1973

Changing Meander Morphology and Hydraulics, Red River, Arkansas and Louisiana.

Oscar Douglas Abington
Louisiana State University and Agricultural & Mechanical College

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Geography

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Changing Meander Morphology and Hydraulics,  
Red River, Arkansas and Louisiana

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy in The Department of Geography and Anthropology

by

Oscar Douglas Abington
M.S., Louisiana State University, 1964
May, 1973
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<tr>
<td>B</td>
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<td>c</td>
<td>Coefficient</td>
</tr>
<tr>
<td>C</td>
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</tr>
<tr>
<td>dQ</td>
<td>Rate of change of discharge per day</td>
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<td>D</td>
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<td>F</td>
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<td>G</td>
<td>Coefficient (except with subscripts a or s)</td>
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\( \bar{M} \) Mean water surface (hydraulic) slope

\( M_V \) Valley slope

\( \bar{M}_V \) Mean valley slope

\( Q \) Dominant discharge; discharge

\( Q_m \) Mean annual discharge (Schumm, 1967 and 1969)

\( Q_t \) Estimator of percentage of total load that is bed load (Schumm, 1967 and 1969)

\( \bar{Q} \) Mean annual discharge

\( R^2 \) Coefficient of determination

\( S \) Sinuosity; stage

\( S_a \) Suspended sand concentration

\( S_i \) Suspended silt concentration

\( S_{a+i} \) Suspended total concentration

\( T \) Time (year minus 1948); water temperature

\( V \) Maximum velocity

\( \bar{V} \) Mean velocity

\( W \) Specific weight; width
ABSTRACT

Historic documents indicate that the nineteenth century Red River occupied a relatively deep and narrow, sinuous channel except in the region of the Great Raft. Destruction of this log jam, confinement of that section of the river to a single channel, and removal of rapids at Alexandria, Louisiana, permitted hydraulic metamorphosis to occur over a few decades.

Morphometric analysis of the Red River meander patterns surveyed in 1838, 1938, and 1957 show progressive increases in meander wave length and decreases in sinuosity. Theoretical considerations and previous studies suggest that this transformation may have resulted from changes in one or more of these variables: (1) valley slope, (2) bed load ratio, (3) total sediment load, (4) discharge, (5) erosional resistance, or (6) climate.

The most probable hypothesis appears to be that an increase in valley slope consequent to earlier channel diversion is the primary variable responsible. Time series analysis of gauge and discharge data indicates a decline of water surface elevation of Red River at Alexandria amounting to 13 feet per century. Comparison of the morphologic results of water surface slope increase on Red River with
the results of laboratory experiments (Friedkin, 1945) suggests a first approximation of the function relating sinuosity to valley slope.

Regression studies of contemporary channel geometry and sediment transport at Alexandria appear to show that these phenomena are controlled primarily by discharge, velocity, and depth of flow. It is probable that channel straightening has been accompanied by widening and shoaling, and this channel metamorphosis is interpreted as being a transition from a meandering to a braided stream pattern.
INTRODUCTION

The channel of Red River in southwestern Arkansas and northwestern Louisiana presents a remarkable opportunity for a study of river metamorphosis. Changes in fluvial dynamics have produced radical changes in meander morphology and channel dimensions. Historical documents, channel surveys, field observations, and gauge and discharge measures extending over several decades all furnish evidence confirming transformations in hydraulic variables and the resulting morphology.

The central theme of this study is Red River metamorphosis through time. The problem is to translate the available data into a precise quantitative statement defining morphological changes in terms of causal variables.

Study Area and Literature

Stream patterns of the Red River are the principal objectives of this investigation, and this discussion begins by introducing the area of study in terms of these phenomena.

The study area of this report is the channel of Red River between the Big Bend at Fulton, Arkansas, and the point of debouchment on the alluvial plain of the Lower Mississippi River at Moncla, Louisiana (figure 1).
This segment is a considerable distance below the river reach described by Lane (1957, p. 103) as being between highly braided and meandering. It is immediately upstream from that portion of Red River in which channel patterns are largely controlled by older Mississippi River courses (Fisk, 1940, pp. 45-46). The channel within the study area is commonly regarded as meandering.

One of the most striking aspects of Red River stream patterns is the morphology of tributary rivers. Almost all tributaries within the study area form sizable lakes or swamps flanking the alluvial plain. Overflow water from the lakes reaches the master stream by way of a maze of anastomosing backwater bayous. Davis (1887, p. 142) expressed the typical pattern most vividly, observing that "the lakes are formed on either side of the Red River of Louisiana, arranged like leaves on a stem."

Although such tributary patterns flank nearly all flood plains, the Red River alluvial plain is unique because every significant tributary below the Big Bend is dammed by alluvium. In intensity and scale, only the lower Danube and the Han Basin (China) are comparable.

The origin of this remarkable phenomenon is commonly ascribed to differing rates of aggradation. Thus Fisk (1938, pp. 49-50), after Darby (1818, p. 87), attributed this pattern to rapid alluviation and channel shifting by the master stream. Red River, according to this hypothesis, has been rapidly increasing the elevation of
its flood plain, thus sealing off the tributary streams.

The discovery that the surface of the alluvial plain is characterized by two distinct levels added a new dimension to this concept of Red River morphology. Fisk (1938, pp. 47-48) initially pointed out that

the two flood-plain levels displayed along this part of the Red River valley appear to be something more than ordinary "extreme flood stage" versus "normal flood stage" flood-plains characteristic of Gulf Coastal Plain valleys. In this case the upper flood-plain is covered so rarely that it is called "Colfax Island."

Two years later, Fisk (1940, p. 48) correlated the lowering of the flood plain level with diversion of Red River into a new course trending northeastward from Echo to the alluvial plain of the Mississippi. The rejuvenation resulting from the increased gradient was believed to have entrenched the flood plain at least as far upstream as the vicinity of Grand Ecore (figure 1). Subsequently, Russell (1967, pp. 32-33) cited evidence of degradation along the river stem in Texas and suggested that most of the flood plain in the study area should be considered a terrace created by the diversion through Moncla Gap.

Thus the unique tributary patterns of Red River are not results of contemporary processes but must be considered a relict morphology which originated during a time of rapid aggradation. Continued entrenchment of the master stream, combined with the resulting downcutting of flood plain tributaries, must ultimately drain the lakes.
Although Fisk (1940) correlated Red River degradation with the gradient increase consequent to piracy, he did not comment on the possibility that these events might influence meander morphology. This omission is somewhat puzzling because he was aware that pattern changes had occurred elsewhere in response to channel steepening. For example, Fisk (1938, p. 21) reported such an event on the Ouachita River in the following words:

The Mississippi captured the Ouachita River on the outside of a large meander, shortening the Ouachita River an unknown distance, and increasing its gradient to a marked degree. A glance at the course of the Ouachita River on the Manifest and Harrisonburg Quadrangles shows that the river has been recently shortened for eight miles immediately above its mouth. Flanking this stretch are four nearly enclosed cut-off lakes (from south to north, Wallace, Mean, Tew, Cypress Brake), as many as are mapped for the next 30 miles upstream. An increase in the gradient of the stream seems sufficient reason for the localization of the cut-off lakes in this area. A slight increase in gradient would accelerate the lateral migration of streams and, therefore, would eventually straighten the channel.

The objective of this investigation is to document the changing morphology of Red River and to determine what variables are responsible for those changes. The foregoing concepts of fluvial patterns and dynamics provide an introductory framework as a basis for investigation.

**Problem and Approach**

The central problem is to determine whether significant changes in meander morphology have occurred and to isolate the responsible variable. Meander morphology will
be expressed in terms of morphometric elements, and hydraulic variables will be tested for long-term changes. Further light is shed on changing fluvial processes by contrasting historic documents with contemporary observations. These diverse elements are then synthesized into a comprehensive scheme of river behavior.

The following aspects of Red River are presented as separate chapters in the text:

1. **Early fluvial dynamics.** Eyewitness accounts by competent observers are combined to reconstruct the dynamics of the Red River of the early nineteenth century. Historical events responsible for hydraulic and morphological transformation are documented.

2. **Changing meander patterns.** Dimensional analysis is used to transform mapped channel patterns into numerical data, which are then subjected to statistical tests of significance.

3. **Changing hydraulic variables.** Four decades of daily gauge and discharge values are tested with time series regression hypotheses, and the result is combined with the data of the preceding chapter.

4. **Present fluvial dynamics.** Multiple regression analysis provides a method of presenting the behavior of the river. Comparison with
the results of preceding sections yields a final concept of the mechanics of Red River metamorphosis.

The last chapter summarizes the major conclusions and synthesizes them into a revised scheme of fluvial change on Red River. The results display considerable variation from the concepts currently prevalent in the literature.
CHAPTER I

ASPECTS OF HYDRAULIC HISTORY

Introduction

Fisk (1940, Fig. 6) and Murray (1948, pp. 15-17 and Fig. 2) have mapped the earlier Red River courses visible on the present alluvial plain over a considerable part of the study area. The results demonstrate that the river has had sufficient hydraulic continuity to produce meanders of approximately the same size throughout the last few centuries. Thus, through the aggradational epoch that produced the upper level of the flood plain, changes in course were succeeded by a duplication of the previous meander morphology along the new channel.

Contemporary Red River channel patterns display a radical departure from the forms characteristic of previous courses. Investigation of documents pertinent to the evolution of the modern Red River indicates that five events have been crucial. In chronological order, these events are as follows:

1. Stream piracy. Diversion of the river into a new channel leading northeastward from Echo to the alluvial plain of the Lower Mississippi River at Moncla
(figure 1). Date unknown.


3. **Confinement of flood water.** Engineering projects confined river flow to the main channel. 1873-1898.

4. **Destruction of the Rapides.** Removal of the rapids at Alexandria by engineers to improve navigation during periods of low water. 1892-1893.

