and channel morphology was sought, and initially it was assumed that the increased cohesion of the high silt-clay channels permitted the development of narrow, deep, sinuous channels (Schumm, 1960b). However, although the physical properties of the bank material may exert an influence on channel morphology, perhaps the most convincing explanation involves the hydraulic conditions necessary for the transport of bedload. The movement of relatively large quantities of bedload in alluvial channels requires a wide channel with steep gradient (Leopold and Maddock, 1953, p. 29), and narrow, deep channels are unable to transport large quantities of bedload (Schumm, 1963a, p. 4–6). Bank stability and channel morphology are interrelated, but the dependent variable is always the sediment that must be moved through the channel.

The observations made on the Riverine Plain and the data in figures 24, 25, and 26 show that the prior-stream channels are bedload channels; whereas the modern- and ancestral-river channels are suspended-load channels. The sediments in the aggraded prior-stream

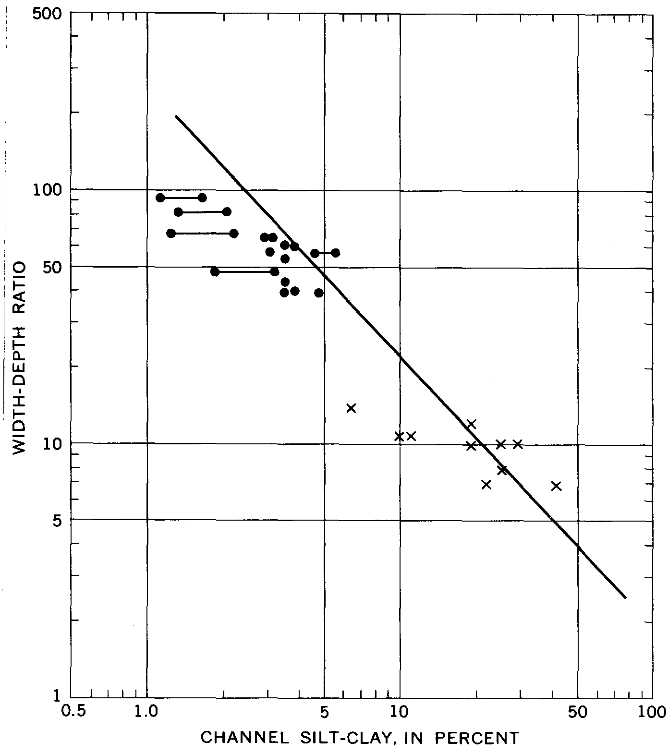


FIGURE 26.—Relation between channel silt-clay and width-depth ratio. Regression line established from data from Great Plains rivers (Schumm, 1960b). X, Murrumbidgee River data; dots, prior-stream data. Horizontal lines connecting five pairs of points show effects of adjustment of channel silt-clay (table 3).

channels are primarily sand, whereas those in the ancestral-river channel are primarily silt and clay, which are also the predominant sediment load of the modern river. The data collected on the Riverine Plain, therefore, supports qualitatively the theory that the type of sediment load moved through a channel controls its shape and sinuosity. The information on total sediment load required for confirmation of this hypothesis was lacking, and the classification has been regarded as tentative.

However, during the investigation of the Murrumbidgee River and its associated ancient channels, new useful information was obtained (Mundorff and Scott, 1964) regarding the total sediment load of four rivers in central and in eastern Kansas: Kansas River at Wamego, Solomon River at Niles, Republican River at Clay Center, and the Saline River at Tescott. These data combined with data on total sediment loads of the Niobrara River near Cody, Nebr. (Colby and Hembree, 1955), provide information for a considerable range of Great Plains river types—that is, the width-depth ratio ranges from 17 to 65, and sinuosity ranges from 1.1 to 2.5.

The maximum percentage of sand in the total sediment load was taken directly from data presented in the reports; also, the average percentage of the total sediment load transported as sand was estimated from the sand load in flows that approximated the mean annual discharge at each sampling site. In these channels, sand-size sediment is the bed-material load or, according to my classification, bedload. Samples of bed and bank sediments had been obtained previously at or near all the sediment sampling stations except one—Republican River at Clay Center. To represent that station, the silt-clay content of the channel previously sampled at the Junction City gaging station, about 40 miles downstream, was used (Schumm, 1960b). The silt-clay content of the Republican River channel is only 2 percent less at the Concordia gaging station about 40 miles above Clay Center, but there is a 1,000-square-mile increase in drainage area between Concordia and Clay Center, and only a 300-square-mile increase in drainage area between Clay Center and Junction City; therefore, the Junction City sample was used.

When these values of sand load are compared with the values of $M$ obtained by sampling the sediment forming the perimeter of the channels, $M$ is found to be a multiple of the reciprocal of the percentage of sand load moved through these channels (fig. 27). This relation, admittedly for only a few rivers, supports the contention that $M$ is a parameter indicative of type of sediment load moving through the channels of the stable rivers of the Great Plains. $M$ is, in fact, related to the ratio of total load (sand, silt, and clay) to bedload (sand) or to bedload as a percentage of total load. The relation shown on figure 27 indicates that the average percentage of sand transported through the channels is lower than the values used to establish the limits of the channel classification as first proposed (Schumm, 1963a). Modification of the limits for the three classes of channels is therefore necessary. Table 5 gives the revised classification of alluvial channels. The major subdivisions or classes of channels depend on the type of sediment load moved through the channel as based on the sediment-load data shown in figure 27. A brief review of the classification follows.

In this classification, "bedload" means simply that part of the total sediment load that is larger than 0.074 mm—in other words, sand-size and larger sediment. A bedload channel, therefore, is one that has a sufficient quantity of sand and coarser particles moving through it to form a characteristic channel. In table 5 a bedload channel is shown to be a channel in which the coarse sediment composes more than 11 percent of the total load (the ratio of suspended load to bedload is 8). Where bedload is less than about 3 percent of the total load

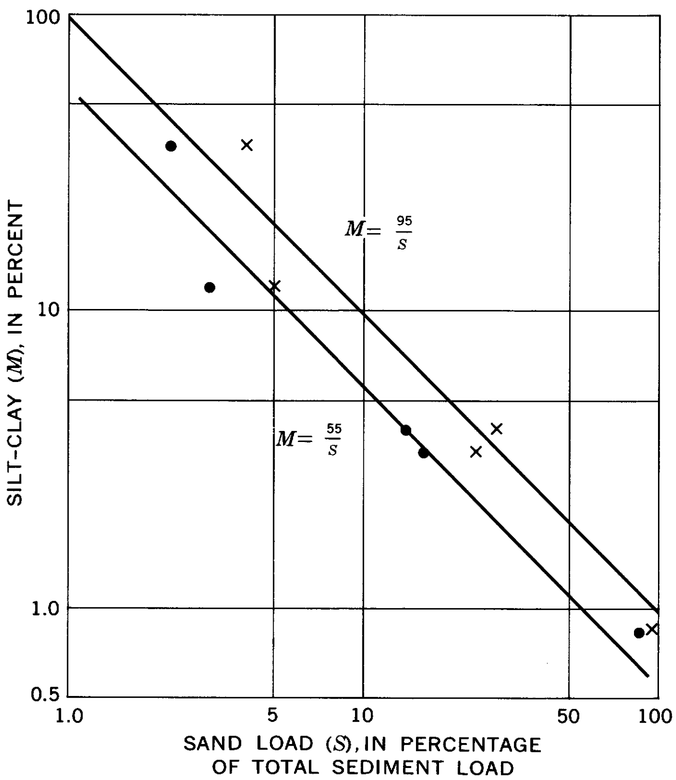


FIGURE 27.—Relation between silt-clay in the perimeter of alluvial channels and sand load. Upper regression line is for the relation between silt-clay content of the channels and the maximum sand load measured at each station. Lower regression line is the relation between silt-clay content of the channels and sand load at mean annual discharge. From upper left to lower right, points are identified as follows: Saline River at Tescott; Solomon River at Niles; Kansas River at Wamego; Republican River at Clay Center; Niobrara River near Cody, Nebr.

(ratio of suspended load to bedload is 32), a suspended-load type of channel is characteristic. The mixed-load channel is transitional between the two end members of the classification. In brief, the proposed classification of river channels is based on the proportions of bedload and suspended load (silt and clay) transported through a stream channel.

Although a single grain size, which would form the boundary between suspended load and bedload, cannot be selected from available sediment-transport data, probably silt and clay are generally transported in suspension and sand and coarser sediment are generally transported on or near the streambed. For example, Hjulstrom's curves (1935, p. 274) suggest strongly that sediment larger than the 200-mesh sieve (0.074 mm) will be transported near the streambed. For a more detailed statement, see the discussion of the earlier classification by Schumm (1963a).

The class "dissolved-load channel" is introduced here to designate those channels through which little sediment moves. These channels transport primarily a chemical load. However, such channels would probably be similar morphologically to the suspended-load channels.

A further subdivision of alluvial channels can be made on the basis of stream stability or lack of it (table 5). These differences can be considered in relation to the total sediment load delivered to the channel. An excess of total load causes deposition; a deficiency causes erosion, and between these extremes is the stable channel. Although in the field a given river channel often cannot be clearly identified as stable, eroding, or depositing, it is possible to think of all rivers as being in one or another of these three classes.

The stable channel is one that shows no progressive change in gradient, dimensions, or shape. The eroding channel is one that is being progressively degraded or widened by bank erosion, or both. Conversely, the depositing channel is one that is being aggraded or is having sediment deposited on its banks, or both.

TABLE 5.—*Classification of alluvial river channels*

| Type of sediment transport | Channel sediment (*M*) percent | Bedload percent (of total load) | Channel stability: Stable (graded stream) | Channel stability: Depositing (excess load) | Channel stability: Eroding (deficiency of load) |
|---|---|---|---|---|---|
| Suspended load and dissolved load. | >20 | <3 | Stable suspended-load channel. Width-depth ratio, less shan 10; sinuosity, greater than 2.0; gradient, relatively gentle. | Depositing suspended load channel. Major deposition on banks cause narrowing of channel; streambed deposition minor. | Eroding suspended-load channel. Streambed erosion predominant; channel widening minor. |
| Mixed load | 5–20 | 3–11 | Stable mixed-load channel. Width-depth ratio, greater than 10 and less than 40; sinuosity, less than 2.0 and greater than 1.3; gradient, moderate. | Depositing mixed-load channel. Initial major deposition on banks followed by streambed deposition. | Eroding mixed-load channel. Initial streambed erosion followed by channel widening. |
| Bedload | <5 | >11 | Stable bedload channel, width-depth ratio, greater than 40; sinuosity, less than 1.3; gradient, relatively steep. | Depositing bedload channel. Streambed deposition and island formation. | Eroding bedload channel. Little streambed ersion; channel widening predominant. |

At present the classification must be restricted to alluvial rivers which contain less than about 20 percent gravel in their channels and which are not influenced by bedrock outcrops in their channels. Discharge is not used as a basis for the classification because the quantity of discharge controls mainly the size of the channel. The differences between types of river channels is most marked in rivers of subhumid, semiarid, and arid regions. The major perennial streams of humid regions seem to show much less variability, and it may be more difficult to relate them to the proposed classification.

By use of the relationship shown in figure 27, the percentage of the total sediment load of the Riverine Plain channels transported as sand or bedload can be estimated. Average $M$ for the prior stream is about 2.5 (table 4), and for an average of the seven Murrumbidgee River cross sections on the Riverine Plain it is 24; thus, the average sand loads are 22 and 2.3 percent, respectively. According to the channel classification (table 6), the prior-stream channels are bedload channels, and the Murrumbidgee River channel is a suspended-load channel.

In the following detailed discussions of river adjustment to altered hydrologic regimen, this classification of river channels will be used to distinguish between the end members of the series of alluvial rivers, bedload channels, and suspended-load channels. The parameter $M$—the percentage of silt and clay in the perimeter of a channel--will represent the type of sediment load moved through the channels, and it will be used to demonstrate the influence of type of sediment load on channel morphology.

## RIVERINE PLAIN CHANNELS—EXAMPLES OF RIVER RESPONSE TO ALTERED HYDROLOGIC REGIMEN

It is unwise to relate the paleochannels specifically to past climatic events because precise dates for these features are lacking. Radiocarbon dates from the prior-stream channels are rare, and the writer was unable to collect either datable material or diagnostic pollen in the sediments of the prior-stream channels. However, Pels' (1964a) date of older than 36,000 years, obtained from a sample collected in the Smith pit at a depth of about 15 feet, and Langford-Smith's (1963) date of older than 28,000 years for a sample collected 12–15 feet below the surface in the Coleambally pit, indicate a Pleistocene age for these channels. Two samples obtained from shallow depths in other channels yield ages of between 4,000 and 5,000 years (Langford-Smith, 1963). Therefore, the surface features of the Riverine Plain are undoubtedly the records of late Pleistocene and Holocene erosion and deposition.

The variations in the discharge of water through these channels could only have been the result of climate changes, but the change in sediment characteristics could have resulted equally from a steepening of the river gradient by uplift in the mountains, or perhaps from a lowering of sea level. The evidence, however, suggests tectonic stability in the Eastern Highlands (van Dijk, 1959), and the presence of late Pleistocene Lake Nawait (David and Browne, 1950, p. 614) on the course of the Murray River demonstrates that sea-level changes probably could not have affected the channels on the Riverine Plain. Changes in climate appear to be the most likely cause of changes in the discharge and sediment load, and therefore of the differences among the channels visible on the surface of the plain. Hence, before one can discuss the nature of the channel adjustments to altered hydrologic regimen, the types of climate change which could have induced the recorded changes of river morphology and the estimated changes in the sediment load and bankfull discharge of the rivers must be considered.

### NATURE OF CLIMATIC AND ASSOCIATED HYDROLOGIC CHANGES

Galloway (1965) concluded that during Wisconsin Glaciation the climate in the Murrumbidgee River headwaters was colder and drier than at present, and the precipitation was about half that falling at present in the Lake George area. In addition, he concluded that temperatures were 9°C (or 47°F) lower during the warmest month, and that a 5°C lowering of the mean annual temperature appears reasonable. Also, Sprigg (1965) suggested that the low sea levels of glacial stages can be correlated with dry climates. However, Ward's (1965) study of the alluvial stratigraphy near Adelaide, South Australia, led him to conclude that the glacial climate was humid and moderate.

Two major climatic fluctuations during the Holocene may also be pertinent to this discussion: the Australian arid period (Hypsithermal), about 4,000–5,000 years ago, and a wetter phase about 3,000 years ago known as the "Little Ice Age" in the Northern Hemisphere (Gentilli, 1961). However, until more information and reliable dates for these events are available, questions as to the sequence of Quaternary climates will arise. For example, Tindale (1959, p. 47) questioned the occurrence of a mid-Holocene arid phase because his evidence indicates that precipitation was similar to that of the present during the Hypsithermal on Mount Gambier, Victoria. Ward (1965) concluded that the interglacials were relatively arid and warm and that the Hypsithermal climate was slightly drier but stormy. Probably, all these conclusions are correct, because the areas studied are separated by long distances. Nevertheless, it is apparent both that we do not know the precise age of the paleochannels and that, even if this information were available, the type of climate that could be associated with them would be open to debate. Indirect evidence must therefore be utilized to suggest the climatic conditions under which the channels could have formed.