5. **Closure of Denison Dam.** Dam closure above the study area, which affected discharge variability and sediment loads as far downstream as the Fulton-Shreveport reach. 1943.

The last of these will be treated in a later chapter.

The impact of each event on the morphology of the river will be evaluated in the following pages, but not in chronological order. The order of presentation is keyed to the significance of the event, with the most important phenomenon being discussed first.

The primary factor responsible for the morphological transformation of the stream is degradation taking place in the lower part of the study area. This phenomenon, which had its origin in the river diversion mentioned
above, is still in progress.

**Origin of Red River Degradation**

Prior to diversion through Moncla Gap, Red River flowed southeastward down a gently sloping alluvial fan, gradually descending to the level of the flood plain of the Lower Mississippi. The new course between Echo and Moncla (figure 1) made it possible for the river to descend from the level of its flood plain to that of the Lower Mississippi River through a gap only 8 miles in length. The previous channel required the river to cross a distance of some 40 miles. Hence the immediate result of diversion was the occupation of a channel segment characterized by a precipitously steep water surface slope for a river of the hydraulic dimensions of the Red River.

The date of diversion through Moncla Gap is unknown, although Fisk (1944, pp. 45-46) thought that it correlated with stage 15 of his chronology for the Lower Mississippi River. This would suggest that the change in course took place some 400-500 years ago. Because historic documents contain no mention of Red River diversion through the gap, it appears certain that this piracy preceded European settlement of the area.

The creation of the oversteepened river segment of the Echo-Moncla reach must have produced changes in meander morphology. This reach was the initial knickpoint, which is still in the process of upstream migration.

The term **knickpoint**, as it is used in this paper,
does not necessarily conform to the meaning of that term as it is used in the geological literature (see, for example, the definition of Brush and Wolman, 1960, p. 60). **Knickpoint** refers to a break in water surface slope on the river such that the steeper slope segment is on the downstream side of the break.

The results of continued upstream migration of the knickpoint were expressed with clarity in the following passage by R. J. Russell (1967, pp. 32-33):

Red River, until less than 1,500 years ago, was actively building its flood plain southeastward from Alexandria into the Mississippi Valley to the east of Opelousas. Then, after its cone became sufficiently alluviated to reach an elevation permitting the river to take advantage of a low gap in its eastern valley wall the Red established a new course, leading across a dissected Pleistocene terrace. The new course reduced to about one quarter the distance required for reaching an elevation on the Mississippi flood plain similar to that along the old course. This increased the river gradient and caused rejuvenation of the Red, so that it began to incise its alluvial cone, leaving a flood plain less than 1,500 years old as a terrace of very recent origin. The incision now extends upstream into Texas and has brought about significant changes. In the vicinity of Shreveport, for example, there was extensive and serious flooding when the Red overtopped its banks in 1908. Although floods in the 1940s brought a greater-than-1908 discharge, no flooding occurred because the incised channel had become deeply cut and its valley walls had widened considerably.

Measurements included in the present report will show that this concept of Red River entrenchment must be modified.

The ability of the Red River at Shreveport to accommodate greater discharges without flooding, which was taken as evidence of entrenchment in the quotation above, is due entirely to decreased sinuosity of the channel at that
station. Model studies at Vicksburg (U. S. Army Corps of Engineers, 1956) have demonstrated that streams with low sinuosity values have greater capacity to accommodate large discharges than do more tortuous rivers. For example, it was shown that increasing flume sinuosities from 1.2 to 1.4, or from 1.40 to 1.57, produced in each case a decrease in discharge of 8 to 10 per cent. Hence the accommodation of greater discharge at a lesser gauge is evidence of declining sinuosity rather than degradation. The lack of any temporal trend in water surface elevation at Shreveport, which will be demonstrated in Chapter III, clinches this argument.

In the process of the upstream translation of the knickpoint, the readily erodible Red River alluvium probably was not a significant obstacle. In places, however, the downcutting river impinged upon resistant rock layers which functioned as local base levels of erosion for the river upstream from the outcrop. One of these resistant rock units played an especially important role in the evolution of the present river.

**Origin and Destruction of the Rapides**

Following the initial diversion through Moncla Gap, the knickpoint was able to migrate upstream readily as far as Alexandria. There the entrenching river encountered a resistant layer of sandy silt which has been identified by Fisk (1940, p. 171) as a unit of the Fleming formation (Miocene). This event was the origin of the **Rapides** for
which the parish was named. Historical evidence suggests that this resistant outcrop effectively held the knickpoint at Alexandria. Thus, gradients upstream from the outcrop were not characterized by significant change.

Historical documents describe the Rapides as being bounded by two distinct zones referred to as the Upper and Lower Falls (for a more detailed description, see Guardia, 1927, pp. 38-39, and U. S. Army Corps of Engineers, 1875, p. 902). In reality the "falls" were the upstream and downstream limits of an exceedingly shoal reach 2 miles long. Measurements of the water surface slope of the Rapides in the 1870's recorded values ranging up to 18.2 feet per mile, remarkably steep for a stream with the hydraulic dimensions of Red River.

The Rapides were a formidable obstacle to navigation, especially during periods of low water. To relieve this problem, in 1892-1893 the U. S. Army Corps of Engineers (1893, p. 1918) excavated more than 270,000 cubic feet of bedrock from the Upper Fall. This event was of great morphological importance because it permitted the knickpoint to resume rapid upstream migration. It will be shown that one of the results of this attempt to improve the navigability of the river was to accelerate processes responsible for excessive shoaling.

The destruction of the Rapides is therefore considered to have been a critical event in the evolution of the modern Red River. In addition, it was the culmination
of more than sixty years of engineering activity on the river. In cumulative effect, previous engineering projects of the nineteenth century had already produced notable changes in the morphology of Red River.

The ultimate cause of the twentieth century trend toward a braided pattern was the diversion through Moncla Gap, which steepened valley slopes beyond the critical upper limit for meandering. However, the rapidity of this change was enhanced by removal of the Rapides and also by earlier engineering projects which had greatly increased the hydraulic efficiency of the stream. To understand the nature of these changes, it is pertinent to describe the river as it was in the early nineteenth century, before it was altered by man.

The Great Raft

Studies of historic documents and the evidence presented in this report show that the nineteenth century Red River above the Rapides had several characteristics which either no longer exist or which are not important features of the regime of the twentieth century channel. In particular, four of these characteristics were significant aspects of the morphology of the river. These were as follows:

1. Flat valley slope. Valley slope above Alexandria changed very little until the destruction of the Upper Fall of the Rapides in 1892-1893. It will be shown
that although the valley slope was sufficient to produce a high sinuosity, it was gentle compared to the valley slope values of recent decades.

2. **High sinuosity.** Mapped channel segments and the subsequent behavior of the river as the valley slope increased show that the stream had attained maximum sinuosity for its hydraulic dimensions.

3. **Bank caving.** Historical documents indicate that bank caving was commonly observed but was largely confined to cut bank locations. This phenomenon is interpreted as evidence of active meandering processes.

4. **Raft accumulation.** Rafting, which is defined in this paper as a marked predisposition of a natural river toward the formation of extensive jams of floating timber, was remarkably active on Red River. The latter characteristic was the most striking phenomenon of the nineteenth century river.

The raft of the Red River, because of its enormous size, was generally referred to as the Great Raft, which name will be retained in this report. The Great Raft was not only the most conspicuous feature of the river above the Rapides but was also a considerable barrier to
navigation. Indeed, the effect of the raft on human activities and settlement in the nineteenth century was so pronounced that considerable traces of its impact on the cultural landscape of the alluvial plain are still visible, a theme touched on in some detail by Guardia (1927) in the most extensive existing study of the Great Raft.

Although numerous early travelers and settlers wrote descriptions of the raft, the most succinct surviving account is that of Sibley (1808, p. 58). Speaking of the Great Raft as it appeared in 1805, he described it as clogging

the main channel for upwards of one hundred miles of the river; not one entire jam from the beginning to the end of it, but only at points, with places of several leagues that are clear. (Emphasis mine.)

The term points refers to the point bar side of a meander. That this meaning was intended by Sibley is shown by the fact that in another document (see Rowland, 1930, p. 165) he observed that although

the channel of the river is very crooked, making sharp points, the jam is only at these places and the intermediate spaces are clear.

Guardia (1927, p. 10), whose reconstruction of the conditions of raft accumulation was based on numerous historical documents, also correlated points of log accumulation with point bar shoals.

Some years after Sibley, Flint (1833, p. 256) described the morphology of the Great Raft as follows:
About thirty leagues above Natchitoches commences the great raft, which is . . . a broad, swampy expansion of alluvion of the river to the width of twenty or thirty miles. The river here spreading into a vast number of channels, frequently shallow of course, has been for ages clogging with a compact mass of timber and fallen trees wafted from the upper regions. Between these masses the river has a channel, sometimes lost in a lake, and found by following the outlet of that lake back to the parent channel. The river is blocked up by this immense mass of timber for a length on its meanders, of between sixty and seventy miles. There are places where the water can be seen in motion under the logs. In other places the whole width of the river may be crossed on horseback, and boats only make their way, in passing these places, by following the inlet of a lake and coasting it to its outlet, and thus finding the channel again. Weeds, flowering shrubs, and small willows have taken root upon the surface of this timber, and flourish above the waters. But in all these places, the course of the river, its outlines and its bends, are distinctly marked by a margin of forest trees which grow here on the banks in the same manner as they do where the channel is open.

With the passage of time, the Great Raft migrated upstream. This gradual motion was due to a combination of accretion of floating logs at the upper end of the raft and disintegration of decayed timber masses at the lower end. On the basis of measurements of the U. S. Army Corps of Engineers, Veatch (1906, p. 60) estimated that the raft was moving upstream at a rate of more than 8 miles per decade during 1820-1872.

Most early writers were so impressed with the significance of the Great Raft that they tended to view all the unique morphological phenomena associated with the Red River as results of rafting. Veatch (1906) and Guardia (1927), for example, attempted to account for
the origin of the tributary lakes, the Rapides, and the diversion through Moncla Gap as responses to raft activity. It was generally assumed that the Great Raft, first accumulating near the mouth of the river, had existed for centuries. The diversion, for instance, was believed to have resulted from enhanced water levels created by rafting, which caused water to overflow across Moncla Gap.

Fisk (1938, pp. 35-50, and 1940, pp. 40-42) reviewed pertinent aspects of the literature but concluded that rafting was not an important morphological factor, at least in the lower part of the study area. His conclusion was as follows (1940, p. 41):

The writer doubts that rafting was ever of more than local importance. If rafts did exist in the lower Red River region, it would seem that quantities of logs would be found buried under subsequent flood sediments, or exposed in the banks of the modern river where it transects older historic channel positions. Small quantities of wood are found disseminated throughout the alluvium of both the Red and Mississippi River valleys; rotten wood is recorded on the logs of many borings (made in this area in the search for oil and water) at much greater depths than would have been necessary for the preservation of rafts. However, neither in the banks of the river, nor in the borings have there been found large quantities of logs such as one would expect from rafts, although the diversion of streams should have isolated log jams in channels from which they could not have been cleared by the decreased volume of water which would have utilized the cut-off channel during flood.

It is important to realize that these conclusions are based on studies of areas below the location of the Great Raft in historic time. The northern limit of the geological investigations of Fisk in the study area was the northern
boundary of Grant Parish (latitude 31 degrees, 42.5 minutes north), some 10 miles below Grand Ecore (figure 1).

Fisk's underestimation of the significance of rafting on the Red River is a direct result of the areal limitation of his studies in the region. Historical and geological evidence of intense raft activity is ubiquitous throughout the study area above Grant Parish. It is interesting to note, for example, that the site of the city of Natchitoches (immediately below Grand Ecore) was selected because at that time it was the upstream limit of navigation on the Red River, at the foot of the Great Raft (Guardia, 1927, p. 73). From the latitude of Natchitoches to the northern end of the study area the flood plain is studded with lacustrine and paludal deposits in locations that are relatively well drained today. Topographic quadrangles show the beds of lakes on the flood plain which now are dry, or only backswamp (see, for example, the Vivian quadrangle, in pocket). Soil surveys (U. S. Department of Agriculture and Louisiana Agricultural Experiment Station, 1962, p. 85) have mapped polygenetic soil units in which the normal flood plain depositional soils are overlain by fine-grained layers that are believed to have been deposited under conditions of high water as a result of rafting. The fine-grained raft deposits commonly have thicknesses to 16 inches (see the description of Gallion clay, overwash, U. S. Department of Agriculture and Louisiana Agricultural Experiment Station, 1962, p. 22).
Field observations by the author of the present report have confirmed the existence of these units in numerous localities. There appears to be no valid reason to doubt the morphological importance of the Great Raft on the flood plain above Grant Parish.

Embarrassment of drainage owing to rafting produced exaggerated water levels. Locations that were normally backswamp or tributary swamp environments were thus converted into lakes. When the Great Raft was finally destroyed these areas reverted to swamp. Canalization of the river by levee construction has prevented deep burial of raft deposits, which consequently may be studied in the field without the necessity of borings. A shovel is sufficient to reach the contact between raft lake deposits and the normal flood plain units.

Although Fisk's conclusion must be rejected as a generalization for the entire study area, it is important because it shows that evidence of raft activity is conspicuous by its absence to the south. Because there is no evidence that rafting occurred below the Rapides, the contentions of Veatch (1906) and Guardia (1927), who attributed both the Moncla Gap diversion and the rapids to raft activity, appear to have no foundation in fact.

Another important characteristic of the river at that time was intense bank caving. It is highly probable, in fact, that excessive caving was responsible for rafting. In April of 1872 the following vivid description
of bank failure was written by a competent observer, E. A. Woodruff, Chief of Engineers (U. S. Army Corps of Engineers, 1873-1874, p. 641):

The caving of the banks is most rapid while the river is falling after a freshet. At these times the continuous falling of the trees on some of the bends makes a noise resembling the distant roar of artillery. The amount of timber thus contributed by the banks at each freshet is immense.

This process ensured the presence of a copious supply of wood for raft accumulation after each flood.

Captain H. M. Shreve (Dorsey, 1941, p. 202), who cleared the first raft during 1833-1838, clearly recognized bank caving to be the origin of the Great Raft. Upon completion of channel clearance, he requested that the War Department provide financial support for timber removal from caving banks along the river as far upstream as Fort Towson, Oklahoma. Funds were not available, and the project was not carried out.

Only 4 months after the removal of the Great Raft, a new raft formed in the vicinity of the upstream end of the former jam. The rapidity of raft growth on the nineteenth century river is illustrated by the fact that, although the raft was only 2,300 feet long when it was first measured in July of 1838, by 1841 it was 20 miles in length.

Two years (1841-1843) were required to remove the new raft, but, only a few months after completion of that project, a third raft formed. By 1872 the new raft was
30 miles long, jamming the river to within 5 miles of the Arkansas state line. This was the last of the Red River rafts, and it was removed by dynamite during 1872-1873.

For 25 years after removal of the last raft, new log jams were removed by engineers as rapidly as they formed. At the same time, a systematic project of snag clearance and closure of overflow channels (utilized by the river when rafting obstructed flow in the main channel) was executed. These efforts increased the hydraulic efficiency of the main channel to the point that it became capable of carrying the entire flow of the river, including timber, without rafting. Thus, in 1899 Veatch stated that the river channel in the raft area had been considerably enlarged, and that only the "possibility of forming jams" remained (Veatch, 1899, pp. 166-167).

Rafting appears to have been a self-perpetuating phenomenon on the nineteenth century Red River above the Rapides. Accumulation of log jams on point bar shoals reduced the effective cross-sectional area of the stream in the axis of the meander bend. Compensation must have taken the form of increasing scour pool depths to accommodate increases in discharge. Falling water levels after flood would then remove the buoyant support of the over-steepened cut bank, which had already been lubricated by lateral seepage of water into the bank materials during high water. The resulting collapse of the cut bank would contribute additional logs and sediment to the river.
sediment would tend to lodge on the next point bar down-
stream, thus increasing its shoalness and rate of lateral
growth, and the timber would tend to jam at the same loca-
tion.

Continuation of this process eventually embarrassed flow in the main channel, producing elevated water levels. The result was overflow into crevasse channels, up tribu-
tary basins, and across low backswamp areas. Hence the eventual result of excessive rafting was the conversion of stream pattern from meandering to anastomosing. Above and below the rafted region, however, the Red River retained a single-channel, meandering form.

The remarkable intensity of bank caving along the river cannot be wholly attributed to the effects of raft-
ing. Red River soils, especially where there is a con-
siderable percentage of clay present, are characterized by notable changes in volume. This characteristic is believed to be important because recent microstudies of bank failures on the Lower Mississippi River have shown that a contributing factor is closely spaced fractures in the bank materials. It has been determined that these fractures are "due largely to earlier dessication" (Stanley et al., 1966, p. 865).

There is considerable evidence that such fractur-
ing activity is uniquely common in the study area. Pedo-
logical investigations have shown that extensive portions of Red River bottom lands have soil types, especially
where fine textured, in which "wide cracks are common during dry weather. The soil begins to shrink when its moisture content is slightly less than field capacity" (U. S. Department of Agriculture and Louisiana Agricultural Experiment Station, 1962, p. 32).

This phenomenon is due to the fact that soils of the Red River area "have clay fractions higher in montmorillonite and other expanding type clays than similar soils of the South Atlantic States" (U. S. Department of Agriculture and Louisiana Agricultural Experiment Station, 1962, p. 88). The same report (p. 90) notes that fine-grained soils of this type "lack a B horizon. The soils expand and shrink greatly when their moisture content changes. This causes a churning or mixing of horizons and accounts for the youthful appearance of the profiles. Hogwallow or gilgai microrelief is characteristic of flat or greatly sloping areas of these soils." Red River soils, especially those with considerable clay content, are highly unstable.

The remarkable propensity for bank caving on the Red River is a result primarily of this instability. During periods of drought and low water the montmorillonitic clay fractions in the river banks contract, producing fractures in the soil. Studies of the physical properties of such clays show that subsequent wetting will not completely heal fractures that develop in this fashion because drying shrinkage produces permanent internal structural changes.
in the clay and also because expansion of the clay to maximum volume requires immersion periods of several days or weeks (Mielenz and King, 1955, p. 231).

The immediate effect of lateral seepage of flood waters into banks containing significant quantities of dessicated expansive clays is lubrication of soil fractures. When flood waters wane, the buoyant effect of immersion is removed, making failure along the wetted fracture zones probable.

Hence the unique predilection toward cut bank collapse during falling water after flood on the nineteenth century river, a phenomenon reported by the Chief of Engineers 100 years ago. It is striking to note that, although clay plugs flanking the meander belt of the Lower Mississippi River inhibit scour pool erosion and lateral shifting (Fisk, 1947), clays in the banks of Red River tend to accelerate shifting by facilitating the collapse of oversteepened bank materials.

High sinuosity and an unusual proclivity toward bank caving in a densely forested environment were causative factors in raft formation. The intensely meandering nature of the river resulted in the formation of deep scour pools that favored cut bank failure and also produced shoal point bar deposits which snagged floating timber.

Evidence presented later in this report suggests that there was an early period during which the downcutting
river increased sinuosity in response to waxing valley slope. At the threshold of maximum sinuosity, downcutting above Alexandria was arrested because the river was then impinging on the resistant ledge of the Rapides.

Confinement of the river in the raft region to a single channel competent to carry the entire flow without snagging, and the destruction of the Rapides, closed the era of the Great Raft. The consequent rapid upstream advance of the knickpoint is reflected by the twentieth century degradation of the water surface at Alexandria and the concomitant decline of sinuosity.