#### EFFECT OF CLIMATE CHANGE ON RUNOFF AND SEDIMENT YIELD

Data collected from drainage basins in the United States have been used to predict how runoff and sediment yields will change as mean annual temperature and precipitation change (Schumm, 1965). These data may also be used to suggest the climatic conditions under which the prior streams and ancestral rivers were functional. As stated previously, the mean annual temperature in the Murrumbidgee catchment above Narrandera is about 60°F, and the mean annual precipitation is about 26 inches. By using the curves developed by Langbein and others (1949) to relate mean annual runoff to mean annual temperature and precipitation, one can estimate that the annual runoff from the 14,000 square-mile drainage basin above Narrandera is about 2,300,000 acre-feet per year (fig. 28, position 1). Average runoff for the years when total runoff was measured at Narrandera (1892–1930) was 2,260,000 acre-feet per year (Water Conservation and Irrigation Comm., New South Wales, 1956). The agreement between the estimated and calculated runoff attests to the validity of this approach.

Average sediment yield, as estimated from a series of curves developed for United States sediment-yield data, obtained for drainage basins 1,500 square miles in area (fig. 29) indicates that under the present climate the sediment yield from the Murrumbidgee basin at Narrandera should be about 550 tons per square mile (fig. 29, position 1). If this value is adjusted to that for a sediment yield from a 14,000 square-mile drainage area (Langbein and Schumm, 1958), it decreases to about 360 tons per square mile, or 5 million tons per year, at Narrandera. As explained previously, erosion is not a serious problem in this drainage basin, and this estimate of sediment yield is much higher than the estimated 70 tons of sediment per square mile delivered to the Burrinjuck Reservoir. However, this difference can be explained partly on the basis of the cooler and moister climate in the upper part of the basin above the reservoir. The sediment-yield rate estimated for only the drainage area above the reservoir is about 240 tons per square mile, or three times that measured in the reservoir. This difference between the estimated and the measured rates of sediment yield is not unrealistic because the curves in figure 29 are based on average sediment yields for a variety of rock types. The area of resistant rocks in the upper Murrumbidgee River basin would be expected to produce less sediment than an area underlain by weak shale and sandstone. Murrumbidgee River sediment-yield data will plot well below the average curves in figure 29, but sediment yield from areas of weak rocks will plot above the curves in figure 29.

Disregarding differences in lithology, the curves of figure 29 do provide predictions of sediment yield under different climatic conditions. In the following discussion the sediment-yield values obtained directly

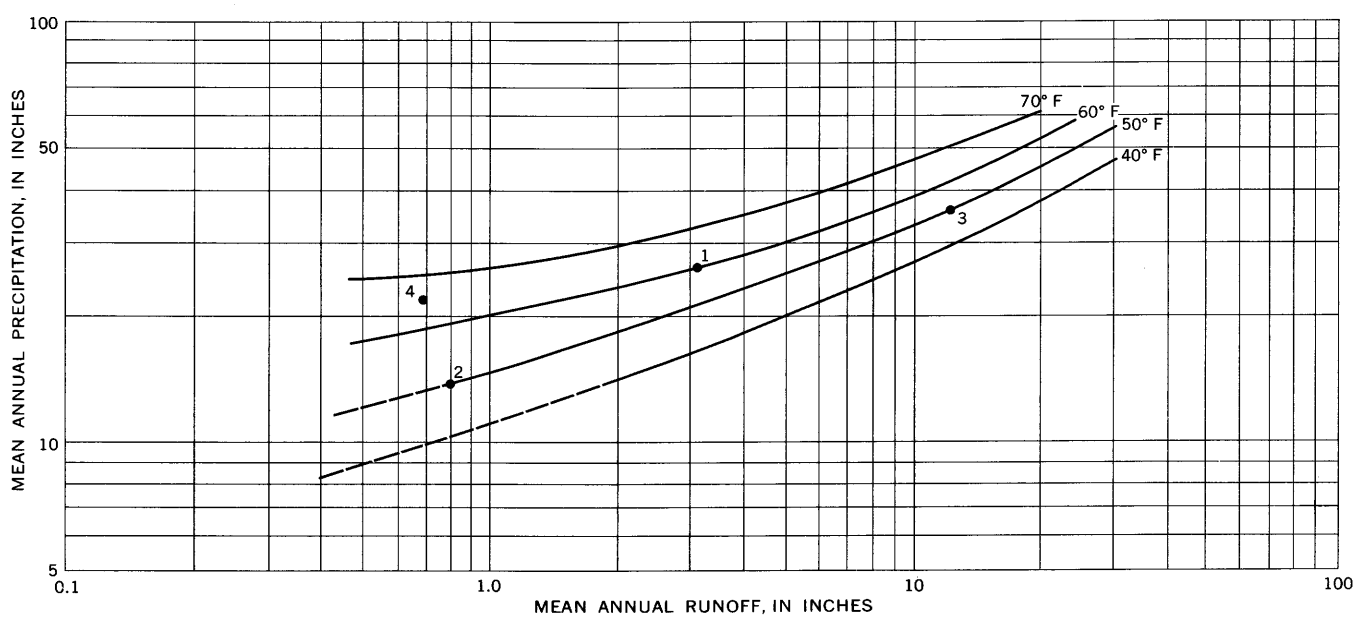


**FIGURE 28.—Curves illustrating the effect of temperature on the relation between mean annual runoff and mean annual precipitation. (After Langbein and others, 1949.)**

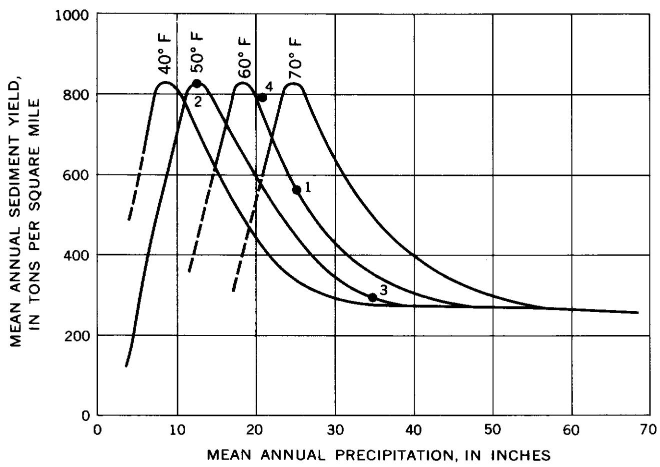


FIGURE 29.—Effect of temperature on the relation between mean annual sediment yield and mean annual precipitation (Schumm, 1965).

from the curves in figure 29 are used. To adjust these values for the large size of the Murrumbidgee River drainage basin, however, only values about two-thirds the size of those obtained from figure 29 would apply. Also, only one-third of the reduced value should be used if a comparison with the measured sediment yield of 70 tons is desired. However, as only the magnitude and direction of the change of sediment yield are being considered here, there is no need to adjust the values obtained from figure 29.

If, for comparative purposes, one uses Galloway's (1965) suggestion that precipitation in the headwater area during a glacial phase was about half that at present (13 in.) and that temperature was about 10°F lower than at present (50°F), and uses these values to estimate the hydrologic changes that would result if such a climate change were to occur, the runoff would decrease from 3 inches to about 0.8 inch (fig. 28, position 2). However, the sediment yield from the basin would show a significant increase as the vegetational cover deteriorated. The sediment yield would increase from about 550 to about 800 tons per square mile (fig. 29, position 2). Thus, runoff could have been one-third that at present and sediment yield could have been at least 50 percent greater than at present. Conversely, if precipitation increased during glaciation by about 10 inches and temperature decreased by 10°F (fig. 28, position 3), the runoff would have been four times greater (from 3 to 12 in.) and sediment yields would have been about half the present yield, or about 300 tons per square mile (fig. 29, position 3).

During the Hypsithermal interval and interglacial phases, if temperatures were 5°F higher and precipitation were about 5 inches less than at present, runoff would have been about a quarter of that of the present, or 0.7 inch (fig. 28, position 4), but sediment yields would have been much greater, about 800 tons per square mile (fig. 29, position 4). Thus, the climate during glaciation, according to Galloway's interpretation, would have had about the same effect on runoff and sediment yield as the climate of the Hypsithermal interval or Holocene arid period.

An important difference would have existed nevertheless, because during glaciation much of the winter precipitation would have been retained in snowfields until the spring melt, when seasonal flooding would have occurred (Langford-Smith, 1960b). Snowmelt floods would have been of longer duration than the flash (high peak, short duration) floods typical of arid and semiarid regions. Snowmelt floods, however, do not normally attain the peak discharges that result from summer storms, although the volume of water passing through channels may be large (Linsley and others, 1949, p. 464; Pardé, 1964, p. 142). It is difficult to relate the aggraded prior-stream channels to the effects of snowmelt floods because, although considerable sediment may be moved out of the drainage system by snowmelt floods, their sediment loads are commonly less than those transported by normal floods (Mundorff, 1962). In any case, the large quantities of water derived from melting snow could have moved the sediment across the plains to the sea. It has been concluded that many of the prior-stream channels did not cross the alluvial plain (Pels, 1966).

The curves which relate modern rates of runoff and sediment yield to average climate (figs. 28, 29) show that the effects of a change of annual precipitation or temperature will be greatest for a change of climate in initially arid, semiarid, or subhumid regions. Fournier's (1960) work showed that sediment-yield rates are also very high where high-rainfall monsoonal climates prevail in areas of high relief. However, we are not now dealing with such a climate, nor is there any evidence that such a climate occurred in this region during the Quaternary.

Unfortunately, the curves provide no information on the size of sediment nor on the type of sediment load that can be expected from a given climatic region, because these depend largely on the geology of that region. Nevertheless, the deterioration of a protective vegetational cover permits the erosion of lower soil horizons and the production of larger amounts of coarser sediment (Garner, 1959). In the Murrumbidgee River headwaters, a drier climate would facilitate the movement of coarse colluvium, and gullying would set into motion large amounts of sand stored within the alluvium of small tributary valleys.

The increased sediment yields accompanying a change to a more arid climate would have provided the sediment, and especially the sands, that fill the prior-stream channels. Little sand is moving out of the upper basin at present, but with the deterioration of hillslope and flood-plain vegetation that would accompany a change to a more arid climate, large quantities of sand would be delivered to the Riverine Plain. Van Dijk's (1959) investigation of the soils and alluvial deposits in the Canberra region supports this conclusion.

### EFFECT OF RUNOFF AND SEDIMENT LOAD ON MEANDER WAVELENGTH

Not all field evidence cited in previous publications supports the conclusion that the climate was drier during prior-stream time. Langford-Smith (1960b) measured the meander-belt width of both the prior-stream channel and the Murrumbidgee River near Maude. Because the widths of both the meander belt and the channel of the prior stream are significantly larger than those of the modern river, he concluded that the snowmelt floods carried in the prior-stream channels were far greater than the maximum discharge of the modern river and that the climate was more humid during this phase of prior-stream activity. Dury (1965) showed that meander wavelength is a better criterion of bankfull discharge than is the meander-belt width, and he presented a relationship between meander wavelength ($l$ in ft) and bankfull discharge ($Qb$, in cfs) as follows:

$$l=30Qb^{0.5}.$$

Inasmuch as the meander wavelengths are greater for the prior streams than for the Murrumbidgee River, this relationship supports Langford-Smith's conclusion (Dury, 1963).

Dury's (1965) relationship is highly significant, but considerable scatter of the data about his regression line is evident. In fact, within the limits of scatter, a tenfold variation in meander wavelength can occur for a given bankfull discharge. Dury recognized that this scatter may reflect the influence of other variables such as sediment type, and Hack (1965, p. 35) and Alexandre (1962) suggested that the sediment transported by

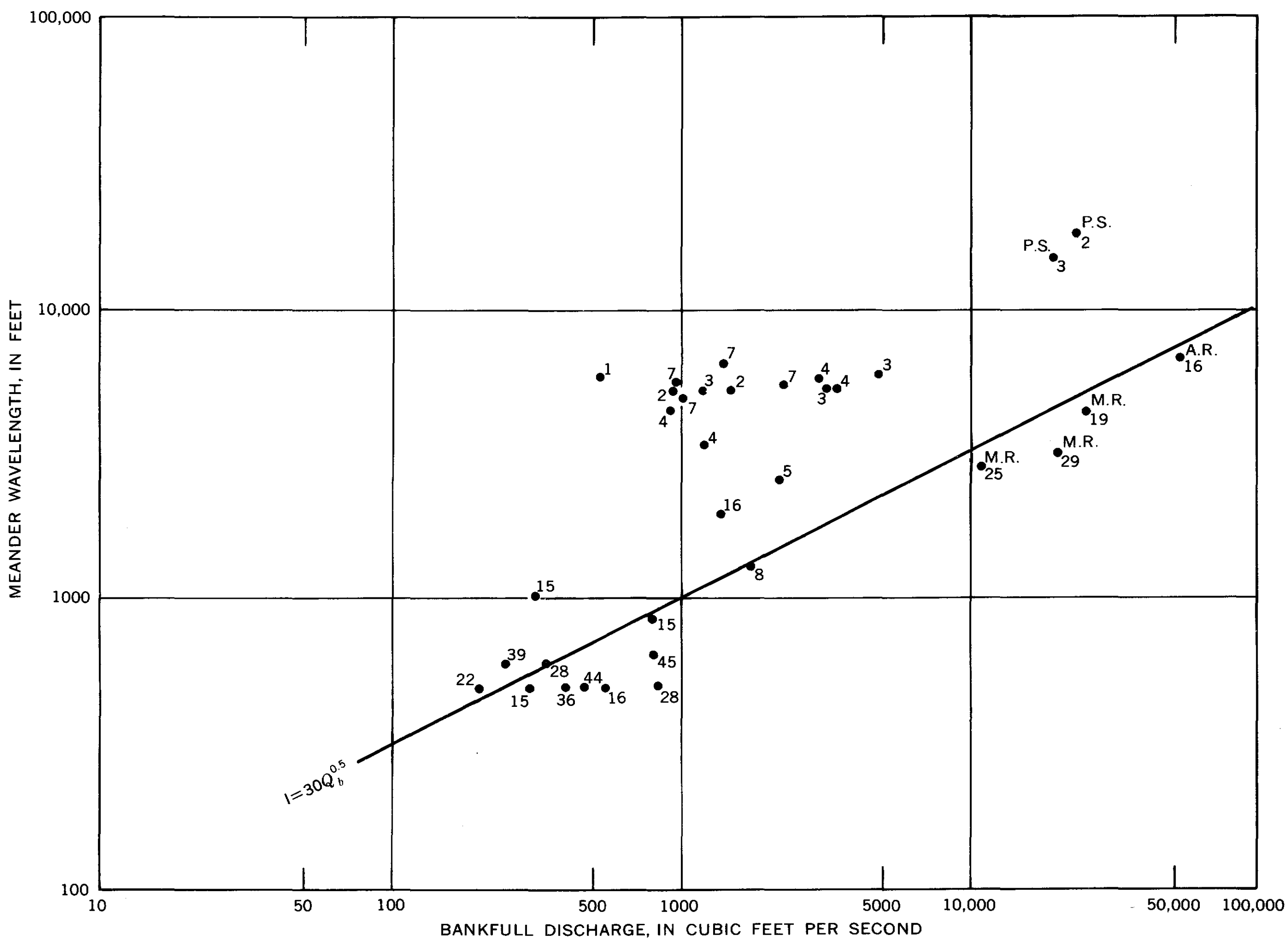


FIGURE 30.—Relation between meander wavelength and calculated bankfull discharge. Number beside each point indicates the silt-clay content, in percent, of each channel. The Australian channels are identified as follows: Murrumbidgee River (M.R.), ancestral river (A.R.), prior stream (P.S.).

streams is a significant factor which can influence the dimensions of the meander pattern.

Some data are now available which allow investigation of this point. The meander wavelengths of 33 United States rivers were measured (table 6), and the bankfull discharge of 28 was calculated. A large range of sediment characteristics and channel morphology is represented, but each river channel had developed in alluvium, and bedrock controls were absent. When the calculated bankfull discharge for these channels is plotted against meander wavelength (fig. 30), the points fall about the regression line established by Dury (1965).

The points for the United States rivers appear to fall into two groups, one of which lies well above Dury's regression line ($l=30Qb^{0.5}$). Beside each point the silt-clay content of the channel is given (fig. 30). It is evident that high silt-clay channels plot near or below Dury's regression line, whereas the low silt-clay channels generally plot well above the regression line. That is, the high width-depth ratio, low sinuosity bedload channels plot above the regression line, and the low width-depth ratio, high sinuosity suspended-load channels plot below the regression line. The distribution of points indicates that a bedload channel may have a meander wavelength considerably greater than that of a suspended-load channel of equal bankful discharge. When more becomes known about this relation, it may be possible to fit a family of curves to Dury's plot, each of which will be dependent upon the type of sediment load moved through the channels. If so, data for the Murrumbidgee and the ancestral rivers should fall on a line passing through the lower part of the scatter and near Dury's regression line, whereas the prior-stream data should plot near a line passing through the upper part of the scatter ($l=150Qb^{0.5}$); which is the case when these data (table 4) are plotted in figure 30.

It appears, then, that the type of sediment load moved through these channels, as expressed by the silt-clay content of the channels, has a major influence on meander wavelength. To test this hypothesis, a multiple-regression analysis of the effect of bankful discharge ($Qb$) and channel silt-clay ($M$) on meander wavelength ($l$) was performed, using data for 28 United States rivers, three Murrumbidgee River sections (table 1), two prior-stream sections (table 4), and one ancestral-river section (table 4), and the following regression equation was obtained:

$$l=438\,\frac{Qb^{0.43}}{M^{0.47}}.$$

TABLE 6.—*Data for rivers of Midwestern United States*

| | Width (ft) | Depth (ft) | Width-depth ratio | Channel silt-clay (*M*) (percent) | Mean annual discharge (cfs) | Bankfull discharge (cfs) | Mean annual flood (cfs) | Meander wave-length (ft) | Valley slope (ft per ft) | Channel gradient (ft per ft) | Sinu-osity |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Norwood Creek near Tensleep, Wyo | 59 | 5.0 | 12 | 16.0 | 100 | 550 | 1,540 | 500 | 0.00095 | 0.00045 | 2.1 |
| 2. Tongue River near Miles City, Mont | 198 | 5.0 | 40 | 3.7 | 357 | 2,040 | 4,400 | 3,400 | .0032 | .0019 | 1.7 |
| 3. Middle Fork Powder River near Kaycee, Wyo. | 37 | 4.0 | 9 | 14.8 | 60 | 308 | 1,450 | 1,000 | .0032 | .0016 | 2.1 |
| 4. Powder River near Locate, Mont | 325 | 6.1 | 53 | 2.5 | 592 | 4,800 | 11,000 | 6,000 | .0013 | .0011 | 1.2 |
| 5. Little Missouri River near Alzada, Mont | 46 | 5.7 | 8 | 44.6 | 82 | 800 | 2,750 | 650 | .0022 | .0009 | 2.5 |
| 6. Lance Creek near Spencer, Wyo | 105 | 4.9 | 21 | 8.0 | 24 | 1,680 | 2,700 | 1,300 | .0023 | .0012 | 1.9 |
| 7. Cheyenne River near Spencer, Wyo | 258 | 4.0 | 65 | 4.5 | 48 | 2,170 | 3,200 | 2,600 | .0018 | .0014 | 1.3 |
| 8. Cheyenne River at Edgemont, S. Dak | 280 | 3.8 | 75 | 3.8 | 102 | 3,000 | 4,300 | 5,800 | .0017 | .0014 | 1.2 |
| 9. White River near Whitney, Nebr | 27 | 5.7 | 5 | 38.8 | 21 | 250 | 900 | 600 | .0029 | .0012 | 2.4 |
| 10. South Fork White River at White River, Nebr. | 98 | 2.5 | 39 | 3.8 | 136 | 910 | 2,300 | 4,500 | .0024 | .0020 | 1.1 |
| 11. Niobrara River near Hay Springs, Nebr | 66 | 2.4 | 28 | 1.3 | 28 | 540 | 1,100 | 5,800 | .0019 | .0018 | 1.1 |
| 12. South Loup River at St. Michael, Nebr | 123 | 4.0 | 31 | 6.7 | 250 | 985 | 4,300 | 5,500 | .0012 | .0009 | 1.4 |
| 13. North Loup River at Taylor, Nebr | 153 | 2.9 | 53 | 2.8 | 454 | 1,200 | 1,500 | 5,300 | .0014 | .0013 | 1.1 |
| 14. Calamus River near Burwell, Nebr | 151 | 3.7 | 41 | 2.0 | 293 | | 580 | 8,000 | .0012 | .0011 | 1.1 |
| 15. North Loup River at Scotia, Nebr | 410 | 5.5 | 75 | 1.5 | 838 | | 6,400 | 11,000 | .0013 | .0012 | 1.05 |
| 16. North Loup River near St. Paul, Nebr | 431 | 5.7 | 75 | 1.8 | 982 | | 8,700 | 8,000 | .0013 | .0012 | 1.2 |
| 17. Elkhorn River at Norfolk, Nebr | 192 | 4.3 | 45 | 7.3 | 570 | 2,310 | 5,200 | 5,500 | .00095 | .0008 | 1.2 |
| 18. Republican River at Benkelman, Nebr | 104 | 3.8 | 27 | 2.3 | 96 | 950 | 4,400 | 5,300 | .0023 | .0020 | 1.3 |
| 19. South Republican River near Benkelman, Nebr. | 207 | 3.0 | 69 | 2.2 | 56 | 1,450 | 5,000 | 5,300 | .0026 | .0022 | 1.2 |
| 20. Frenchman Creek at Palisade, Nebr | 30 | 5.4 | 6 | 27.8 | 91 | 339 | 1,030 | 600 | .0025 | .0016 | 1.6 |
| 21. Frenchman Creek at Culbertson, Nebr | 74 | 4.5 | 16 | 14.9 | 123 | 795 | 1,450 | 850 | .0019 | .0013 | 1.5 |
| 22. Republican River at McCook, Nebr | 115 | 4.5 | 26 | 6.8 | 248 | 1,050 | 3,500 | 5,000 | .0017 | .0015 | 1.3 |
| 23. Red Willow Creek near Red Willow, Nebr | 45 | 7.1 | 6 | 44.4 | 42 | 475 | 2,250 | 500 | .0017 | .00077 | 2.1 |
| 24. Republican River at Cambridge, Nebr | 320 | 3.5 | 93 | 2.9 | 407 | 3,150 | 7,800 | 5,300 | .0014 | .0012 | 1.2 |
| 25. Republican River near Orleans, Nebr | 146 | 6.0 | 24 | 6.7 | 385 | 1,400 | 6,600 | 6,500 | .0013 | .00083 | 1.6 |
| 26. Beaver Creek near Beaver City, Nebr | 55 | 10 | 6 | 22 | 34 | 200 | 1,050 | 500 | .0020 | .0010 | 1.8 |
| 27. Beaver Creek at Ludell, Kans | 28 | 8.0 | 4 | 36 | 20 | 400 | 635 | 500 | .0023 | .0012 | 2.3 |
| 28. Sappa Creek near Stamford, Nebr | 60 | 10 | 6 | 28 | 88 | 830 | 2,100 | 500 | .0013 | .0007 | 1.8 |
| 29. Prairie Dog Creek at Norton, Kans | 50 | 10 | 5 | 15 | 45 | 300 | 3,200 | 500 | .0017 | .0011 | 1.6 |
| 30. Republican River at Concordia, Kans | 251 | 7.1 | 35 | 4 | 904 | 3,300 | 9,300 | 5,300 | .0009 | .0006 | 1.5 |
| 31. Solomon River at Niles, Kans | 126 | 7.6 | 17 | 16 | 595 | 1,400 | 8,000 | 2,000 | .0007 | .00026 | 1.9 |
| 32. Kansas River at Wamego, Kans | 636 | 10 | 64 | 3.8 | 4,400 | | 39,000 | 19,200 | .00096 | .0008 | 1.2 |
| 33. Kansas River at Topeka, Kans | 800 | 18 | 44 | 3.0 | 5,155 | | 48,000 | 23,200 | .00055 | .0005 | 1.1 |

This equation explains 88 percent of the variation of meander wavelength from the mean ($r=0.94$, standard error is 0.17 log units), whereas bankfull discharge alone explains only 48 percent of the variation. Bankfull discharge was calculated, by using this equation, for each of the three Riverine Plain channels, and the results are given in table 7.

The position of the channels in figure 30 and the calculated values of bankfull discharge (table 4) support the conclusion that the bankfull discharge of the prior-stream and ancestral-river channels on the Riverine Plain (section 5) was considerably more than that of the modern river at Darlington Point. However, bankfull discharge values tell little about the relative wetness or dryness of the basin, for although high bankfull discharge is often associated with high mean annual discharge, many rivers draining semiarid regions have a low annual discharge but a high bankfull discharge.

In an effort to obtain information on the expected annual discharge of the Riverine Plain channels, the mean annual discharge of the 33 United States rivers (table 6) is plotted against meander wavelength in figure 31.

Carlston (1965) has plotted mean annual discharge ($Qm$) against meander wavelength, and his regression line ($l=106Qm^{0.46}$) passes through the lower part of the plot in figure 31.

The mean annual discharge for the three Murrumbidgee River cross sections is known. When plotted in figure 31, after adjustment for upstream diversions, these points fall below Carlston's regression line in the lower range of scatter. Of course, information on mean annual discharge of the ancestral and prior-stream channels is not available, but a multiple-regression analysis of the data collected from the United States rivers and the Murrumbidgee River yields the following relation among meander wavelength ($l$), mean annual

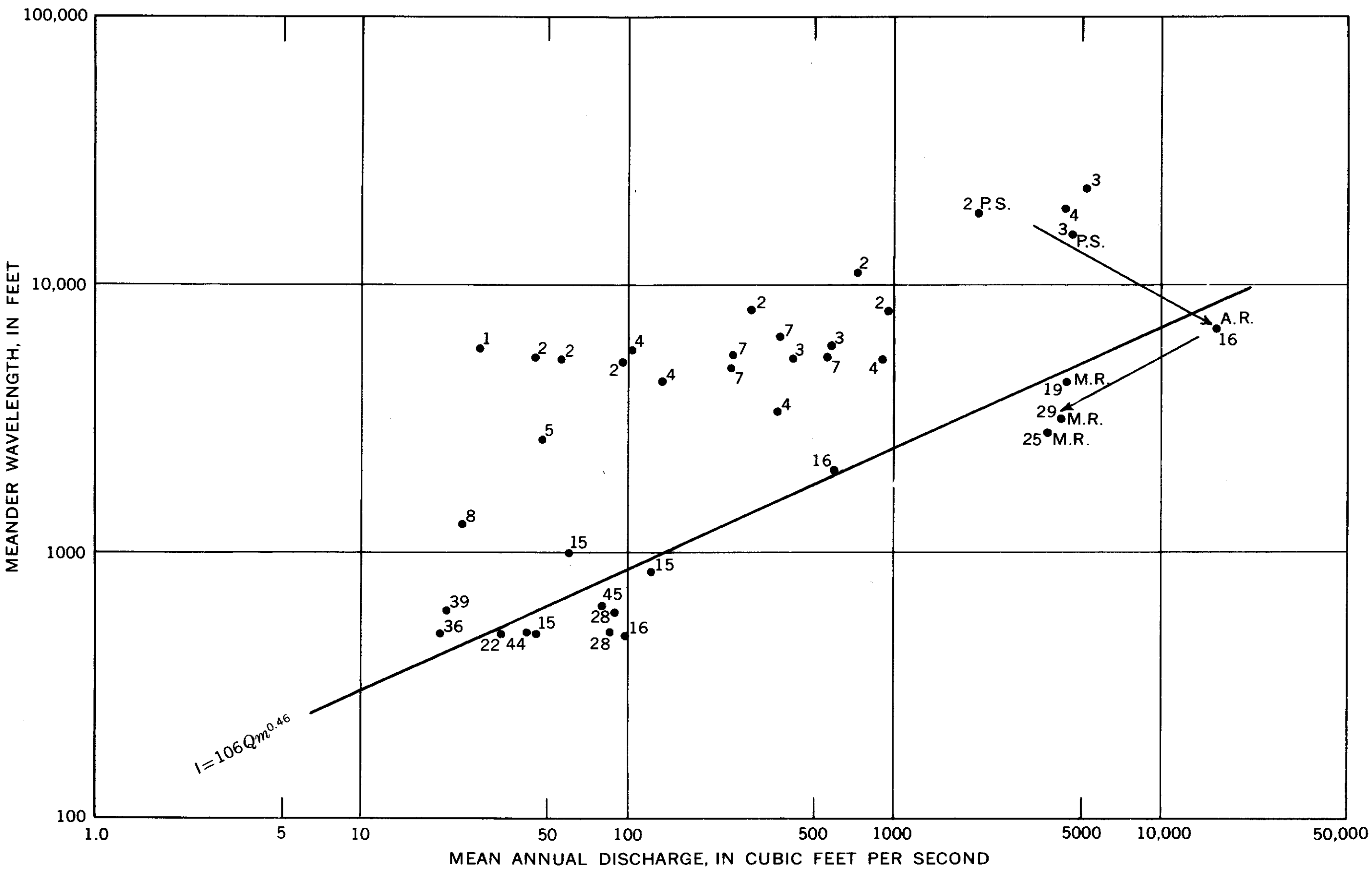


**FIGURE 31.**—Relation between meander wavelength and mean annual discharge. Number beside each point indicates the silt-clay content, in percent, of each channel. Position of the Murrumbidgee River (M.R.) point is based on measured discharge. Mean annual discharge for the prior streams (P.S.) and the ancestral river (A.R.) was calculated from the regression equation, which relates meander wavelength to mean annual discharge and channel silt-clay.

discharge ($Qm$) and the percentage of channel silt-clay ($M$):

$$l=1{,}890\ \frac{Qm^{0.34}}{M^{0.74}}.$$

This equation explains 89 percent of the variation of meander wavelength from the mean ($r=0.96$). Standard error is 0.16 log units. The agreement between measured and calculated meander wavelength is shown in figure 32. For this set of data, only 43 percent of the variation of meander wavelength from the mean is explained by mean annual discharge alone.