Although the nineteenth century river above Alexandria was in a state of arrested degradation, localities in the immediate vicinity of raft sites were characterized by rapid aggradation. Measurements of the U. S. Army Corps of Engineers during 1871-1872 (see Guardia, 1927, p. 19) showed that the natural levees between Shreveport and the Arkansas border had increased in elevation by 3 to 5 feet, this increase having taken place during 30 years of raft accumulation.

In general, the persistence of phenomena usually associated with aggradational processes (notably tortuous meanders, relatively flat gradients, tributary lakes, and rafting) into the late nineteenth century is attributed to the inability of the knickpoint to pass beyond the Upper Falls. By the close of the century the tendency toward raft accumulation was no longer a conspicuous
aspect of the Red River, and raft prevention activities were terminated. No twentieth century rafts have formed.

**Tributary Lakes**

The tributary lakes flanking the Red River alluvial plain in Louisiana should be considered relics dating from a lengthy time of aggradation which preceded the present downcutting. The aggradational epoch on the river began to close when the Moncla Gap diversion occurred, and its end was hastened by the destruction of the Rapides.

William Darby (1816, pp. 55-57) expressed the origin of the tributary lakes as follows:

> The beds of the lakes are much lower than that of the channel of the river. When we passed the Black Lake in the month of September, 1811, after the great fresh of that year, the marks of high water on the trees along the shores were upwards of 20 feet above the then level of the water, whilst similar marks near the river, did not exhibit more than half the elevation.... The ... lakes ... are reservoirs emptied and filled annually by the hand of nature.

This explanation, combined with concepts of natural levee construction and channel shifting, has been echoed by numerous subsequent authors, including W. M. Davis (1887), I. C. Russell (1898), and H. N. Fisk (1938).

Degradation of the water surface elevation at Alexandria in the present century, however, is rapidly changing the base level relation between the trunk stream and the tributary lakes. It will be shown in this report that at the latitude of Alexandria, for a given discharge,
water surface elevations on the river have probably declined some 9 feet over the 70 years of this century. Continuation of this trend as the knickpoint migrates northward would eventually drain all the tributary lakes.

Dam construction across lake outlets has prevented this occurrence and has largely restored the lakes to the high water levels produced by the Great Raft. Only the intervention of man has preserved the Red River tributary lakes from destruction by sedimentation of their beds, in combination with degradation of their outlet channels.

**Conclusion**

Historical documents offer qualitative evidence of Red River metamorphosis. Diversion into a steep-gradient course through Moncla Gap initiated processes that would close the era of the Great Raft. The actual destruction of the sinuous and rafted channel of the nineteenth century was accelerated by activities of man.

Raft removal, snag clearance, and the destruction of the Rapides contributed to this result. More recently, closure of Denison Dam has affected the morphology of the northern end of the study area. The impact of dam construction will be evaluated later in this report.
CHAPTER II

CHANGING MEANDER PATTERNS

Introduction

Map comparisons of the same channel segment as it appeared in different years indicate that important changes in morphology have occurred. A typical sample of channel metamorphosis is offered by comparing a segment of the Red River below Shreveport as it was mapped by surveys in 1835, 1938, and 1957 (figure 2). The extremely tortuous alignment of 1835 contrasts markedly with the smooth bends of 1938. By 1957 a tendency toward a braided channel is evident.

Pattern changes farther upstream suggest a somewhat different situation. In this case no clear-cut decrease in sinuosity occurred during the 100 years between the mapped channels of 1838 and 1938 (figure 3). However, the survey of 1957 shows a distinct decrease in the number of meanders.

Thus two river segments, one some 15 miles below Shreveport and the other halfway between Shreveport and Fulton, show different patterns of change. Inasmuch as these reaches were selected because they typify the morphological changes manifest above and below Shreveport,
Figure 2. Changing meander morphology, vicinity of Shreveport.
Figure 3. Changing meander morphology, vicinity of Spring Bank, Arkansas.
the following conclusions are indicated:

1. The main stem of the Red River was extremely tortuous in the early nineteenth century.

2. Considerable portions of the river had ceased meandering before the survey of 1957.

3. Channel straightening began in the lower part of the study area, becoming noticeable above Shreveport only in recent decades.

4. A braided tendency is evident over considerable parts of the study area below Shreveport, but above that point the river still displays a meandering pattern.

Impressive changes in mileage between points along the river prove that the straightening tendencies noted above have become almost ubiquitous in the study area. In 1938, river mileage from the mouth of Lower Old River to Fulton totaled 462.6 miles (figure 1). This distance had declined to only 404.8 miles by 1957, a decrease of nearly 58 miles. In only two decades the distance between these two points decreased 14 per cent.

Such drastic changes in length prove that sinuosity has been diminishing along the Red River, but it is not clear where these changes took place. It is possible that mileage decreases occurred along certain portions of the stream and that other reaches experienced little change.

To identify those parts of the river where significant shortening was localized, measurements of river
mileages between 27 control stations were conducted along the channels of 1938 and 1957. Distances were determined along midchannel between adjacent stations distributed along the entire river from the mouth of Lower Old River to Fulton (figure 1); a Bruning map measurer was used.

The results show that the hydraulic conditions that favor channel straightening prevailed in all parts of the study area (table 1). During the 20-year period (1938-1957) the only river segment which displayed a high percentage increase in length across a sizable reach was on the alluvial plain of the Mississippi River, outside the study area. The tendency for channel straightening, which began with the diversion and entrenchment through Moncla Gap, prevailed everywhere in the study area by midcentury.

Fundamental Dimensions of a Meander

The demonstrated river shortening that occurred between 1938 and 1957, and earlier, was accomplished by changes in meander morphology. Correlation of changing meander patterns with hydraulic variables requires that the elements of the meanders produced by the river at different times must be expressed numerically.

In the absence of adequate hydrographic data, the parameters that are measurable are restricted. Among the missing variables are channel widths and depths. Although widths were measured by most surveys, such
TABLE 1

SUMMARY OF CHANNEL DISTANCES, RED RIVER, 1938 AND 1957

<table>
<thead>
<tr>
<th></th>
<th>1938</th>
<th>1957</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Segment Length*</td>
<td>6.1</td>
<td>5.3</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>3.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

*Distances measured in statute miles.

values cannot be realistically extrapolated into a mean width representative of the year. The measured widths are doubtless a reflection of the momentary condition of the river.

The fundamental unit form of a meandering stream is illustrated by a portion of the 1957 channel of the river (figure 4). Viewed from one side of the stream, the typical bend is composed of portions concave toward the observer and portions that are concave toward the opposite direction. If the individual bend unit is conceived of as a concavity facing an observer, bounded on each side by an opposing concavity, then the successive bend units as seen on one side of the stream would be the segments AC, CE, EG, and GI. Seen from the other side, the bend units would be the segments BD, DF, FH, and HJ.

An individual bend unit illustrates the elements measured in this report (figure 5). Lines XX' and ZZ' are the boundaries of the bend unit. Lines AA' and BB'
Bend units: AC, BD, CE, DF, EG, FH, GI, HJ
Figure 6. Bend unit dimensions.
are constructed tangent to the cut banks, and line YY' is perpendicular to the cut bank within the bend unit. The following dimensions were found useful:

1. **Miles by river.** This dimension is the distance measured along the center of the channel. Thus it is the river mileage from line XX' to line ZZ'.

2. **Wave length.** This is the distance measured in a straight line across the bend unit. Thus it is the length of line AA', measured from the intersection with XX' to the intersection of ZZ'.

3. **Meander width.** This is the maximum distance across the bend unit, measured in a straight line perpendicular to the wave length. On the figure it is the length of line YY', measured from the intersection with BB' to the intersection with AA'.

4. **Bending ratio.** This is miles by river divided by the wave length. Straight river segments have values near unity, whereas tortuous bends produce large numbers.

The selection of these measures of meander intensity is based on considerable application. Although radius of curvature is commonly cited in the literature, it did not prove to be practical for many Red River meanders. Large numbers of bends are characterized by such marked asymmetry...
that differing radii appear to be expressed in a single meander. These deformed meanders, as Matthes (1941, p. 635) called them, are believed to result from structural controls and nonuniform distribution of bed and bank materials.

The meander ratio of Inglis (1947, p. 4), defined as meander width divided by wave length, was also rejected because many highly tortuous bends are only vaguely reflected by this measure and because statistical tests showed it is not a significant indicator of changing meander patterns.

The measures of meander intensity used in this report are summarized (table 2). Miles by river and bending ratio are introduced because the statistical tests that follow will demonstrate that they are significant measures of meander morphology. In general, the original terminology of Matthes (1941) is preferred because it is simple and descriptive.

Sinuosity is the ratio of channel length to valley length. Thus it is a dimensionless index of tortuosity, and is one of the most subtle measures of meander intensity. Lane (1957, pp. 63-64) regarded it as

an important definition in the development of the science of stream pattern, as it gives an easily measured quantitative value for the crookedness or tortuosity of the stream. Over a long section of the river the slope of the river multiplied by this ratio gives the slope of the valley. This value then is also the ratio of the valley slope to the river channel slope and should be extensively studied in future research in the field of
### TABLE 2

**SELECTED TERMINOLOGY FOR MEANDER DIMENSIONS**

<table>
<thead>
<tr>
<th>Name</th>
<th>Author</th>
<th>Synonyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles by River</td>
<td>Abington (this paper)</td>
<td>...</td>
</tr>
<tr>
<td>Wave Length</td>
<td>Matthes (1941, Fig. 2), Inglis (1947, pp. 3-4 and Fig. 1), Leopold et al. (1964, Fig. 7-40)</td>
<td></td>
</tr>
<tr>
<td>Meander Width</td>
<td>Matthes (1941, Fig. 2)</td>
<td>Meander Belt (Inglis, 1947, p. 4 and Fig. 1), Meander Belt Width (Lane, 1957, p. 62)</td>
</tr>
<tr>
<td>Bending Ratio</td>
<td>Abington (this paper)</td>
<td>...</td>
</tr>
<tr>
<td>Sinuosity</td>
<td>Leopold et al. (1964, p. 281)</td>
<td>Tortuosity (Inglis, 1947, p. 4), Tortuosity Ratio (Lane, 1957, p. 63)</td>
</tr>
</tbody>
</table>

river pattern.

Bending ratio is the logical extension of the concept of sinuosity to an individual meander. Sinuosity will be considered in the next chapter.

**Red River Meander Morphometry**

Each bend unit from valley mile zero (Moncla) to valley mile 216 (Fulton) was measured from the published channel surveys (U. S. Army Corps of Engineers, 1958), and all measures were double checked.
In addition to the surveys of 1938 and 1957, a substantial sample of the Red River channel of the 1830's has been preserved in the form of political boundaries. This sample consists of the eastern boundaries of Miller County, Arkansas, and Caddo Parish, Louisiana. Although this channel has been preserved over a distance of only 100 valley miles from Fulton southward, it is notable that it contains a total of 145 meanders. Thus the Red River, at the time of this survey (1835-1838), must have had a substantially larger number of meanders than in 1938 (231 bend units) or 1957 (177 bend units). A general decrease in the number of bend units is evident with the passage of time.

The results of the meander measurements for the channels of 1835-1838, 1938, and 1957 may be summarized by comparisons of histograms (figure 6). It is notable that in all cases the meander parameters display a distinct positive skewness, so that none of the distributions is Gaussian.

Comparison of miles by river per bend unit (figure 6-A) shows that values have progressively shifted toward the right. Thus the maximum frequencies in 1838 were associated with meander mileages of only 1 to 2 miles, whereas by 1957 the most frequent bends were 3 to 4 miles in length. The tendency toward the right is also reflected by the fact that in 1838 the skewed distribution to the right was discontinuous, later surveys showing
Figure 6. Percentage relative frequency of meander dimensions. A. Miles by river. B. Wave length. C. Meander width. D. Dimensionless bending ratio.
continuity in that direction.

Because the 1838 channel sample is situated toward the upstream end of the study area, somewhat smaller meanders are to be expected in consequence of the lesser discharge. Nonetheless, the order of magnitude of the change shown by the shift to the right is considerably in excess of what might be expected as a result of increased size alone.

Similar tendencies are visible in the case of wave length (figure 6-B). Here the frequency shift toward larger wave lengths includes a clear-cut decrease in frequencies of short distances. The rate of change displayed during the two decades from 1938 to 1957 is remarkable.

In contrast, it is interesting to note that meander width (figure 6-C) shows no consistency of trend through time.

Dimensionless bending ratio (figure 6-D), however, provides additional evidence of changing meander morphology. As time passes, bending ratios near unity become increasingly common, and large numbers decline in frequency.

The evidence may be summarized as follows:

1. Over a period of 120 years, the Red River has increased river mileages and wave lengths of individual meanders by decreasing the sinuosity of its channel.
2. Because sinuosity has systematically decreased and meander width has not displayed any clear trend, these two morphological factors are not controlled by the same variable (or variables). Thus the hydraulic regime of the Red River has changed over the decades in such a fashion that sinuosity was transformed without affecting the width of the meander zone.

Inspection of summary statistics for the channels of 1838, 1938, and 1957 reveals further evidence of the magnitude of the pattern changes (table 3). As before, all dimensional quantities are presented in statute miles.

Data from the table confirm the conclusions drawn from the histogram analysis. Notable instances include the following:

1. **Miles by river.** River mileage per meander has systematically increased, as reflected by the values of the midrange, median, and mean. However, changes in the standard deviation and the extremes do not show this trend clearly. Variability was at a maximum in the 1830's and was least in the 1950's.

2. **Wave length.** The minimum, midrange, median, and mean have all increased. Standard deviation has markedly increased in the 20 years between the last two surveys.
<table>
<thead>
<tr>
<th></th>
<th>Miles by River</th>
<th>Wave Length</th>
<th>Meander Width</th>
<th>Bending Ratio</th>
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<tbody>
<tr>
<td><strong>Minimum</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>1.0</td>
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<td>0.1</td>
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<td>1957</td>
<td>1.2</td>
<td>0.9</td>
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<td><strong>Maximum</strong></td>
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<tr>
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<td>9.5</td>
<td>5.2</td>
<td>2.7</td>
<td>11.3</td>
</tr>
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<td>3.3</td>
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<td>1957</td>
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</tr>
<tr>
<td>1838</td>
<td>3.0</td>
<td>1.7</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>1938</td>
<td>3.2</td>
<td>2.1</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>1957</td>
<td>3.7</td>
<td>2.5</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Mode</strong></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1838</td>
<td>3.0</td>
<td>1.2</td>
<td>1.0</td>
<td>1.1</td>
</tr>
<tr>
<td>1938</td>
<td>4.2</td>
<td>2.1</td>
<td>*</td>
<td>1.1</td>
</tr>
<tr>
<td>1957</td>
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<td>2.0</td>
<td>1.6</td>
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<td></td>
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<tr>
<td>1838</td>
<td>3.2</td>
<td>1.8</td>
<td>1.1</td>
<td>2.1</td>
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<tr>
<td>1938</td>
<td>3.4</td>
<td>2.2</td>
<td>1.0</td>
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<td>1957</td>
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<td>1.6</td>
<td>0.9</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>1938</td>
<td>1.5</td>
<td>0.9</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>1957</td>
<td>1.6</td>
<td>1.2</td>
<td>0.6</td>
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<tr>
<td><strong>Variation Coefficient</strong></td>
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<tr>
<td>1838</td>
<td>0.50</td>
<td>0.50</td>
<td>0.55</td>
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<tr>
<td>1938</td>
<td>0.44</td>
<td>0.41</td>
<td>0.60</td>
<td>0.44</td>
</tr>
<tr>
<td>1957</td>
<td>0.41</td>
<td>0.44</td>
<td>0.50</td>
<td>0.40</td>
</tr>
</tbody>
</table>

*Modes are 0.2, 0.9, 1.1, and 1.5.
Variability was greater in the 1830's, but the 1938 and 1957 data do not suggest systematic trends.

3. **Meander width.** No trends are evident.

4. **Bending ratio.** The maximum, midrange, and mean all suggest decreasing sinuosity through time. The standard deviation decreased considerably between the 1830's and the 1930's, but little change is evident later (probably owing to the short time span). Bending ratio variability has declined.

Thus there is considerable statistical evidence to corroborate the conclusions based on map studies, river mileage tabulations, and analysis of histograms of meander dimensions. Red River, over a period of 120 years, has shown a consistent tendency toward a decrease in sinuosity.

Although the foregoing data demonstrate that the meander patterns of today differ from those of a century ago, it is not clear whether such changes might be attributed to chance or whether they represent a fundamental change in the nature of the river.

**Significance of Pattern Changes**

The usual procedure at this point would be analysis of variance. However, as Ostle (1964, p. 338) points out, the assumption of normality is essential for the standard
techniques of variance analysis. Histogram inspection has shown that the fundamental meander dimensions all display a distinct positive skewness. Furthermore, chi-square tests demonstrate that these distributions do not conform to the Gaussian model.

It is therefore appropriate to invoke the central limit theorem. Ostle (1964, p. 72) defines this theorem as follows:

If a population has a finite variance of $\sigma^2$ and mean $\mu$, then the distribution of the sample mean approaches the normal distribution with the variance $\sigma^2/n$ and mean $\mu$ as the sample size $n$ increases.

Inasmuch as the sample sizes for 1838, 1938, and 1957 total 145, 177, and 231, respectively, all sample sizes are adequate for analysis of means.

Three hypotheses must be considered:

1. $\mu_{1838} = \mu_{1938}$,
2. $\mu_{1938} = \mu_{1957}$, and
3. $\mu_{1838} = \mu_{1957}$.

The hypotheses state that the variations among means are due to chance. Thus, if they are accepted, it must be concluded that there has been no significant change in the hydraulic factors controlling meander morphology.

The test results are presented for 0.05, 0.01, and 0.001 levels of significance (table 4). The table shows the standardized variable (Z score) for each hypothesis and each meander parameter. The method of calculation is shown by Spiegel (1961, pp. 170-171 and p. 181) and others.
### TABLE 4

**ANALYSIS OF SIGNIFICANCE, MEAN MEANDER DIMENSIONS, RED RIVER OF 1838, 1938, AND 1957**

<table>
<thead>
<tr>
<th></th>
<th>Miles by River</th>
<th>Wave Length</th>
<th>Meander Width</th>
<th>Bending Ratio</th>
</tr>
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<tbody>
<tr>
<td><strong>1838 - 1938</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z Score</td>
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<td>-4.000</td>
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</tr>
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<td>0.05 Level</td>
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<td>Accepted</td>
<td>Rejected</td>
</tr>
<tr>
<td>0.01 Level</td>
<td>Accepted</td>
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<td>Accepted</td>
<td>Rejected</td>
</tr>
<tr>
<td>0.001 Level</td>
<td>Accepted</td>
<td>Rejected</td>
<td>Accepted</td>
<td>Rejected</td>
</tr>
<tr>
<td>Probability</td>
<td>0.317</td>
<td>0.00006</td>
<td>0.317</td>
<td>0.0005</td>
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<tr>
<td><strong>1938 - 1957</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Z Score</td>
<td>-3.125</td>
<td>-4.909</td>
<td>-3.000</td>
<td>2.500</td>
</tr>
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<td>0.05 Level</td>
<td>Rejected</td>
<td>Rejected</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>0.01 Level</td>
<td>Rejected</td>
<td>Rejected</td>
<td>Rejected</td>
<td>Accepted</td>
</tr>
<tr>
<td>0.001 Level</td>
<td>Accepted</td>
<td>Rejected</td>
<td>Accepted</td>
<td>Accepted</td>
</tr>
<tr>
<td>Probability</td>
<td>0.002</td>
<td>0.0000009</td>
<td>0.003</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>1838 - 1957</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z Score</td>
<td>-4.188</td>
<td>-7.833</td>
<td>-2.000</td>
<td>5.000</td>
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<tr>
<td>0.05 Level</td>
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<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>0.01 Level</td>
<td>Rejected</td>
<td>Rejected</td>
<td>Accepted</td>
<td>Rejected</td>
</tr>
<tr>
<td>0.001 Level</td>
<td>Rejected</td>
<td>Rejected</td>
<td>Accepted</td>
<td>Rejected</td>
</tr>
<tr>
<td>Probability</td>
<td>0.00003</td>
<td>0.0000000*</td>
<td>0.046</td>
<td>0.0000006</td>
</tr>
</tbody>
</table>

*Actual value between 0.000000000003 and 0.000000000000001.