The above equation was used to calculate mean annual discharge for the prior-stream and ancestral-river channels because meander wavelength for both could be measured, and the percentage of silt and clay in these channels could be estimated with some assurance (table 3). Calculations indicate that the ancestral-river channel had the largest mean annual discharge of the three types of channels and that the mean annual discharge of the prior-stream channels was of the same order of magnitude as that of the modern river channel (fig. 31; table 7).

The same set of data was used to establish the relationship of meander wavelength ($l$), mean annual flood ($Qma$), and percentage of silt and clay in the channel perimeter ($M$) as follows:

$$l=234\ \frac{Qma^{0.48}}{M^{0.74}}.$$

This equation explains 86 percent of the variation of meander wavelength from its mean, but only 40 percent of the variation is explained by mean annual flood alone.

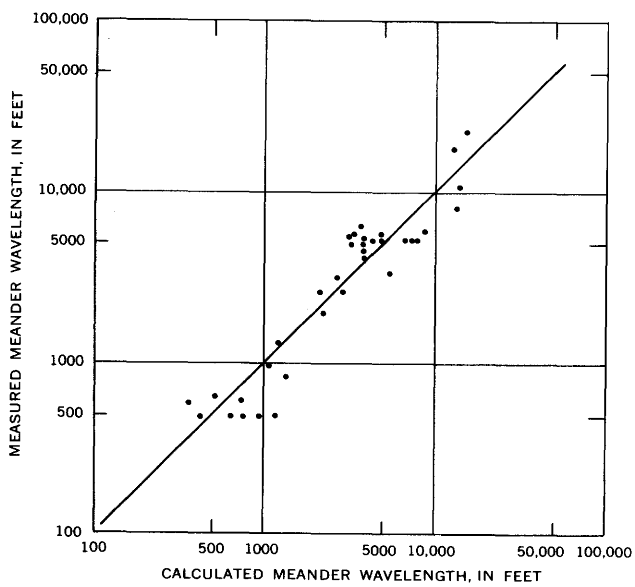


FIGURE 32.—Relation between calculated and measured meander wavelength.

Standard error is 0.19 log units. If the above equation is used to calculate the mean annual flood for the paleochannels, the highest discharge is once again associated with the ancestral river (table 7).

Data for the discharge of the Riverine Plain channels are summarized in table 7. The data were obtained in three ways: (1) bankfull discharge was calculated by use of the Manning equation and the channel area; (2) bankful discharge, mean annual discharge, and mean annual flood were calculated for the ancestral-river and prior-stream channels by use of the regression equations; and (3) the mean annual flood and mean annual discharge for the Murrumbidgee River was obtained at Darlington Point gaging station. Where two different methods of obtaining discharge values were used, the results are, except for two values, in reasonable agreement. For example, the estimated mean annual flood for the modern river is twice that as measured at Darlington Point. This suggests that the peak discharge is reduced considerably by overbank flooding at and above Darlington Point. In fact, the mean annual flood at Narrandera, about 55 river miles upstream, is 15,000 cfs, and at Wagga Wagga, 190 miles upstream, it is 25,000 cfs.

Nevertheless, at all stages of discharge the ancestral-river channel was associated with the highest flood peaks and runoff. The bankfull discharge in the prior-stream channels was about twice that associated with the modern-river channels, but according to these calculations, the mean annual flood and the mean annual discharge of the prior streams were of the same order of magnitude as those now occurring in the channel of the modern river.

TABLE 7.—*Summary of discharge data for Riverine Plain channels*

[Data are in cubic feet per second]

| Type of discharge | Murrumbidgee River | Ancestral river | Northern prior stream | Southern prior stream |
|---|---|---|---|---|
| Mean annual discharge: | | | | |
| Estimated [1] | 3,200 | 17,000 | 2,000 | 5,600 |
| Measured [2] | 3,700 | | | |
| Mean annual flood: | | | | |
| Estimated [1] | 25,000 | 86,000 | 18,000 | 39,000 |
| Measured [2] | 11,000 | | | |
| Bankfull discharge flood: | | | | |
| Estimated [1] | 11,000 | 51,000 | 23,000 | 19,000 |
| Calculated [3] | 11,000 | 48,000 | 12,000 | 25,000 |

[1] From regression equations.
[2] From gaging-station data.
[3] From Manning equation and area of channel.

The evidence for a relatively drier climate during the time when the prior-streams were functioning can be enumerated as follows:

1. The variations in salinity of soils of the Riverine Plain show a close correspondence to the distribution of prior-stream channels. Butler (1950, p. 240) believed that the original salinity increased

with distance down the prior streams and that the salinity increase suggests increased aridity.

2. Weathering characteristics of Riverine Plain paleosols indicate that at the time of the Quiamong and Mayrung prior streams the climate was drier than at present (Butler, 1958). The leaching of lime and clay occurred between the phases of prior-stream development and indicates a more humid climate.
3. The association of eolian deposits with the prior-stream channels and their absence along the modern river suggest that flow in the prior-stream channels was ephemeral and that relative dryness prevailed during prior-stream time.
4. The paucity of datable organic material in the prior-stream channels suggests that, unlike present channels, the prior-stream channels were not bordered by trees.
5. Within the limits of the climate changes postulated for this region, a more arid climate than that prevailing today would be required to produce the large quantities of sand transported through, and deposited in, the prior-stream channels (fig. 29). At present, 60 percent of the sediment source area above Narrandera receives less than 25 inches of precipitation. This area would be significantly affected by a decrease in precipitation, for such a decrease would weaken the protective cover of vegetation and increase sediment yield.
6. The dimensions of the ancestral-river channel indicate that it transported higher discharges than does the modern-river channel. Because the shape, sinuosity, and sediment characteristics of the ancestral-river channel are similar to those of the modern river (fig. 9), it is evident that an increase in precipitation and runoff will not convert the modern-river channel to a bedload channel of the prior-stream type, but rather to a suspended-load channel of the ancestral-river type.
7. The relationship between meander wavelength and mean annual discharge does not indicate that mean annual discharge was significantly greater in the prior-stream channels than in the present channel (fig. 31). In fact, because of the variability shown by the data (table 7), probably no conclusions regarding mean annual discharge should be reached that would be based wholly on the dimensions of the meander patterns.
8. Perhaps the most significant conclusion (Butler, 1961) is that the prior streams did not flow to the sea. Apparently the flow in these channels was dissipated on the plain, and this could only have occurred during a climate drier than at present.
9. Finally, at a discharge higher than that carried by the modern river, the sands that fill the abandoned prior-stream channels would have been transported across the Riverine Plain to the sea. This has been demonstrated for the Irrawaddy River of Burma, where the enormous runoff of the monsoon season transports 80 percent of the annual sediment load across the delta and out to sea.[3]

The morphologic differences between the prior-stream channels and the ancestral-river channels reflect a change from a relatively dry to relatively wet climate, as compared with the climate of today. In figure 31 the arrows indicate the change in position of the points that would occur with a transition from prior stream to ancestral river and with a transition from ancestral river to modern river. The high sediment yield, high proportion of sand load, and probably higher peak discharges associated with the prior streams maintained channels of low sinuosity, high width-depth ratio, relatively steep gradients, and long meander wavelengths. The high discharges of the ancestral river were associated with a more humid climate than that of the present, denser vegetational cover, and reduced sediment yields from the drainage basin. The resulting sinuous, low width-depth ratio channel had a gentler gradient but had a meander wavelength of intermediate size.

The modern Murrumbidgee River channel formed when the high discharge of the ancestral-river channel ceased. The change in climate which caused this change in channel morphology was not great enough to cause a significant increase in erosion within the catchment, but it caused runoff to decrease and caused channel dimensions and meander wavelength to be reduced in size but with little or no change in shape, pattern, or gradient of the channel. If the climate were to become even drier, sediment yields from the Eastern Highlands would increase and the modern-river channel would become a bedload channel or prior-stream-type channel, and the position of the Murrumbidgee River points in figure 31 would be shifted upward.

Meander wavelength is related to discharge, but, as figures 30, 31, and 32 show, scatter about the regression line is related to *M* and, therefore, to the type of sediment load moved through the channel. Low-sinuosity channels will have a much greater meander wavelength for a given discharge than meandering channels. Although higher peak discharge may have moved through the prior-stream channels, the relation between meander wavelength and mean annual discharge cannot be used as evidence of higher runoff. Along with the other evidence, the relationship supports the conclusion that

[3] K. S. Rodolfo, in "Marine sedimentation off the Irrawaddy River, Burma": abstract of paper presented at the 1966 annual meeting of the Geological Society of America.

runoff during prior-stream time was less than at present; hence, the climate was drier.

### MECHANICS OF CHANNEL ADJUSTMENT

The comparisons of the modern river and the paleochannels of the Riverine Plain have provided information concerning the adjustment of a major river system to changed hydrologic regimen. Past discussions of river-channel adjustment to the effects of climate change have centered on changes of river cross section and gradient in response to changed ratios of sediment load and runoff (Rubey, 1952, p. 129–136; Mackin, 1948). In addition, the relation established between meander dimensions and discharge has been used to suggest how meander patterns change with changed mean annual or bankfull discharge (Hjulstrom, 1949; Dury, 1965). Geologists have relied mostly on the longitudinal profile and gradient of river channels for information on which to base an interpretation of river history. Hydraulic engineers concerned with the design of stable channels have developed equations for the dimensions of canal cross sections based on discharge and sediment size (Lacey, 1930). (See also Leliavsky, 1955, p. 192–245, or Blench, 1957, p. 12–26.) Similar regime equations were developed for rivers by Leopold and Maddock (1953) and these equations permit the calculation of width and depth of stable alluvial channels.

In all the previously developed regime equations, both width and depth are shown to increase as discharge increases, whereas gradient decreases with an increase in discharge. Both gradient and width-depth ratio increase as sediment size increases (Lacey, 1930). These conclusions are based on the empirical relations that have been shown to exist between stable river (and canal) dimensions and discharge. They are not based on the documentation of channel changes which have resulted from a change in hydrologic regimen. Therefore, the information to be gleaned from considering the channels of the Riverine Plain and their adjustments due to climate change may be of general interest.

A climate change can alter the volume of both runoff and sediment leaving a source area, and it can also greatly alter the proportions of bedload and suspended-sediment load leaving the system. (See figures 28 and 29.) The changes in bedload and in suspended-sediment load are of major importance in establishing the type of channel that will form as a result of each change in climate. These changes are so important, in fact, that most of the changes documented for the Riverine Plain channels do not conform to the regime equations used to design stable canals and river channels. For example, according to most regime equations, including those of Leopold and Maddock (1953), channel width should change as the square root of mean annual discharge, depth should vary with the 0.4 power of discharge, and width-depth ratio should vary as the 0.1 power of mean annual discharge. Meander wavelength should change as the square root of bankfull discharge (Dury, 1965). If, however, annual runoff has increased since the prior streams were operational, as the above-cited evidence suggests, the changes in channel width, width-depth ratio, and meander wavelength are in the wrong direction. This, however, should not be too surprising, as a decrease in the width and depth of river channels with increasing discharge has been demonstrated for those rivers in which the type of sediment load transported through the main channel has been significantly altered by the sediment load introduced at tributary junctions (Schumm, 1960b). In the following discussion, channel dimensions, shape, meander wavelength, gradient, and sinuosity are considered in relation to changes in discharge and in type of sediment load transported by a river.

#### CHANNEL DIMENSIONS AND SHAPE

Data previously collected along United States rivers (table 6) have been combined with the data collected at the Wagga Wagga, Narrandera, and Darlington Point cross sections on the Murrumbidgee River (table 1) to demonstrate the influence of discharge and type of sediment load on channel morphology. A multiple-regression analysis of the data yields the following relationships between channel width ($W$), mean annual discharge, ($QM$), mean annual flood ($Qma$), and channel silt-clay ($M$):

$$W=37\,\frac{Qm^{0.38}}{M^{0.39}}, \text{ and}$$

$$W=2.3\,\frac{Qma^{0.58}}{M^{0.37}}.$$

These equations explain about 87 percent of the variation of channel width from the mean ($r$=0.93 and $r$=0.94; standard error for both equations is 0.13 log units). $M$ alone explains 41 percent of the variation of channel width from the mean; its influence on channel width is such that it can cause width to increase when discharge decreases and vice versa. Figure 33 demonstrates the extent of agreement between measured and calculated channel widths and indicates that the family of curves relating channel width to discharge can be reduced to one curve by the introduction of a parameter expressing the type of sediment load moved through the channel.

Bankfull discharge is not used in the multiple-regression analysis of channel dimensions and shape because it was calculated by the use of the cross-sectional area of the channel. Its use would put channel width and depth on both sides of the equation.

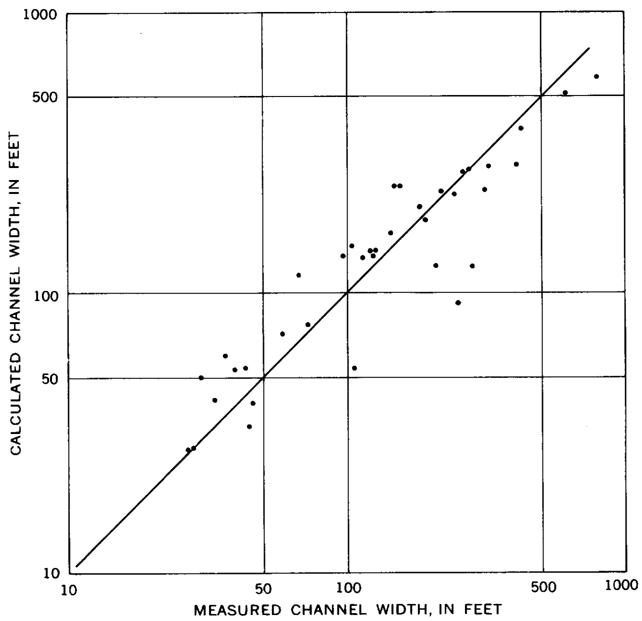


FIGURE 33.—Relation between measured channel width and calculated channel width. Width calculated by use of equation involving channel silt-clay ($M$) and mean annual discharge ($Qm$).

The same set of data was used to determine the effect of discharge and type of sediment load on channel depth ($d$). Mean annual discharge alone explains 42 percent of the variability in channel depth, and $M$ alone explains 19 percent of the variation in depth from the mean. If these two variables are used in a multiple-regression analysis, the following equation is obtained:

$$d=0.59M^{0.34}\,Qm^{0.29}.$$

This equation explains 79 percent of the variation in depth from the mean ($r$=89). If data for the mean annual flood are used, an equation that explains 73 percent of the variation in depth is obtained ($r$=0.86):

$$d=0.09M^{0.35}\,Qma^{0.42}.$$

The standard error for both equations is 0.13 log units. These equations demonstrate, as do the equations for channel width, that $M$ exerts a significant control on channel dimensions and that it is possible for both channel width and depth to increase with a decrease in discharge. For example, the change in dimensions from those of a prior-stream channel to those of the modern river can occur with increased runoff if a significant increase in $M$ (increase in the ratio of suspended load to bedload) occurs. It was concluded from a comparison of the sediments sampled from the Riverine Plain channels that such a change in sediment loan did, indeed, occur.

On the other hand, the size decrease of the large ancestral-river channel to dimensions of the Murrumbidgee River channel resulted primarily from a decrease in runoff alone; therefore, channel width, depth, and meander wavelengths decreased in the manner predicted from the standard regime equations.

The shape of stable alluvial-stream channels, as expressed by the width-depth ratio ($F$), has been shown to be dependent primarily on the percent of silt-clay in the channel perimeter ($M$) as follows (Schumm, 1960b):

$$F=255M^{-1.08}.$$

The data used here to obtain the equation relating channel width and depth to discharge and sediment load (tables 1, 6) includes a smaller range of channel shape values, and the equation developed from these data is different from the one above, as follows:

$$F=106M^{-0.78}.$$

Nevertheless, 85 percent of the variation of width-depth ratio from the mean is explained by $M$ alone. If discharge is introduced the following equations result:

$$F=56\frac{Qm^{0.10}}{M^{0.74}},$$

$$F=21\frac{Qma^{0.18}}{M^{0.74}}.$$

The inclusion of discharge in the relationship between width-depth ratio and $M$ improves the correlation significantly, but only an additional 1.5 percent of the variation is explained by the addition of $Qm$, and only 2.5 percent is explained by the addition of $Qma$. Standard error for both equations is 0.15 log units.

Although the relation between width-depth ratio and $M$ differs from that obtained previously, the general relationship that bedload channels are wide and shallow, whereas suspended-load channels are narrow and deep, pertains.

Channel dimensions for a given type of sediment load are known to be controlled by the quantity of runoff that must pass through the channel; nevertheless, a significant control on channel width and depth is also exerted by the type of sediment load passing through the channel. A large width-depth ratio is required before a channel can convey significant bedload, and width and depth will adjust to provide the most efficient shape for the type of sediment load and the quantity of runoff.

### CHANNEL GRADIENT AND VALLEY SLOPE

Not only did the shape and dimensions of the Riverine Plain channels change significantly in response to a change in hydrologic regimen, but the pattern, gradient, and longitudinal profile (fig. 7) were also altered significantly. Because of the degradation that occurs below dams if sediment loads are reduced, and because of the presence of terraces in most river valleys, reduction in river gradient is generally assumed to occur largely by incision of the alluvial deposits. In many places, however, the slope of a terrace is very similar to that of the modern-river flood plain, and, therefore, although the position of the river has changed, the gradient of the valley has changed only slightly. This appears to be true of the Riverine Plain. Some lowering of the channel has occurred, and the flood plain now lies 3–5 feet below the plain (table 1). At Wantabadgery there is a terrace surface 15 feet above the river. At Wagga Wagga the terrace surface is 8 feet above the modern flood plain. At Maude the surface of the Riverine Plain is about 5 feet above the flood plain. Therefore, between Wagga Wagga and Maude the river has decreased its slope by downcutting by only 3 feet in about 400 miles.

The river distance from Wantabadgery to Maude is 450 miles, but the distance is only 225 miles along the flood plain. Present-day decrease in altitude over this distance is 382 feet. In the past the difference in altitude was 392 feet. The sinuosity today is about 2.0 over this part of the Murrumbidgee, and the gradient is 0.85 foot per mile. On the assumption that sinuosity was about 1.1 in the past, the gradient of a prior stream following the course of the Murrumbidgee would have been about 1.55 feet per mile. If so, there has been a 0.7 foot per mile decrease in gradient, but only 0.02 foot per mile of this change is due to channel incision. The remainder is due to a lengthening of the river course by an increase in its sinuosity.

Valleys that have been heavily aggraded by the products of glaciation or those that have had their valley slopes steepened by diastrophism are more likely to entrench. However, when valley slope is unchanged, gradient is more readily reduced by the development of a meandering or sinuous river pattern than by incision. Further, Dury (1964) has shown a decrease in the overall gradient of a river by incision would require erosion of an improbable magnitude in the headwaters.

Figure 34 provides a graphic illustration of such a change in channel gradient. Channel gradient is related to the slope of the valley over which the river flows. The correlation seems trivial because slope is plotted against slope. Nevertheless, the valley slope is the surface on which the modern river flows, and it can be considered an independent variable for the purpose of this discussion (Schumm, 1963b; Schumm and Lichty, 1965).

In figure 34 a channel having a gradient identical with the slope of its valley would have a sinuosity ($P$) of 1.0. However, some of the channels plot near the line indicating a sinuosity of 3.0. In figure 34, the low-silt-clay channels fall near the upper line of low sinuosity, and, as expected, the high-silt-clay channels fall near the lower lines of high sinuosity.

An analysis of the data (tables 1, 6) shows that 83 percent of the variability in gradient ($Sc$) from the mean is explained by the slope of the valley floor ($Sv$) on which the river flows.

Forty percent of the variability in gradient can be explained by the use of any of the three discharge parameters ($Qm$, $Qma$, $Qb$). Mean annual discharge was used in the following multiple-regression analysis:

$$Sc=59.5M^{-0.38}Qm^{-0.32}.$$

In this equation 79 percent of the variation in gradient from the mean is explained by $M$ and $Qm$ ($r=0.84$; standard error is 0.15 log units). If valley slope is also used, the following equation results:

$$Sc=1.3\frac{Sv^{0.94}}{M^{0.23}Qm^{0.02}}.$$

This equation explains 95 percent of the variation in gradient from the mean ($r=0.97$; standard error is 0.07 log units), and it demonstrates that on a given valley slope a straight channel will begin to meander if

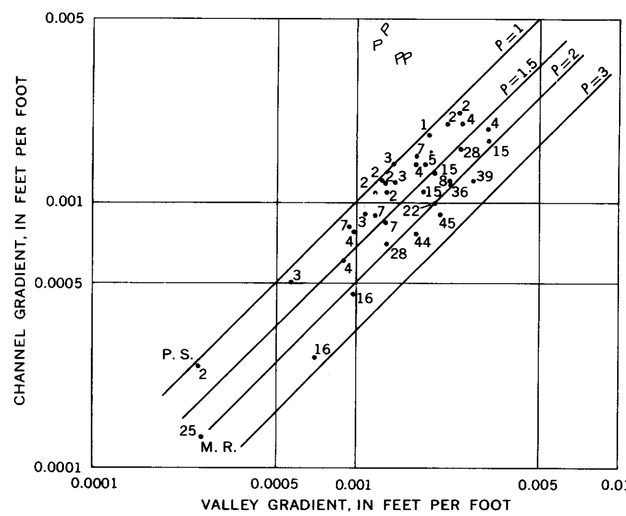


FIGURE 34.—Relation between valley slope and channel gradient, illustrating effect of channel silt-clay on channel gradient. Lines of equal sinuosity are shown, and the silt-clay content ($M$), in percent, of each channel is given for each point. The positions of the points for the Murrumbidgee River (M.R.) at Darlington Point and the northern prior stream (P.S.) at the Kearbury pit illustrate the major change of river gradient that has occurred on the Riverine Plain. The gradient of the prior-stream channel was measured at the pit and, therefore, is different from the value obtained from plate 2 (table 3).

mean annual discharge or $M$ increases (bedload decreases). Valley slope and $M$ alone explain 86 percent of the variance with a standard error of 0.16 log units.

River gradient is therefore dependent primarily on the slope of the valley, which was established by the river during possibly very different climatic and hydrologic conditions and, to a lesser degree, is dependent on the type of sediment load and quantity of discharge moving through the modern channel.

#### CHANNEL PATTERN

The sinuosity ($P$) of many channels has been shown previously (Schumm, 1963b) to be related to $M$ as follows:

$$P=0.94M^{0.25}.$$

Discharge does not influence this relationship significantly because the sinuosity of a small stream can be very similar to that of a large river, if the two are transporting similar types of sediment. For the data used in this report, the relationship changes somewhat, as follows:

$$P=1.06M^{0.18}.$$

In this equation $M$ explains 50 percent of the variability of sinuosity from the mean ($r=0.70$). The relation suggests that those channels that are now characterized by a high silt-clay content and whose data plot near the lines of high sinuosity in figure 34 were, at one time, straight steep channels, but a change in discharge and in sediment load caused changes in their channel sinuosity and gradient (Schumm, 1963b). The location of the points representing the prior stream and Murrumbidgee River in this figure confirms this, because for virtually the same valley slope (slope of the Riverine Plain), the gradient of the Murrumbidgee River is much less (fig. 7).

Relationships among meander wavelength, channel silt-clay and discharge have been discussed, and the conclusion was reached that the wavelength of meanders reflects not only the magnitude of discharge but also the type of sediment load transported through the channels. However, relations between meander wavelength and channel width have also been established. (See Leopold and Wolman, 1960, p. 773.) A similar relationship can be demonstrated for these data as follows:

$$l=11.7w^{1.1}.$$

The constants of this equation are slightly greater than those obtained by other workers, but for my data 75 percent of the variation of meander wavelength is explained by width alone ($r=0.87$). Nevertheless, this correlation is not particularly meaningful, as both meander wavelength and channel width have been shown to be significantly related to discharge and $M$.

The previously noted relationships and the obvious changes of channel pattern that have occurred on the Riverine Plain lead one to a consideration of the phenomenon of meandering. Freidkin (1945) suggested that rivers meander because their banks are erodible. The suggestion is fallacious, however, for nonmeandering rivers also have erodible bank materials. Also erroneous is the suggestion that, because gradients of meandering streams are less for a given discharge than gradients of less sinuous streams (Leopold and Wolman, 1957, fig. 46), the gentleness of the slope is the cause of meandering (Lane, 1957). Dury (1964, p. 5) suggested that this reasoning may result from an attempt to place a meandering river within the sequence of events of an erosion cycle.

Brice (1964) concluded from his investigations of the morphology of the Loup River system in Nebraska that the most sinuous reaches of this system are associated with gradients of moderate inclination—that is, the steepest and gentlest reaches are not sinuous. Other factors may also be important, but, nevertheless, highly sinuous streams are not associated with very steep valley slopes or very gentle valley slopes.

There are sound hydraulic reasons why rivers should meander and thereby increase their sinuosity (Leopold and Wolman, 1960), but in many field situations these hydraulic factors can be of significance only if the controlling geologic conditions are favorable (Schumm, 1963b). For example, figure 34 demonstrates that the slope of a valley can be almost three times steeper than the gradient of the stream that flows in the valley.

This disparity between channel gradient and valley slope has been explained as a result of late Pleistocene and Holocene changes in climate and their effects on the hydrologic regimen of a drainage basin. Depending on the geology of a drainage basin, the sediment load of a river might change from gravel and sand to sand alone or from silt, clay, sand, and gravel to predominantly silt and clay as the valley alluvium was deposited. In streams draining areas underlain by sandstone, therefore, the caliber of the sediment load decreased, but the ratio of suspended load to bedload probably changed very little. Streams draining areas of sandstone and shale underwent not only a decrease in the caliber of sediment load but also an increase in the ratio of suspended load to bedload. As a result, the streams draining areas of mixed sediments, after losing the coarser fraction of their sediment load, flowed over alluvium on a gradient greater than that required for transport of the predominantly suspended load. A reduction of gradient by degradation would have been only partly effective, for with incision the stream would have reached the coarser sediments transported during a previous regime, and these would have acted as an armor against further degradation. The development of a sinuous course appears to have been the only alternative. Streams draining areas of relatively coarse or sandy sediments were less affected by the change in caliber of sediment load and continued to flow on a gradient that is virtually the same as the slope of the valley itself, because these streams have transported relatively large amounts of bedload throughout their history (Schumm, 1963b, p. 1096–1097).

It is perhaps, significant that Dury (1964, p. 63) remarked, after a study of many European and United States rivers, that "In all valleys so far investigated which contain manifestly underfit streams, the alluvium contains a high silt-clay fraction." The conclusion appears to be that the most sinuous of all the underfit rivers studied were those that suffered not only a decrease in discharge but also a change in the ratio of suspended to bedload.

In some experimental studies of meandering, the model channels were assumed to meander, although the channels were transporting predominantly sand loads. A tendency toward development of a sinuous channel was detected in these experiments (Freidkin, 1945; Ackers, 1964); however, the model channel at the conclusion of the experiments was still almost straight. The meandering channel developed by Freidkin was not a channel which carried the bankfull flow of water; rather, it was a thalweg, or low-water channel, visible when the discharge was reduced to a very small fraction of that used to develop the stable bankfull channel. The entire channel was therefore only slightly sinuous, even when the water was introduced into the flume at an angle that should have induced some meandering. In fact, Freidkin (1945, p. 10) found that when water was introduced into the flume parallel to its sides, no sinuosity developed, and the channel became so wide and shallow that bank erosion ceased. In all of Freidkin's experiments except those in which the bank materials had been rendered more cohesive by additions of silt or cement, the sediment load was sand. Perhaps true channel meandering would have developed if the sediment load had been changed from predominantly sand to a mixture of sand, silt, and clay.

One therefore returns to the postulate that meandering is a principal means of dissipating stream energy (Leopold and Wolman, 1960, p. 787). The ancestral river and the Murrumbidgee River developed a very sinuous course as a result of dissipating the energy no longer required for the transport of bedload. For a river to dissipate its excess energy by decreasing its gradient by incision over the entire length of its channel would have involved much work, and large quantities of sediment would have to be removed from the system during a short period of time. Whereas by reworking of the alluvium, a river could develop a meandering course of low gradient without having to transport large quantities of sediment from the system.

If one wished to discuss meandering in the context of an erosion cycle, the highly sinuous alluvial rivers would probably appear only after denudation had progressed to the degree that only relatively fine sediments are produced in the source area. Erosion early in the cycle would have produced relatively steep gradient streams capable of transporting the coarse sediments from the high-relief source area. A reduction in the altitude of the source area and a cessation of river incision at the source area would have permitted the weathering processes to produce the fine sediments required for the development of a meandering alluvial river.

## MODERN CHANNEL ADJUSTMENTS TO CHANGED HYDROLOGIC REGIMEN—MAN INDUCED AND NATURAL

The climate change in the headwaters of the Murrumbidgee River, which resulted in the transformation of the prior-stream channels to the modern-river channels, also involved four marked changes in the hydrologic regimen of these channels, as follows:

1. Increase in runoff, or mean annual discharge.
2. Decrease in magnitude of flood discharges.
3. Decrease in annual sediment yield, or sediment concentration.
4. Increase in ratio of suspended load to bedload.

Changes 1, 2, and 4 probably had the greatest effect on stable-channel morphology.

Similar hydrologic changes have been induced by the efforts of man to control river behavior. For example, a flood-control structure may have the effect of a major climatic change in the hydrologic regimen of a river. That is, most of the bedload will be held in the reservoir, and flood peak discharges will be greatly reduced. Therefore, if the conclusions reached through a study of the Riverine Plain channels are correct, the modern rivers that are morphologically similar to the prior streams should show a tendency to acquire the character of the modern Murrumbidgee River, below a flood-control structure. The completeness of the change depends, of course, on the magnitude of the hydrologic change induced by the control structures. On the other hand, rivers adjusting to a deterioration of erosion conditions in the catchment could change from a Murrumbidgee-type channel to a prior-stream-type, bedload channel.