The table indicates whether each hypothesis was accepted or rejected for each significance level. It is important to bear in mind that the decisions are based on two-tailed tests because the likelihood of false rejection is lessened.

The probabilities given for each case are the probabilities that the differences in sample means may be attributed solely to chance. The probability that the
disparity between the observed means is a result of the samples' being drawn from fundamentally different meander populations is unity minus the listed value. Like the test decisions, all probabilities are two-tailed.

The information provided in the table includes overwhelming proof of significant changes in meander morphology. Among the important conclusions are the following considerations:

1. Wave length is the most sensitive indicator of Red River pattern change. It is the only measure that caused rejection of each hypothesis at every level of significance. The Z score associated with the comparison of the means of 1838 and 1957 is phenomenal: so small are the probabilities that are associated with such a value that most tables of the normal distribution do not include them. Even the extensive tables of Pearson and Hartley (1966, p. 117) only make it possible to define the probability by a range, as the footnote does. It is remarkable to observe that the probability that the samples of 1838 and 1957 came from the same population is considerably less than 1 in 400 billion.

2. It is also interesting to note that changes in wave length that occurred during the 20 years from 1938 to 1957 were more significant
than those that took place over the whole century preceding. The rate at which wave length increases appears to be waxing.

3. Bending ratio is also an important measure of the changing meander morphology of the Red River. Changes that occurred over long periods of time were significant. The fact that the decrease between 1938 and 1957 was significant only at the 0.05 level is due to a somewhat slower rate of change than that of the wave length.

4. The total decrease in river mileage per bend unit over the whole 120-year period has considerable significance. However, it is not possible to make such unconditional decisions for the other hypotheses. The primary importance of miles by river lies in its relation to wave length, expressed as the bending ratio.

5. Meander width is not significant at the 0.001 level.

Extremely important changes in Red River meander morphometry have occurred. Increase in wave length is by far the most significant component of the changing dimensions of bend units. Waxing of wave lengths has been accompanied by a less spectacular, but nonetheless consistent, decrease in the dimensionless bending ratio.
Conclusion

In the early nineteenth century the Red River was a classic example of a tortuously meandering stream. Landforms of fluvial aggradation, including the tributary lakes, accompanied the degradation which Fisk hypothesized for the Red River. Map evidence, river mileage evidence, and analysis of histograms of meander dimensions all indicate that over the 120-year period the river has experienced important changes in meander morphology. Finally, application of the central limit theorem to the measured meander data proves that certain aspects of this channel straightening have extreme significance.
CHAPTER III

CHANGING HYDRAULIC VARIABLES

Introduction

The independent variables responsible for channel dimensions include the following:

1. Valley slope. Gauge data in the study area will be analyzed to test the hypothesis that significant changes in valley slope are taking place.

2. Bed load. The exact quantity, composition, and ratio of bed load entering the study area at Fulton are unknown. Although this is also true of the contributions by tributary streams, conclusive morphological evidence shows that it is highly unlikely that significant quantities reach the main channel from this source. It seems probable that dam construction above the study area may have diminished the coarseness and quantity of bed load in part of the study area. Studies of models and small streams should be the most realistic approach to this problem inasmuch as at present there appears
to exist no adequate technique of sampling that is practical for large rivers.

3. **Total load.** Because the bed load is not a known quantity, the total load is also unknown. While there are contemporary samples of suspended sediment (evaluated in Chapter IV), sampling procedures of the necessary accuracy do not extend over enough years for time series regression analysis. It is possible that the expansion of agriculture across the flood plain accelerated erosion, increasing the suspended and total load. Studies of numerous rivers suggest that decline in bed load ratio should tend to increase sinuosity (Schumm, 1969), whereas increases in total load tend to effect a shift toward the straighter channels associated with braided streams (Lane, 1957). Thus these opposing tendencies may offset each other somewhat.

4. **Discharge.** Time series regression analysis is used to test the hypothesis that discharge has been changing in the study area.

5. **Resistance to erosion.** This variable is important, especially in cases of diversion into new courses across a lithologic unit of differing cohesiveness. In the case of this report, erosion resistance is believed to have remained
constant.

6. **Climate**. Although climate is also a crucial variable, climatic fluctuations over the past 130 years in the Red River basin do not seem sufficient to account for the consistent morphological trends displayed by the river. Pilot studies of the available records at several stations do not seem to suggest prominent trends.

7. **Time**. The factor of time is included by analyzing variables with time series regression hypotheses. Using this method makes it possible to express changing variables in terms of rate of change, as will be illustrated in this chapter.

8. **Preexisting morphology**. In the case of a river that is actively changing its pattern it is necessary to consider the original stream form. If erosion or deposition has obscured the former channel, then any surveyed reach of considerable length will suffice, given that some decades have elapsed since the date of survey. This initial morphology may be regarded as having been stable under a set of conditions which no longer exist. A change in one or more of the independent variables rendered that pattern unstable, necessitating a shift in dimensions
toward a morphology that will be stable under the new conditions.

The dependent variables which result from the interrelations between these variables include such items as flow resistance, cross-sectional geometry of the channel, and meander form, among others.

For purposes of this study it is convenient to regard the channel forms of 1835-1836 as the preexisting morphology (presented in the second chapter). Bed load and total load variables through time are unknown. Resistance to erosion and climate are regarded as constants. The remaining variables to be explored are valley slope, discharge, and time.

Selection of Variables

The foregoing list is a revision of the original variables proposed by Matthes (1941, pp. 632-633), who believed that meandering resulted from the following: (1) valley slope, (2) bed load, (3) discharge, (4) bed resistance, and (5) transverse oscillation.

Transverse oscillation is not regarded as an independent variable in this paper. The lateral pulsations responsible for meandering have been described by Friedkin (1945, p. 4) in these words:

The natural process might be likened to the oscillatory course taken by a ball which has been started down a grooved incline so that it oscillates from side to side.

Meandering results from natural lateral pulsations that
occur when certain fundamental conditions are met. These conditions are the independent variables, and the transverse oscillations that produce meandering are dependent results.

Bed resistance was eliminated because the word resistance does not clarify whether erosional or flow resistance is pertinent and because some authors distinguish between the bed and banks of a stream.

Erosional resistance is an independent variable. Impingement against a lithologic unit or revetment which the river cannot erode produces localized pattern distortions which Matthes (1941, Fig. 2) called deformities. R. J. Russell (1958, p. 12) summarized several fundamental types of deformities.

Russell (1958, pp. 12-14) has documented cases in which pattern changes were produced by tectonic influences. Meander morphology may be distorted by a tendency for a river to flow along planes of weakness resulting from faulting. Such factors may favor diversion into courses characterized by marked differences in erosional resistance. In this case the erodibility of the new channel periphery is a critical morphological factor.

The results may be illustrated by consideration of the effects of diversions into two extreme geological environments: (1) a cohesive clay and (2) a cohesionless sand. Morisawa (1968, pp. 112-113), Lane (1957, pp. 12-13), and others have shown that significant differences
... An excellent example of the first case is offered by the Lower Mississippi River below New Orleans. Russell (1958, p. 17) described the bird-foot delta, noting that its pattern depends on the fact that the river is confined to a single channel for about 70 miles below the Lake Borgne fault zone... by compact clay. Through this clay the channel is deep, flat-floored, and comparatively straight.

The channel is trapezoidal in cross section, and development of meanders is inhibited by the rigidity of the clay.

The origin of this pattern is explained by the boundary layer concept, first demonstrated by Prandtl (Leliavsky, 1966, p. 47). Although the flow of a fluid may be fully turbulent, under most conditions there will exist a thin layer in contact with the channel perimeter which is not in motion. Above this layer is a zone of very slight thickness in which flow is wholly laminar. This is the boundary layer.

Extremely fine grained materials, such as clays, are individually too small to project through the boundary layer. Thus extremely small objects are shielded from turbulent pulsations which would otherwise easily lift them into the flowing fluid. The effect is clearly explained by Raudkivi (1967, p. 20) as follows:

In nature this implies that once fine particles have settled on the ground they will be sheltered in the viscous sublayer, are out of reach of the turbulent eddies and cannot be swept up again individually—for example, soft dust on the ground in a strong wind.
Channel banks of cohesive clay are as indestructible as concrete revetments. The only effective erosional agent is dragging the bed load across the channel bottom. As the bed load cuts deeper, the width of the bed decreases because the deepened cross section may accommodate discharge with less width. The end result is the trapezoidal form and a relatively straight channel.

In the case of diversion across noncohesive sands, the necessity to cut a channel sufficient to accommodate discharge requires entrainment and transport of notable quantities of sand. Excessive erodibility of the channel periphery therefore results in an appreciable increase in that portion of the sediment load which is coarser than silt.

Schumm (1967, p. 1549, and 1969, p. 257) found the empirical function

\[ Q_t = \frac{55}{M}, \]

where \( Q_t \) is an estimator of the percentage of the total sediment load that is bed load and \( M \) is the percentage of silt and clay (material less than 0.074 millimeters in diameter) in the perimeter of an alluvial river.