If such man-induced changes in river morphology can be demonstrated, they will not only support the conclusions derived from the Riverine Plain investigation but also provide a basis for the prediction of river changes to be expected when the hydrologic regimen of certain types of drainage systems are altered.

Most examples to be cited are in semiarid and subhumid regions where adjustments to changes of hydrologic regimen will be greatest (figs. 28, 29). The data are not as complete as desired for each example cited, and the causes of river adjustment and their effects, therefore, are not completely known; however, the most apparent hydrologic causes and their obvious morphologic effects can be considered.

First, a few examples of the conversion of suspended-load channels to bedload channels will be cited. These changes occurred on rivers that were not subject to significant regulation of flow, and the formerly meandering rivers were converted to straight channels by a combination of high peak discharges and an influx of coarser sediment into the channel. For example, the highly sinuous, relatively narrow and deep Cimarron River channel was destroyed by the major flood of 1914 (McLaughlin, 1947; Schumm and Lichty, 1963). Between 1914 and 1939 the river widened from an average of 50 feet to 1,200 feet, and the entire flood plain was destroyed. Large floods moved considerable sand and caused this transformation despite the fact that annual discharge was probably less during the drought of the 1930's. The hydrologic record is short, but an abrupt increase in annual discharge after 1940 was recorded at the Wyanoka, Okla., gaging station (U.S. Geological Survey 1955a, 1964a).

Precipitation data indicate that the years 1916–41 were generally a period of below-average precipitation. Thus, during years of low runoff and high flood peaks, the Cimarron River was converted from a narrow sinuous channel characterized by low sediment transport to a very wide, straight bedload river. These changes were apparently the result of climatic fluctuations, although agricultural activities within the basin may have increased the flood peaks and the sediment loads by destruction of the natural vegetation (Schumm and Lichty, 1963).

Destruction of natural forest vegetation on steep slopes in the humid regions of New Zealand and replacement of this vegetation with exotic grasses has caused erosion problems of major proportions. Stable narrow sinuous rivers have changed to wide straight channels as a result of an influx of coarse sediment into the channels from the steep slopes and an increase in flood peaks (Grant, 1950; Campbell, 1945). A somewhat similar problem arose in California when hydraulic mining debris was fed in great quantities into the rivers draining from the gold fields of the Sierra Nevada (Gilbert, 1917).

Similar downstream changes in river morphology have been described where a major tributary introduces large quantities of sand into a river transporting a relatively high silt-clay sediment load. The differences in channel characteristics between the Smoky Hill River and the Kansas River above and below the junction of the Republican River illustrates this change (Schumm, 1960b). The Smoky Hill River in central Kansas receives a high silt-clay sediment load from its tributaries, the Solomon and Saline Rivers. Near the junction of these tributaries the sinuosity of the Smoky Hill River is greater than 2 and its width-depth ratio is about 10. At the junction of the Republican River, farther downstream, the Smoky Hill River becomes the Kansas River and assumes the character of a bedload stream owing to the introduction of sand from the Republican River. The sinuosity of the Kansas River at Topeka is 1.1, and width-depth ratio is 45.

The above examples indicate that a Murrumbidgee-type river will be converted to a bedload-type river when an increase in bedload and a major increase in flood peaks occur. Generally, an increase in flood peaks should begin to move coarser sediments through the channel, so the two causes cannot easily be separated.

Equally common during historic times are river changes corresponding to a decrease in the magnitude of peak discharges and a decrease in the proportion of the sand load. For example, after the great widening of the Cimarron River between 1914 and 1942, a period of well-above-average rainfall ensued, and although annual runoff increased, no major floods moved through the channel between 1942 and 1951. According to measurements made on aerial photographs taken in 1939 and 1954, the average width of the river decreased from 1,200 to 500 feet, so that, in effect, the width-depth ratio was reduced by half (Schumm and Lichty, 1963).

Equally great changes along some major rivers east of the Rocky Mountains can be documented if the dimensions of a modern river are compared with the descriptions provided by western explorers and settlers and with the channels as shown on old topographic maps. Especially impressive is the conversion of the broad North and South Platte Rivers and the Arkansas River to relatively insignificant streams owing to flood-control works and diversions for irrigation.

The width of these rivers, as shown on topographic maps published during the latter part of the 19th century, can be compared with the width shown on new maps of the same areas. For example, the North Platte River near the Wyoming-Nebraska boundary has narrowed from about ½–¾ mile wide to about 200 feet wide. (Scotts Bluff quadrangle, Nebraska, as prepared from aerial photographs taken in 1962), and in eastern Nebraska just upstream from the junction of the Loup River at Columbus, the river has narrowed from three-quarters of a mile wide (David City quadrangle, Nebraska, surveyed in 1893) to 2,000 feet wide (Columbus quadrangle, Nebraska, as prepared from aerial photographs taken in 1951).

The South Platte River has always been cited as a classic example of a braided stream. About 55 miles above its junction with the North Platte River, the South Platte River was about half a mile wide at the Ogallala Bridge in 1897 (Ogallala quadrangle, Nebraska, surveyed in 1897), but the South Platte had narrowed to about 200 feet wide at the new bridge (which is only 500 feet wide) by 1959 (Brule quadrangle, Nebraska, as prepared from aerial photographs taken in 1959).

The tendency of these rivers is to form one narrow well-defined channel in place of the previously wide braided channels. In addition, the new channel is generally somewhat more sinuous than the old.

The narrowing of the North Platte can be attributed to a decrease in the mean annual flood from 13,000 to 3,000 cfs and to a decrease in the mean annual discharge from 2,300 to 560 cfs as a result of river regulation and the diversion of flow for irrigation (R. W. Lichty, oral commun., 1964). Figure 35 shows that a major decrease in annual runoff occurred about 1930. A similar change occurred on the South Platte during the drought of the 1930's. However, the annual discharge of the South Platte was higher after 1940, partly as a result of transmountain diversions (fig. 36), whereas, because of upstream regulation, the discharge of the North Platte was not (fig. 35). A decrease in the magnitude of the annual momentary maximum discharge (U.S. Geol. Survey, 1955a, b; 1964a, b) occurred for both rivers, and this decrease was undoubtedly the major factor determining the present channel size.

Similar changes have occurred along the Arkansas River. In eastern Colorado and western and central Kansas, the Arkansas River was about 1,000 feet wide in 1890 (Great Bend quadrangle, Kansas, surveyed in 1889; Lamar quadrangle, Colorado, surveyed in 1890–91), but it was about 200 feet wide in 1950 at the same locations (Ellinwood quadrangle, Kansas, as prepared from aerial photographs taken in 1954; Lamar West quadrangle, Colorado, as prepared from aerial photographs taken in 1947). The width of the river has changed significantly, apparently in response to man-induced changes of hydrologic regimen. A long record of discharge of the Arkansas River at Holly, Colo., just

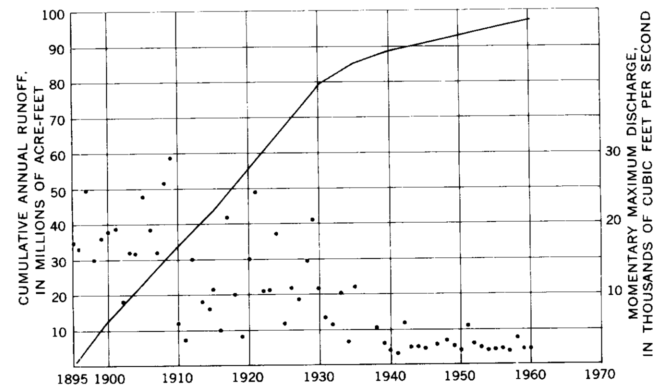


FIGURE 35.—Plot of cumulative annual runoff and momentary maximum discharge against time for the North Platte River at North Platte, Nebr.

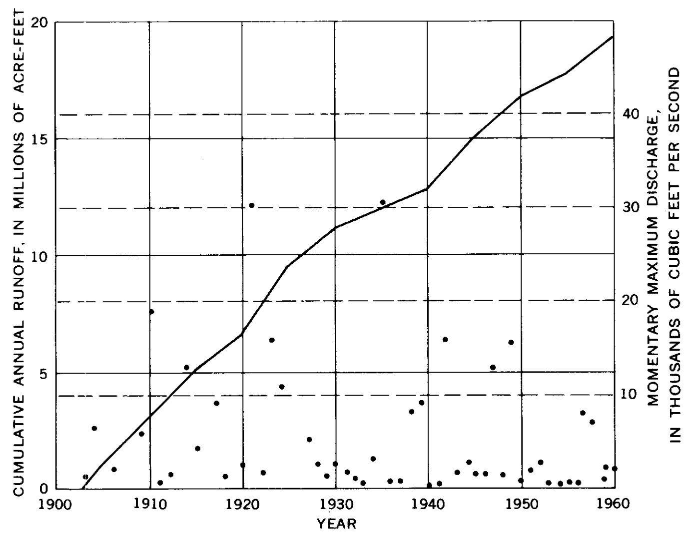


FIGURE 36.—Plot of cumulative annual runoff and momentary maximum discharge against time for the South Platte River at Julesburg, Colo.

west of the Colorado-Kansas boundary, shows no significant change in annual discharge between 1910 and 1950, although flood peaks did decrease. It may be that the significant hydrologic changes were initiated even before the gage was established. In fact, Mead (1896) recognized that as early as 1880 the hydrologic regimen of the Arkansas River had changed significantly owing to man's activities in the basin.

A reduction in both the magnitude of peak discharge and mean annual discharge at the Bloomington, Nebr., gaging station on the Republican River has resulted in a major reduction in channel capacity since 1952, when regulation of flow began at the Harlan County Dam (Northrop, 1965). The reduction in channel capacity has increased the possibility of flood damage along the channel. Two-thirds of the effective capacity of the channel was lost in 1952–57 owing to the growth of willows in the channel and to formation of islands and flood plains similar to those documented for the Cimarron and Red Rivers (Schumm and Lichty, 1963).

The Republican and Cimarron Rivers rise on semiarid plains and flow toward regions of greater precipitation. The Arkansas and the North and South Platte Rivers rise in the Rocky Mountains and flow eastward across semiarid plains toward a zone of higher precipitation. These rivers are all characterized by high peak discharges, but the peak discharges of those that rise in the mountains are seasonal and result largely from spring snowmelt. Even with regulation of flow, these channels are almost dry during the late summer. The documented natural and man-induced changes of channel morphology indicate that bedload rivers will narrow significantly over a long distance if their peak discharges are significantly reduced. Therefore, if a wide sandy unstable channel needs to be stabilized, perhaps the most effective control would be the construction of a dam which would decrease the magnitude of floods.

The records of relatively recent channel changes on the Great Plains of the United States reveal that where man's activities have altered the hydrologic regimen of these bedload channels in a manner similar to that assumed to have been necessary for the change from prior stream to Murrumbidgee River, the wide sandy bedload channels have changed such that, with time, they may assume the character of a suspended-load channel. It is doubtful that the adjustments will be complete, because the channel changes are not in response to a climate change, which would alter the hydrologic regimen of the entire drainage basin. The tributary streams below the point of main-channel regulation still introduce their burdens of water and sediment into the main channel, and until the water and sediment yields from the tributary basins are controlled, transformation of the main channels to a suspended-load type of channel cannot be complete. Nevertheless, the tendency toward this type of change has been demonstrated locally along these rivers.

## SUMMARY AND CONCLUSIONS

### ORIGIN OF RIVERINE PLAIN CHANNELS

The conclusions regarding the nature of the climate changes and the subsequent river adjustments that have occurred permits development of a tentative explanation of the origin of certain Riverine Plain fluvial features. The present state of knowledge concerning the chronology of the Riverine Plain is too incomplete to warrant an attempt to improve on past suggestions regarding the age of the features. Nevertheless, several distinct events can be discussed, and these are listed chronologically as follows:

1. Deep channels eroded into the Katandra sediment.
2. Deposition of Quiamong Riverine sediments.
3. Development of the surficial prior-stream channels.
4. Deposition of Mayrung riverine sediments.
5. Development of ancestral-river channels.
6. Development of the Murrumbidgee River channel.

Butler (1958) concluded that before the incision of the Katandra sediments, a period of humid climate prevailed over the Riverine Plain (his "Katandra Stable Period"). This period, which was characterized by soil formation and little or no erosion on the plain, may have been similar to the present period, when major flooding across the plain surface is infrequent, and the Murrumbidgee River maintains a course across the plain.

If a change from climatic conditions similar to those of the present toward a drier climate began, annual runoff would decrease, but the sediment yield from the Eastern Highlands would increase (figs. 28, 29). This change would occur either if the temperature decreased, during a drier glacial phase (Galloway, 1965), or if the temperature increased, as the climate changed to that which is assumed to have prevailed during the Hypsithermal, or interglacial, phase.

A change to a drier climate than that of the present would have caused deterioration of the protective vegetation in the Eastern Highlands, as discussed previously, and the resulting hillslope erosion and gullying (fig. 1*F*) would have provided increased amounts of sediment to the tributary streams, as van Dijk's (1959) investigations near Canberra showed. However, a channel similar to that of the modern river could have accommodated neither the high flood peaks nor a greatly increased sand load. The narrow sinuous channel would have aggraded and a low-sinuosity channel would have developed. Laboratory experiments have confirmed the tendency of a meandering river to straighten its course during floods (Toebes and Sooky, 1965), and the tendency would be reinforced by aggradation.

Prior to the development of the several river-control structures along the modern river, extensive flooding of the Riverine Plain occurred. In 1891, widespread flooding occurred west of Hay and for several miles north and south of the river between Wagga Wagga and Hay. The floodwaters moved down Yanko, Bubblebundi, Coleambally, and Gum Creeks, as well as along other depressions in the plain both north and south of the river. (Information on the extent of the 1891 flood is shown on Water Conservation and Irrigation Comm. Plan 147/49.) Aggradation in a paleo-Murrumbidgee channel would have increased the frequency and extent of flooding from the aggrading channel.

During major flooding, the greatest velocities of flow would have occurred where the flow was concentrated and on locally steeper parts of the Riverine Plain. Erosion could have occurred at these locations just as discontinuous gullies form on steeper parts of the alluvial valley floors (Schumm and Hadley, 1957). Incision could also have begun where unconfined floodwaters plunged into another valley or channel—for example, into the paleo-Murray River.

The deep scours into the cohesive Katandra sediments must have initially resembled the arroyos of Southwestern United States. There, arroyos have been eroded as deep trenches, many of which are more than 30 feet deep, in the fine-grained alluvium of semiarid valleys. The arroyos seem to have been initiated and subsequently extended and enlarged during major floods (Schumm and Hadley, 1957). A similar origin could account for the deep scours on the Riverine Plain.

No matter how the original incision began, once formed, such a channel would have become enlarged and would have concentrated floodwaters. It would have eroded upslope until it intersected the paleo-Murrumbidgee channel, the source of the floodwaters. Until the new channel intersected the main channel, it would have been transporting only the sediment eroded from bed and banks and the sediment held in suspension by the diverted floodwaters. However, when the paleo-Murrumbidgee channel was tapped, both water and sediment from this channel would have been diverted into the new channel, which, because of its initially low sediment load, would have been incised to a greater depth than the aggrading main channel. Therefore, the greater part of the water and sediment carried by the paleo-Murrumbidgee River would have been diverted into the new channel. The new relatively deep narrow channel would have aggraded rapidly, as large quantities of bedload were introduced into it. The reader will recall that, at those locations where lateral shifting of the channels occurred, the depth of planation was considerably shallower than the deep scours into the Katandra sediments. Aggradation in, and widening of, the prior-stream channel would have occurred until a stable channel capable of transporting the runoff and sand load delivered to it was formed. This prior-stream channel probably resembled those channels of intermediate size (largest stable channel) sketched on the cross sections in figures 19, 21, and 22.

Two radiocarbon dates have been obtained from samples taken from sediments assumed to have been associated with these deep channels. Neither is definitive, being in excess of 25,000 years (Langford-Smith, 1963) for a presumably Quiamong channel, and in excess of 36,000 years (Pels, 1964a) for a presumably Mayrung channel. However, the dates do indicate a Pleistocene age for the channel sediments at depth, and suggest that the deep sediments in all prior-stream channels may be Quiamong and of Pleistocene age. The large prior-stream channels were probably associated with floods during a relatively dry climate (table 7) of glacial (Galloway, 1965) or interglacial age.

Incision of the Riverine Plain could also have occurred during less frequent floods associated with a warmer and drier Hypsithermal climate. These flows could have incised through the eolian deposits and into depressions previously occupied by the Quiamong prior streams and could have formed the Mayrung channels, which are smaller than those that previously existed at depth. Evidence for this is the apparent decrease in age of alluvium from bottom to top in the prior-stream deposits for example, two ages determined from samples collected near the surface in such channels are on the order of 5,000 years (Langford-Smith, 1963).

During a period of general aridity and higher average temperatures, the lessened flow of water from the headwaters area onto the more arid plain would have been further diminished by large water losses, and dissolution of the channels could have occurred (Butler, 1958; Pels 1966). Under such conditions perhaps no permanent channel capable of transporting water across the plain existed, and the smaller surficial channels, now visible on the plain surface, were subject to frequent abandonment and distributary formation (Pels, 1964a).

With an increase of rainfall in the headwaters, the vegitational cover would have improved, and the sediment yields would have decreased. Under conditions of greater rainfall than at present, the through-flowing ancestral rivers would have formed large channels of high discharge but low sand transport. These channels may have been associated with the climate of the "Little Ice Age" of about 3,000 years ago (Gentilli, 1961). If this was a time of cooler weather, the large increase in discharge associated with ancestral-river development could have occurred with only a moderate increase in precipitation (fig. 28). A climatic change to the present warmer temperatures and somewhat less precipitation would have allowed the smaller channel of the modern Murrumbidgee River to develop in the fine-grained alluvial deposit of the flood plain of the ancestral river.

The adjustment from the bedload channel of the prior stream to the narrow, deep suspended-load channels of the ancestral and modern rivers probably occurred in the same manner as the channel narrowing of the Cimarron River (Schumm and Lichty, 1963). With increased precipitation, vegetation would have colonized the wide sandy prior-stream channels. Vegetation induced deposition along the margins of the channel, and a new flood plain formed by vertical accretion. Eventually, reworking of this alluvial deposit resulted in the sinuous channel characteristic of the ancestral and the modern rivers.

Much of the field evidence for such a sequence of events has been obscured by dry-period eolian activity and humid-period flooding, but there is no question that large prior streams existed more than 25,000 years ago. Ages determined for smaller surface channels and distributaries are 4,000 to 5,000 years. The ancestral-river channels seem very recent and appear most likely to be related to a recent phase of greater discharge, rather than to Pleistocene activity.

The evidence indicates that on the Riverine Plain a straight, high width-depth ratio, bedload, prior-stream channel should be related to a drier climate than that of the present. Additional evidence is required before a given prior-stream channel can be designated as being of interglacial, glacial, or Hypsithermal age.

The story is complex, but, as more information is accumulated, the sediments of the Riverine Plain will yield a fascinating history of climate change and alluvial deposition. Nonetheless, the objective of this study was to explain the mechanism of Riverine Plain channel changes, rather than to attempt to place a given channel into a sequence of events describing the Riverine Plain history.

## CHANNEL TRANSFORMATION

The reader should be reminded here that the river channels described in this report are alluvial channels that contain only a very small amount of sediment coarser than sand. Also, the conditions that made possible the preservation of the paleochannels differ from those which have prevailed in many valleys. Finally, the geologic and, especially, the climatic conditions that now exist in the Murrumbidgee River drainage basin are such that a change to a drier climate will significantly alter the type of sediment yielded to the river. In a more humid climate, a marked change in precipitation might not alter the sediment yield appreciably (fig. 29).

The United States and the Australian river data provide a means of illustrating the changes of channel morphology that can occur as an alluvial channel is subjected to a change in hydrologic regimen. It is evident that a change from a bedload to a suspended-load channel will cause an increase in sinuosity (fig. 25). Conversely, the width-depth ratio will decrease, and in figure 26 a point representative of a prior-stream channel will shift down the regression line, to the right, to a position characteristic of a suspended-load channel like that of the modern Murrumbidgee River.

When discharge alone changes, meander wavelength will change as a function of about the 0.5 power of discharge, as demonstrated by the change in position that occurred when the ancestral river assumed the characteristics of the modern channel (fig. 31). However, if the type of sediment transported through the channels changes, a major change in meander wavelength can occur with only a minor change in discharge. Meander wavelength, therefore, is significantly controlled by the sediment load in a stream.

Channel width has been shown to be significantly influenced by discharge and type of sediment load ($M$). The multiple-regression equation for channel width that is based on mean annual discharge and $M$ reveals that width can decrease with an increase in discharge, if the proportion of bedload moved by the channel is significantly reduced. An example is the decrease in width and accompanying increase in discharge associated with the change from the prior streams to the ancestral rivers. Conversely, with an increase in discharge and a decrease in bedload, channel depth will increase; however, an influx of sand into a channel with increased discharge causes depth to decrease.

Figure 34 shows the changes in channel gradient and sinuosity that have occurred during the transition from a prior stream to the modern channel; the effect of these changes on the longitudinal profile of the rivers is shown in figure 7. Channel slope was halved when the discharge increased and the bedload decreased. Channel gradient is strongly influenced by the slope of the surface over which the river flows. The valley slope is related to the geologic history and paleohydrology of the drainage system (Schumm and Lichty, 1965).

The decrease in gradient was accomplished not by incision of the alluvial deposits, but by channel lengthening and sinuosity increase. Meandering therefore occurs because it is the simplest mechanism for reducing the gradient of a stream in response to changes in runoff and sediment yield. The shape of meanders reflects the laws of hydraulics (Langbein and Leopold 1966), but an explanation of meandering must include the reason why some rivers do not meander. It has been noted that those alluvial rivers characterized by very steep slopes or by very gentle slopes do not meander (Leopold and Wolman, 1960, p. 785; Brice, 1964; Schumm, 1963b, p. 1098). Meandering cannot occur under either of these conditions, for the decrease in gradient caused meander development would prevent the sediment load from moving through the channels.

Nonmeandering rivers of low gradient that transport small quantities of bedload seem to be anomalous; however, the river, because of its low gradient, does not have sufficient flow velocity to permit the bank erosion necessary for meandering. Generally, low gradient is the result of an event in the history of the river for which it was unable to compensate. For example, the Illinois River assumed its present, low-sinuosity course over a very gentle surface when its original course was blocked during the Pleistocene (Rubey, 1952).

The channels of the Riverine Plain have adjusted their dimensions, shapes, patterns, and gradients in response to changes in discharge and sediment load. Therefore, a river cannot maintain dynamic equilibrium by adjusting only its gradient (Lane, 1955). Rubey (1952, p. 132) suggested that both slope and channel shape must adjust to altered sediment load and discharge. The hydraulic geometry of Leopold and Maddock (1953) indicated that channel width and depth will increase with increased discharge. However, the changes in channel morphology that have occurred on the Riverine Plain have involved changes in all these variables, and some changes were opposite from the previously described relationships. A river will maintain dynamic equilibrium by adjusting to changes in type and amount of sediment load, $Qs$ (ratio of bedload to suspended load $\left(\frac{1}{M}\right)$ and total quantity of load), and discharge, $Qw$ (mean annual discharge and bankfull discharge), through alteration of channel width ($w$), depth ($d$), shape $\left(\frac{w}{d}\right)$, sinuosity ($P$), meander wavelength ($l$), and gradient ($S$) as follows:

$$Qw \propto \frac{wdl}{S}, \text{ and}$$

$$Qs \propto \frac{wls}{dP}.$$

It is unfortunate for the student of rivers that neither water ($Qw$) nor sediment ($Qs$) discharge will change alone. Sometimes the change can be in opposite directions—that is, a decrease in runoff with an increase in sediment load. The fact that channel depths will change directly with $Qw$ but inversely with $Qs$ and that gradient will decrease with an increase in $Qw$ but will increase with an increase in $Qs$ further complicates any attempt to predict the manner in which a river will adjust until information on both runoff and sediment load becomes available. When this information can be obtained, the multiple-regression equations relating channel morphology to both discharge and type of sediment load ($M$) can be used to indicate the direction and the magnitude of changes to be expected.[4]

[4] S. A. Schumm, in press, River metamorphosis: Am. Soc. Civil Engineers Proc., Jour. Hydraulics Div.

River-channel transformations occur because of the necessity for a channel to cope with a change in the amount and characteristics of the water and the sediment discharge. Larger quantities of water require a larger channel, and channel width and depth will increase as a function of discharge. If no appreciable change in either the volume or the type of sediment load accompanies an increase in discharge, the width and depth will accordingly increase to accommodate the larger flow, and meander wavelength will increase with a possible minor increase in sinuosity, all of which will cause a decrease in gradient. When (with or without a change of discharge) the ratio of bedload to total load changes appreciably, channel transformation occurs and involves both the dimensions and the dimensionless characteristics of the channel.

First consider the change from a suspended-load channel, like the Murrumbidgee, to a bedload channel, like a prior stream. Experimental evidence shows that a sinuous channel will not transport large quantities of bedload or sand (Brush, 1959). Also, large floods will tend to destroy a sinuous channel (Schumm and Lichty, 1963; Toebes and Sooky, 1965). Therefore, when bedload is introduced into a suspended-load channel, aggradation will occur, which, in turn, will increase the frequency of overbank flooding and of peak discharge. The combination of these factors leads to the destruction of the meandering channel, for a steeper gradient is required to move the increased bedload and a straight channel results. In addition, for a given velocity of flow and water depth, a certain quantity of bedload will be moved per unit width of channel (Colby, 1964 fig. 26). Therefore, a wide channel is required for efficient bedload movement. A necessary response to increased bedload is apparently an increase in gradient and channel width, which for a given discharge increases the width-depth ratio and meander wavelength. Sinuosity, of course, decreases.

The transformation of a bedload channel to a suspended-load channel requires a decrease in the ratio of bedload to total load. The reduced bedload transport permits stabilization of parts of the channel floor by the encroachment of vegetation into the channel at low water and by the deposition of fine sediment on the banks and on the floor of the channel adjacent to the thalweg. Unless a major flood interrupts the process, a new flood plain will be constructed by vertical accretion in the channel (Schumm and Lichty, 1963). A hydrologically efficient narrow, deep channel will result. A much lower gradient is required to move the smaller quantities of bedload, and the river is free to form a meandering pattern that increases sinuosity and reduces the gradient of the channel.

The manner in which the Murrumbidgee River has adjusted to changes of hydrologic regimen reveals a mechanism, in addition to that of incision or aggradation, whereby an alluvial river can adjust its gradient. If river gradient can be altered primarily by an increase or decrease in river length or sinuosity rather than by incision or channel aggradation, then most alluvial river channels have a considerable margin of safety built into their morphology. For example, minor fluctuations in base level or slight warping along the lower course of a river may not require incision or aggradation for considerable distances upstream to compensate. A river having a gradient of 0.5 foot per mile, a valley gradient of 0.75 foot per mile, and a sinuosity of 1.5 can adjust to a 10-foot fall in the base level over a valley distance of 80 miles by an increase in sinuosity to about 1.8. That is, the river gradient would remain 0.5 foot per mile, although the lowering of the base level by 10 feet has increased the slope of the valley to 0.87 foot per mile over this distance. Incision of the channel near sea level would occur, but the increased velocity of flow engendered by the lowering of base level would enlarge meander loops and increase sinuosity, thereby decreasing the stream gradient to its former value. Such an adjustment of channel pattern would limit the distance upstream to which the effects of minor changes in base level would occur.

Descriptions of the Riverine Plain should make it clear that the slope of river terraces do not necessarily indicate the gradient of the stream which flowed on the terrace surface. In fact, parallel river terraces are not an indication that the streams which deposited the terrace sediment had a similar gradient. For example, Hadley (1960, p. 14–15) described three parallel terraces in a single valley which are composed of different types of sediment. On the basis of evidence presented here as to the differences between prior streams and modern rivers, terraces composed of different types of sediment are believed to have been deposited by morphologically very different rivers.

One aspect of channel adjustment that may interest the stratigrapher and the sedimentologist is the effect of a change in river sinuosity on the type and volume of sediment delivered to a given position in a depositional environment. A change in hydrologic regimen comparable to past changes in the headwaters of the Murrumbidgee River will, of course, have a major influence on the sediments deposited in a piedmont area. However, this effect is compounded by the decrease of sinuosity and shortening of channel length, which will, in effect, shift the sediment source area toward the site of sediment deposition. In figure 7, Hay was effectively nearer the sediment-source area when prior streams were functioning. Abrupt changes in the type of fluvial sediment delivered to a depositional site can be attributed in many places to a change in channel sinuosity and the resulting major shortening and steepening of the river course. These changes can be induced either by diastrophism or by a major climate change. However, a major flood resulting from an infrequent but heavy storm could also destroy a meandering channel (Schumm and Lichty, 1963; Toebes and Sooky, 1965), so that the distance between the sediment-source area and the site of deposition would be shortened appreciably. For example, where the sinuosity of a river changes from about 2 to about 1, the distance between the source area and the site of deposition decreased by half. Some of the recurrence of sand deposits in terrestrial or deltaic sediments (that is, some types of cyclic bedding) may be attributed to this process.

The natural changes that have occurred on the Riverine Plain should be a graphic warning as to the long-term consequences of man's attempts to control climate and river basins. Local adjustments of rivers to the effects of engineering structures are well known (Lane, 1955) and can be anticipated. But the hydrologic changes which produced the transformation from prior-stream channel to Murrumbidgee River can be duplicated by the reduction of bedload and peak discharges in our modern rivers. The long-term adjustment of long reaches of a major river system to these changes may not cause serious problems initially. However, in future years of high runoff, enlargement of the channel—now narrowed as a result of reduced discharge—could be disastrous if the newly formed flood plain has been developed. Again, such adjustments would probably be most pronounced along the channels of bedload rivers in arid, semiarid, and subhumid regions.

Finally, the study has demonstrated that the morphology of a stable alluvial river channel reflects the hydrologic, climatic, and geologic characteristics of the drainage basin. It would be difficult to find a better example to illustrate this than that provided by the Murrumbidgee River and its associated paleochannels on the Riverine Plain of New South Wales.