Schumm (1969, pp. 257-258) also observed that

\[ S = c(Q_t)^{-0.25}, \]

where \( S \) is sinuosity and \( c \) is a constant, and that
\[ L = c(Q_m)^{0.34} (Q_t)^{0.74}, \]

where \( L \) is meander wave length, \( c \) is a constant, and \( Q_m \) is mean annual discharge in cubic feet per second.

These functions appear to show that increasing the sand concentration carried by an alluvial river will produce increased bed load ratio, decreased sinuosity, and increased meander wave length. Thus channel straightening is one result of flow across noncohesive sands.

The tractive force (shear) equation (see Lane, 1957, Appendix II, for a detailed explanation) is

\[ F = W H M, \]

where \( F \) is the tractive force per unit bed area, \( W \) is the specific weight of the fluid, \( H \) is the depth of the fluid, and \( M \) is the water surface slope.

Channel straightening increases water surface slope (\( M \)), and augmented sediment concentration increases the specific weight (\( W \)) of the fluid-sediment mixture: these tendencies increase tractive force. Destruction of the channel bed is prevented by increased rugosity and shoaling. Both are accomplished by deposition of excessive sediment in localities of low turbulence, which produces a shallow channel littered with bars and islands.

A meandering alluvial stream, such as Red River, requires a channel periphery with erodibility between the extremes exhibited by the straight clay channel and the
braided sandy channel. Between Fulton and Moncla (figure 1) Red River flows 216 valley miles across a diversity of geological environments, ranging from bedrock and backswamp deposits to point bar and natural levee deposits. Although the local resistance of the channel perimeter is critical to the morphology of individual bends, it is improbable that mean bed resistance of the study area has changed significantly. Erodibility is regarded as a constant and is within the limits required for meander development.

Flume investigations (Leopold et al., 1960) and studies of natural rivers (Leopold and Wolman, 1960) indicate that some relation may exist between meander dimensions and flow resistance. Meander forms were conceived as an adjustment toward minimal resistance to flow, and measures of channel dimensions suggested to Leopold and Wolman (1960, p. 769) that "most river curves have nearly the same value of the ratio of curvature radius to channel width, in the range of 2 to 3."

This sweeping conclusion contrasts markedly with the cautious evaluation of Bagnold (1960, pp. 143-144), who observed that strong evidence has been found that the resistance to flow in a channel of uniform cross section falls to a sharply defined minimum within the narrow range of the curvature ratio . . . between 2 and 3 approximately. But we have yet to show that the same minimum of resistance does in fact occur in a natural meandering channel whose cross section is not uniform.
If the same resistance minimum is found to occur in a natural channel, we have still to explain why the configuration of the natural channel should tend towards that giving minimum resistance. The reason is far from being self-evident.

Any explanation which may be put forward must remain speculative until the nature of the general dynamic mechanism is understood whereby flow in a deformable channel tends to mould its channel to a certain preferred configuration.

The present author is not convinced that most river curves have a curvature ratio between 2 and 3. Indeed, critical examination of Leopold and Wolman's data (1960, Appendix following p. 791) is sufficient to cause doubt. Although the median curvature ratio was 2.7 (Leopold and Wolman, 1960, p. 774), the mean was 3.1. Even the authors observed that only "about one quarter of the [measured] values lie between 2.0 and 3.0." It appears obvious that most river curves do not fall within the range of 2 to 3.

Two of the meanders measured by Leopold and Wolman (1960, Appendix following p. 791) are in the study area. In the terminology of this paper, both bends had river mileages less than or equal to 3.5 miles, wave lengths less than or equal to 2.2 miles, and bending ratios greater than or equal to 1.6. Of 177 bend units measured, only 14 (8 per cent) fall into this range. The selected meanders were anomalous, although Leopold and Wolman (1960, Appendix following p. 791) state that "each sample is considered representative of the local reach of river."

The probability of drawing such a biased sample is
only 6 in 1,000. The origin of this unique selection may derive from the fact that it was required that the meanders be "reasonably symmetrical" (Leopold and Wolman, 1960, Appendix following p. 791). The typical Red River meander is not notable for its symmetry, which consideration led to the conclusion that radius of curvature is impossible to measure on many bend units.

Broad generalizations based on such data may well be unrealistic, especially when they are extended to include "most river curves." The fatal flaw in using the curvature radius (or ratio) in the case of natural streams is that it can be measured accurately only in highly symmetrical bends and that therefore all samples are biased. The well-known flowing curves of the S-shaped Mississippi River meanders at Greenville are famous, not because they are typical, but because they are unique.

Flow resistance is a complex variable that is considered to be dependent in this paper. Variables such as depth of flow, water surface slope, bed rugosity, and velocity affect flow resistance and are regarded as interrelated functions of discharge, valley slope, sediment load, and erodibility, among other parameters. Flow resistance can even be considered partially dependent on the dependent variables of channel cross section and stream pattern, and it is believed that all independent variables of flow resistance are included in the foregoing list.

The continued inclusion of valley slope is justified
by the model studies of Friedkin (1945, p. 10), who found "an increase in sinuosity or length of channel with increase in discharge or slope."

Inclusion of bed load is warranted because Schumm (1967 and 1969) found significant regressions of sinuosity on bed load ratio and meander wave length on discharge and bed load ratio.

Total load has been added because Lane (1957, p. 72 and pp. 77-83) appears to have shown that braiding may result from an excess quantity of total sediment load, as exemplified by the Upper Mississippi River.

Although the temporal trends of Red River bed and total load are not known, dam closure above the study area and expansion of agricultural activity across the flood plain suggest that changes may have occurred. Evidence will be introduced later in this report showing that sediment deficiencies caused by damming are probably compensated above Shreveport.

Studies of flood plain environments near Shreveport (U. S. Department of Agriculture and Louisiana Agricultural Experiment Station, 1962, pp. 22-62) indicate that erosional risks range from moderate to severe and that the soil types exposed by agricultural activity range from clay to fine sandy loam. Because the point bar sediment study of Harms et al. (1963, p. 570) indicates that Red River bed load ranges from fine sand to gravels 11 millimeters in diameter at that latitude, the result of
increased erosion attributable to agriculture should be to decrease bed load ratio and increase total load.

The investigations of Schumm (1967 and 1969) and Lane (1957) seem to show that these two changes correlate with opposing tendencies. Decreased bed load ratio should produce increased sinuosity, whereas increasing total load should result in straightening. In the absence of further data it will be assumed that sediment load changes have not significantly affected meander morphology in most of the study area.

The discharge variable may be readily justified because numerous writers have regarded it as a fundamental variable. Inglis (1947, pp. 10-13) presented the function

$$L = c \sqrt[1/2]{Q}$$

where $L$ is wave length, $c$ is a constant, and $Q$ is "dominant discharge."

His concept is confusing because Inglis (p. 13) states that "the dominant discharge in rivers is of the order of 60 per cent. of the maximum discharge." In the next paragraph he remarks that "the dominant discharge is usually of that order, although it varies in different rivers, being sometimes less than half."

Somewhat more precise is bankfull discharge, a measure which is considered to have morphological significance by numerous authors, notably Leopold et al. (1964, pp. 319-322). However, as these writers observe, bankfull
discharge is difficult to calculate; it is, in fact, impossible to calculate where river banks are ill defined. Furthermore, the findings included in this chapter will demonstrate that a concept of this sort is meaningless at a station such as Alexandria.

Matthes (1941, p. 632) defined the discharge variable in a very complex fashion:

This concerns the seasonal stream-flow variations as represented in the average yearly discharge hydrograph. In experimental work definite assumptions are necessary as regards proportioning the duration of the low, medium, and high stages. The importance of this will be appreciated because of the close relation that exists between rate of discharge and rate of bed-load movement in natural streams.

Indeed, the problem is not whether discharge is significant, but it is rather a question of which measure of discharge should be used. The present writer regards the foregoing concepts as being oversimplifications (Inglis), impractical in many cases (Leopold et al.), or excessively complex (Matthes). The approach of Matthes is undoubtedly best for study of daily and hourly scour and fill activity, but it requires too many assumptions to be practicable in many cases.

In view of the excellent results obtained by Schumm (1967 and 1969) using mean annual discharge, this variable will be used in this paper. The fact that his correlations were highly significant for streams in semiarid regions is notable because such streams are characterized by extreme variability of flow.
Climate is significant for several reasons. Viscosity and (to a lesser extent) density of water are both functions of the temperature. Of the two, changes in viscosity have the greater morphological impact.

Decreasing water temperature increases viscosity. The effective result is to increase the potential sediment-carrying capacity of the river, while competence remains unchanged. Study of the sediment load of the Colorado River by Lane et al. (1949, pp. 619-620) showed a distinct correlation between low temperatures and an increase in sediment. Because the increase affected only particles smaller than 0.3 millimeter in diameter, it has no appreciable consequence for particles much coarser than fine sands.

In channels with erodible perimeters containing appreciable quantities of sediment smaller than 0.3 millimeter, the result may be a considerable increase in total load. Given a constant slope and depth of flow, equation (1) shows that this in turn would augment the tractive force on the bottom to some degree because the additional suspended materials would increase the specific weight of the fluid-sediment mixture.

On the other hand, increased viscosity would also increase the thickness of a (presumably) laminar boundary layer, thus actually strengthening the erosional resistance of uniform fine clays. It is clear that the impact of low temperatures on sediment load is affected by the erodi-
bility and particle sizes of the channel periphery.

The temperature variable is only one aspect of cli­
mate. Precipitation is also important, especially in
regard to quantity, time of occurrence, and form. Coin­
cidence of floodwater passage with times of low tempera­
tures (during periods of snow melt, for example) may have
considerable morphological significance on rivers with
vulnerable bank and bed materials.