## REFERENCES CITED

Ackers, Peter, 1964, Experiments on small streams in alluvium: Am. Soc. Civil Engineers Proc., Jour. Hydraulics Div. HY4, p. 1–37.

Alexandre, J., 1962, Les facteurs du développement des méandres à la lumière des observations faites le long de rivierès intertropical (Lufira et haut Lualoba): Internat. Assoc. Sci. Hydrology Pub. 59.

Blench, Thomas, 1957, Regime behavior of canals and rivers: London, Butterworth's Scientific Publications, 138 p.

Bowler, J. M., and Harford, L. B., 1966, Quaternary tectonics and the evolution of the Riverine Plain near Echuca, Victoria: Geol. Soc. Australia Jour., v. 13, p. 339–354.

Brice, J. C., 1964, Channel patterns and terraces of the Loup Rivers in Nebraska: U.S. Geol. Survey, Prof. Paper 422–D, p. D1–D41.

Brush, L. M., Jr., 1959, Exploratory study of bedload transportation in a meandering channel: Internat. Assoc. Hydraulic Res. Proc., 8th Cong. (Montreal), v. 4, p. 9.1–9.3.

Butler, B. E., 1950, A theory of prior streams as a casual factor of soil occurrence in the Riverine Plain of southeastern Australia: Australian Jour. Agr. Research: v. 1, p. 231–252.

———1956, Parna—an aeolian clay: Australian Jour. Sci., v. 18, p. 145–151.

———1958, Depositional systems of the Riverine Plain in relation to soils: Commonwealth Scientific and Industrial Research Organization, Soil Pub. 10, 35 p.

———1960, Riverine deposition during arid phases: Australian Jour. Sci., v. 22, p. 451–452.

Butler, B. E., 1961, Ground surfaces and the history of the Riverine Plain: Australian Jour. Sci., v. 24, p. 39–40.

Butler, B. E., and Hutton, J. T., 1956, Parna in the Riverine Plain of southeastern Australia and the soils thereon: Australian Jour. Agr. Research: v. 7, p. 536–553.

Campbell, D. A., 1945, Soil conservation studies applied to farming in Hawke's Bay, Part 2, Investigations into soil erosion and flooding: New Zealand Jour. Sci. Tech. (sec. A), v. 27, p. 147–172.

Carlston, C. W., 1965, The relation of free meander geometry to stream discharge and its geomorphic implications: Am. Jour. Sci., v. 263, p. 864–885.

Chow, Ven-Te, 1959, Open channel hydraulics: New York, McGraw-Hill Book Co., 680 p.

Colby, B. R., 1964, Discharge of sands and mean-velocity relationships in sand-bed streams: U.S. Geol. Survey Prof. Paper 462–A, p. A1–A47.

Colby, B. R., and Hembree, C. H., 1955, Computations of total sediment discharge, Niobrara River near Cody, Nebraska: U.S. Geol. Survey Water-Supply Paper 1357, 187 p.

Commonwealth Bureau of Meteorology, 1945, Maps of average monthly and annual temperature Australia: Commonwealth of Australia, 4 p.

———1948, Results of rainfall observations made in New South Wales: Commonwealth of Australia sec. 11, 232 p., 38 maps.

Cotton, C. A., 1963, Did the Murrumbidgee aggradations take place in glacial ages?: Australian Jour. Sci., v. 26, p. 54–55.

Craft, F. A., 1935, The relationship between erosion and hydrographic changes in the upper Murray catchment NSW: Linnean Soc. New South Wales, Proc., v. 60, p. 121–144.

Cumpston, J. H. L., 1951, Charles Sturt, his life and journeys of exploration: Melbourne, Hawthorne Press, 195 p.

David, T. W. E., and Browne, W. R., 1950, The geology of the Commonwealth of Australia: 3 vols., London, Edward Arnold Co.

Dijk, D. C. van, 1959, Soil features in relation to erosional history in the vicinity of Canberra: Commonwealth Scientific and Industrial Research Organization, Soil Pub. 13, 41 p.

Dijk, D. C. van, and Talsma, Tjeerd., 1964, Soils of portion of the Coleambally Irrigation Area, New South Wales: Commonwealth Scientific and Industrial Research Organization, Soils and Land Use Series 47, 46 p.

Dury, G. H., 1963, Prior stream deposition: Australian Jour. Sci., v. 25, p. 315–317.

———1964, Principles of underfit streams: U.S. Geol. Survey Prof. Paper 452–A, p. A1–A67.

Dury, G. H., 1965, Theoretical implications of underfit streams: U.S. Geol. Survey Prof. Paper 452–C, p. C1–C43.

Fournier, M. F., 1960, Climat et érosion: Paris, Presses France Univ., 201 p.

Freidkin, J. F., 1945, laboratory study of the meandering of alluvial rivers: Vicksburg, Miss., U.S. Waterways Experimental Sta., 40 p.

Galloway, R. W., 1963, Glaciation in the Snowy Mountains: A reappraisal: Linnean Soc. New South Wales Proc., v. 88, p. 180–198.

———1965, Late Quaternary climates in Australia: Jour. Geol., v. 73, p. 603–618.

Garner, H. F., 1959, Stratigraphic-sedimentary significance of contemporary climate and relief in four regions of the Andes Mountains: Geol. Soc. America Bull., v. 70, p. 1327–1368.

Gentilli, J., 1961, Quaternary climates of the Australian region: New York Acad. Sci. Annals, v. 95, p. 465–501.

Gilbert, G. K., 1917, Hydraulic-mining debris in the Sierra Nevada: U.S. Geol. Survey Prof. Paper 105, 154 p.

Gill, E. D., 1955, The Australian arid period: Australian Jour. Sci., v. 17, p. 204–206.

Gottschalk, L. C., 1964, Reservoir sedimentation, *in* Handbook of applied hydrology: (Ven-Te Chow, ed.) New York, McGraw-Hill Book Co.

Grant, A. P., 1950, Soil conservation in New Zealand: New Zealand Inst. Eng. Proc., v. 36, p. 269–301.

Hack, J. T., 1965, Postglacial drainage evolution and stream geometry in the Ontonagon area, Michigan: U.S. Geol. Survey Prof. Paper 504–B, p. B1–B40.

Hadley, R. F., 1960, Recent sedimentation and erosional history of Fivemile Creek, Fremont County, Wyoming: U.S. Geol. Survey Prof. Paper 352–A, p. 1–16.

Harris, W. J., 1939, The physiography of the Echuca district: Royal Soc. Victoria Proc., v. 51, p. 45–60.

Hawkins, C. A., and Walker, P. H., 1956, Study of layered sedimentary materials in the Riverine Plain: Royal Soc. New South Wales Jour. and Proc., v. 90, p. 110–127.

Hjulstrom, Filip, 1935, Studies of the morphological activity of rivers as illustrated by the river Fyris: Uppsala Univ. Geol. Inst. Bull., v. 25, p. 221–527.

———1949, Climatic changes and river patterns, *in* Glaciers and climate: Geografiska Annaler: v. 31, nos. 1, 2, p. 83–89.

Lacey, Gerald, 1930, Stable channels in alluvium: Inst. Civil Eng. Proc., v. 229, p. 259–285.

Lane, E. W., 1955, The importance of fluvial morphology in hydraulic engineering: Am. Soc. Civil Eng. Proc., v. 81, no. 745, 17 p.

———1957, A study of the shape of channels formed by natural streams flowing in erodible material: U.S. Army Corps of Engineers, Missouri River Div., Omaha, Nebr., Sediment Ser. 9, 106 p.

Langbein, W. B., and Leopold, L. B., 1966, River meanders—Theory of minimum variance: U.S. Geol. Survey Prof. Paper 422–H, H1–H15.

Langbein, W. B., and others, 1949, Annual runoff in the United States: U.S. Geol. Survey Circ. 52, 14 p.

Langbein, W. B., and Schumm, S. A., 1958, Yield of sediment in relation to mean annual precipitation: Am. Geophys. Union Trans., v. 39, p. 1076–1084.

Langford-Smith, Trevor, 1958, Landforms, land settlement, and irrigation on the Murrumbidgee, New South Wales: Unpub. Dissert., Australian National Univ.

Langford-Smith, Trevor, 1959, Deposition on the Riverine Plain of southeastern Australia: Australian Jour. Sci., v. 22, p. 73–74.

———1960a, Reply to Mr. Butler: Australian Jour. Sci., v. 22, p. 452–453.

———1960b, The dead river systems of the Murrumbidgee: Geog. Rev., v. 50, p. 368–389.

———1962, Riverine Plains geochronology: Australian Jour. Sci., v. 25, p. 96–97.

———1963, Murrumbidgee Plain series, New South Wales: Radiocarbon v. 5, p. 328–329.

Leliavsky, Serge, 1955, An introduction to fluvial hydraulics: London, Constable & Co., 257 p.

Leopold, L. B., and Maddock, Thomas Jr., 1953, The hydraulic geometry of stream channels and some physiographic implications: U.S. Geol. Survey Prof. Paper 252, 57 p.

Leopold, L. B., and Wolman, M. G., 1957, River channel patterns—braided, meandering, and straight: U.S. Geol. Survey Prof. Paper 282–B, p. 39–84.

———1960, River meanders: Geol. Soc. America Bull., v. 71, p. 769–794.

Linsley, R. K., Jr., Kohler, M. A., and Paulhus, J. L. H., 1949, Applied hydrology: New York, McGraw-Hill Book Co., 689 p.

Mackin, J. H., 1948, Concept of the graded river: Geol. Soc. America Bull., v. 59, p. 463–512.

McLaughlin, T. G., 1947, Accelerated channel erosion in the Cimarron Valley in southwestern Kansas: Jour. Geology. v. 55, p. 76–93.

Mead, J. R., 1896, A dying river: Kansas Acad. Sci., Trans. (1893–94), v. 14, p. 111–112.

Morland, R. T., 1958, Erosion survey of the Hume catchment area [New South Wales]: Soil Conservation Jour., July 1958, p. 1–35.

Mundorff, J. C., 1962, Sediment discharge during floods in eastern Nebraska: U.S. Geol. Survey Circ. 470, 8 p.

Mundorff, J. C., and Scott, C. H., 1964, Fluvial sediment in the lower Kansas River basin: A progress report 1957–60: Kansas Water Resources Board Bull. 7, 67 p.

Newman, J. C., 1955, Tumut catchment area survey of vegetation and erosion: New South Wales Soil Conservation Jour., January, p. 1–14; April, p. 1–16; July, p. 1–16.

Northop, W. L., 1965, Republican River channel deterioration: U.S. Dept. Agr. Misc. Pub. 970, p. 409–424.

Pardé, Maurice, 1964, Fleuves et rivierés: Paris, Librairie Armand Colin, 223 p.

Pels, Simon, 1960, The geology of the Murrumbidgee Irrigation Areas and surrounding districts: Water Conservation and Irrigation Commission, New South Wales, Groundwater and Drainage Series, Bull. 5, 43 p.

———1964a, Quaternary sedimentation by prior streams on the Riverine Plain, southwest of Griffith, New South Wales: Royal Soc. New South Wales, Jour. and Proc., v. 97, p. 107–115.

———1964b, The present and ancestral Murray River system: Australian Geog. Studies, v. 2, p. 111–119.

———1966, Late Quaternary chronology of the Riverine Plain of southeastern Australia: Geol. Soc. Australia Jour., v. 13, p. 27–40.

Rose, G., and Mathews, R. R., and others, 1962, Geologic map of New South Wales: Geological Survey of New South Wales, Dept. Mines, Sydney.

Rubey, W. W., 1952, Geology and mineral resources of the Hardin and Brussels quadrangles (in Illinois): U.S. Geol. Survey Prof. Paper 218, 179 p.

Schumm, S. A., 1960a, The effect of sediment type on the shape and stratification of some modern fluvial deposits: Am. Jour. Sci., v. 258, p. 177–184.

———1960b, The shape of alluvial channels in relation to sediment type: U.S. Geol. Survey Prof. Paper 352–B, p. 17–30.

———1961, Effect of sediment characteristics on erosion and deposition in ephemeral-stream channels: U.S. Geol. Survey Prof. Paper 352–C, p. 31–70.

———1963a, A tentative classification of alluvial river channels: U.S. Geol. Survey Circ. 477, 10 p.

———1963b, Sinuosity of alluvial rivers on the Great Plains: Geol. Soc. America Bull., v. 74, p. 1089–1100.

———1965, Quaternary paleohydrology: *in* Quaternary of the United States (Wright, H. E., Jr., and Frey, D. G., eds.) p. 783–794, Princeton Univ. Press.

Schumm, S. A., and Hadley, R. F., 1957, Arroyos and the semiarid cycle of erosion: Am. Jour. Sci., v. 255, p. 161–174.

Schumm, S. A., and Lichty, R. W., 1963, Channel widening and flood-plain construction along Cimarron River in southwestern Kansas: U.S. Geol. Survey Prof. Paper 352–D, p. 71–88.

———1965, Time, space, and causality in geomorphology: Am. Jour. Sci., v. 263, p. 110–119.

Sprigg, R. C., 1965, Consequences of Quaternary climatic fluctuations in Australia: Geol. Soc. America Spec. Paper 82, p. 193–194.

Stannard, M. E., 1962, Prior-stream deposition: Australian Jour. Sci., v. 24, p. 324–325.

Sturt, Charles, 1833, Two expeditions into the interior of Southern Australia during the years 1828, 1829, 1830, and 1831; with observations on the soil, climate and general resources of the colony of New South Wales: London, Smith, Elder, & Co., v. 2, 271 p.

Tindale, N. B., 1959, Ecology of primitive aboriginal man in Australia, *in* Biogeography and ecology in Australia: p. 36–51, The Hague, Vitgeverig, Dr. W. Junk, 640 p.

Toebes, G. H., and Sooky, A. A., 1965, The hydraulics of meandering rivers with flood plains: School of Civil Eng., Purdue Univ., Hydromechanics Lab. Tech. Rept. 10, 79 p.

U.S. Geological Survey, 1955a, Compilation of records of surface waters of the United States through September 1950, Part 7, Lower Mississippi River Basin: U.S. Geol. Survey Water-Supply Paper 1311, 606 p.

———1955b, Compilation of records of surface waters of the United States through September 1950, Part 6B, Missouri River Basin below Sioux City, Iowa: U.S. Geol. Survey Water-Supply Paper 1310, 619 p.

———1964a, Compilation of records of surface waters of the United States, October 1950 to September 1960, Part 7, Lower Mississippi River Basin: U.S. Geol. Survey Water-Supply Paper 1731, 552 p.

———1964b, Compilation of records of surface waters of the United States, October 1950 to September 1960, Part 6B, Missouri River Basin below Sioux City, Iowa: U.S. Geol. Survey Water-Supply Paper 1730, 514 p.

Ward, W. T., 1965, Eustatic and climatic history of the Adelaide area, South Australia: Jour. Geol., v. 73, p. 592–602.

Water Conservation and Irrigation Commission, New South Wales, 1956, Surface water supply of New South Wales, Stream flow records, period to 31st December 1950: v. 2, Murray River basin, 578 p.

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