The climatic variables may be conceived as inter­
acting with the preexisting channel environment to produce
the characteristic scour and fill regime of the river.
Over the decades, climatic changes may be expressed by
aggradation, degradation, or simply by a change in channel
form.

It has been demonstrated by Leopold et al. (1964,
pp. 227-241), Morisawa (1968, pp. 61-64 and pp. 115-118),
and others that at a given discharge there are important
differences in channel dimensions, velocity of flow,
sediment load, and elevation of the bed of a river between
waxing and waning discharges. It therefore seems probable
that any climatic change which would change the relative
duration (or rate) of waxing to waning phases of flow
would have important effects on channel morphology. Such
a transformation might affect the relative rates of scour
and fill, producing aggradation or degradation, or it
could conceivably result in changing channel form without
effecting changes in level.
So large a number of interrelated variables would be involved that a given climatic change might well be expressed differently by different rivers. It is hardly surprising that there is disagreement concerning the response of a channel to discharge changes, as Morisawa (1968, p. 116) observed. Every river channel is unique, so that broad generalizations not based on the whole spectrum of independent variables have little meaning.

As in the cases of all landforms, the factor of time must be included as an independent variable. Given that a channel has achieved morphological stability, any change in value of one or more of the independent variables that act as controls on channel form should result in a response. Ideally, such a response should be expressed as a time series regression equation, linking it to the controlling variable or variables.

Finally, preexisting morphology (usually in the form of an early river survey) is necessary to express channel changes quantitatively through time.

The goal is a comprehensive equation for channel form such as Werner (1951) attempted. Although his result is not realistic for natural channels, as noted by Leopold and Wolman (1960, p. 785), this shortcoming is probably due to the lack of an adequate theoretical concept for meandering. The empirical approach suggested herein should produce results fully applicable to natural channels inasmuch as it would be largely drawn from them. The form
of the equations derived in the process should shed considerable light on the fundamental mechanisms involved in meandering.

**Gauge-Discharge Analysis**

On the main stem of Red River between Fulton and Moncla (figure 1), only two sections have long and continuous records of daily stage and discharge. Shreveport has complete records for every year beginning with 1929, and measures at Alexandria extend back to 1928. Data from other stations in the study area are either incomplete or of insufficient length to be suitable for time series analysis.

Because of the variable nature of the gauge-discharge relation at both stations, special procedures are used to insure the accuracy of published daily discharge values. Field observations of discharge form a basis on which loop curves may be defined (U. S. Geological Survey and Louisiana Department of Highways, 1964, p. 59 and p. 117). Published discharge data are based, not on a rigid rating curve, but on a flexible system designed to offset the effects of shifts in the rating.

Discharge measurements by field personnel of the U. S. Army Corps of Engineers are made approximately once a week. These observations are the basic data from which a mean annual rating curve is computed at the end of each calendar year. The curve is used as the basis for
calculation of daily discharge from daily gauge elevation.

This procedure has resulted in a high degree of accuracy. Testing indicates that deviation of daily computed discharge from actual discharge does not exceed 1-2 per cent. In no instance should computed discharge be in error by more than 5 per cent.

Discharge units of the equations of this report are thousands of cubic feet per second. Gauge zero is the mean low water of 1935-1967, which was used as a base level in pilot studies. This does not conform to the zero of the gauge as it is defined in published gauge reports. To convert the gauge values of this report to mean sea level, add 135.83 feet for Shreveport or 44.63 feet for Alexandria.

Because the objective is to investigate long-term changes, it is convenient to convert daily values into mean annual values. The gauge and discharge values of the following equations were obtained by summing the daily gauge elevation (discharge) and dividing the total by the number of days in that year.

To test the possibility that discharge at Shreveport and Alexandria may have changed through time, three hypotheses were tested:

1. \( \bar{Q} = A_0 + A_1T \)
2. \( \bar{Q} = A_0 + A_1T + A_2T^2 \)
3. \( \bar{Q} = A_0 + A_1T + A_2T^2 + A_3T^3 \).

In these equations, \( \bar{Q} \) is the mean annual discharge, \( T \) is
the calendar year minus 1948, and the remaining values are constants derived by the method of least squares.

Transformation of the calendar year as indicated will be followed throughout this report. This procedure eases calculation burdens and also produces coefficients that are simple. The time variable for 1947 under this system is minus one, 1948 is zero, 1949 is plus one.

The results (table 5) show that the morphological changes demonstrated on the Red River cannot be accounted for by discharge. In all cases low values of the coefficient of determination lead to rejection of the hypothesis. Red River discharge has remained essentially constant over the four decades of record.

The same method may be used to test the hypothesis that valley slope has changed. An increase or decrease in slope through time should be reflected in the gauge readings in the study area. As before, time is conceived as the independent variable for each station, and gauge is the dependent variable. Three hypotheses were tested:

1. \( \bar{G} = B_0 + B_1T \)
2. \( \bar{G} = B_0 + B_1T + B_2T^2 \)
3. \( \bar{G} = B_0 + B_1T + B_2T^2 + B_3T^3 \).

Here \( \bar{G} \) is the mean annual gauge reading, \( T \) is defined as before, and the other terms are the least square constants. The results are presented in table 6.

Inspection of the determination coefficients is
TABLE 5
LEAST SQUARE REGRESSION CURVES, DISCHARGE ON TIME, SHREVEPORT (1929-1967) AND ALEXANDRIA (1928-1967)

<table>
<thead>
<tr>
<th>Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{Q}_s = 27.9355 - 0.0321, T$</td>
<td>0.1078</td>
</tr>
<tr>
<td>$\bar{Q}_s = 27.9355 - 0.1603, T - 0.0321, T^2$</td>
<td>0.1344</td>
</tr>
<tr>
<td>$\bar{Q}_s = 27.9355 - 0.0653, T - 0.0321, T^2 - 0.0004, T^3$</td>
<td>0.1361</td>
</tr>
<tr>
<td>$\bar{Q}_a = 35.5406 - 0.0391, T$</td>
<td>0.1209</td>
</tr>
<tr>
<td>$\bar{Q}_a = 35.7067 - 0.2236, T - 0.0412, T^2$</td>
<td>0.1573</td>
</tr>
<tr>
<td>$\bar{Q}_a = 35.7492 - 0.1388, T - 0.0417, T^2 - 0.0004, T^3$</td>
<td>0.1583</td>
</tr>
</tbody>
</table>

Note: R² is the coefficient of determination, $\bar{Q}_s$ is the mean annual discharge at Shreveport, $\bar{Q}_a$ is the mean annual discharge at Alexandria, and T is the calendar year minus 1948. Discharges are in thousands of cusecs.

sufficient to reject the hypothesis of changing gauge readings at Shreveport. It is interesting, nevertheless, that at least 24 per cent of the variation is explained by the hypothesis in the case of Alexandria. Although such a low value for the coefficient of determination cannot be accepted as indicating a significant correlation, it is sufficient to justify further investigation.

Inasmuch as it is reasonable to expect that most of the variation of the gauge value is due to discharge differences, it is useful to define the nature of the gauge-discharge relation for both stations. This may be
TABLE 6
LEAST SQUARE REGRESSION CURVES, GAUGE ON TIME, SHREVEPORT (1929-1967) AND ALEXANDRIA (1928-1967)

<table>
<thead>
<tr>
<th>Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{G}_s = 6.3477 - 0.0309 T )</td>
<td>0.0232</td>
</tr>
<tr>
<td>( \bar{G}_s = 6.6648 - 0.0025 T - 0.0002 T^2 )</td>
<td>0.0386</td>
</tr>
<tr>
<td>( \bar{G}_s = 6.6648 + 0.0516 T - 0.0025 T^2 - 0.0004 T^3 )</td>
<td>0.0699</td>
</tr>
<tr>
<td>( \bar{G}_a = 10.6246 - 0.1868 T )</td>
<td>0.2432</td>
</tr>
<tr>
<td>( \bar{G}_a = 11.9057 - 0.1964 T - 0.0096 T^2 )</td>
<td>0.3121</td>
</tr>
<tr>
<td>( \bar{G}_a = 11.9139 - 0.1799 T - 0.0097 T^2 - 0.00007 T^3 )</td>
<td>0.3125</td>
</tr>
</tbody>
</table>

Note: \( R^2 \) is the coefficient of determination, \( \bar{G}_s \) is the mean annual gauge at Shreveport, \( \bar{G}_a \) is the mean annual gauge at Alexandria, and \( T \) is the calendar year minus 1948. Gauge datum is the mean low water of 1935-1967 for each station.

done most simply by analysis of the following regression equations:

1. \( \bar{G} = C_0 + C_1 \bar{Q} \)
2. \( \bar{G} = C_0 + C_1 \bar{Q} + C_2 \bar{Q}^2 \)
3. \( \bar{G} = C_0 + C_1 \bar{Q} + C_2 \bar{Q}^2 + C_3 \bar{Q}^3 \)

\( \bar{G} \) is the mean annual gauge reading, \( \bar{Q} \) is the mean annual discharge, and the other terms are the appropriate constants.

The resulting data (table 7) show excellent correlation of gauge elevation with discharge. Despite the variability of the gauge-discharge relation for individual
TABLE 7
LEAST SQUARE REGRESSION CURVES, GAUGE ON
DISCHARGE, SHREVEPORT (1929-1967)
AND ALEXANDRIA (1928-1967)

<table>
<thead>
<tr>
<th>Equation</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{G}_s = 1.8226 + 0.1896 \tilde{Q}$</td>
<td>0.8476</td>
</tr>
<tr>
<td>$\tilde{G}_s = 0.3285 + 0.3146 \tilde{Q} - 0.0021 \tilde{Q}^2$</td>
<td>0.8705</td>
</tr>
<tr>
<td>$\tilde{G}_s = -0.1718 + 0.3831 \tilde{Q} - 0.0048 \tilde{Q}^2 + 0.00003 \tilde{Q}^3$</td>
<td>0.8710</td>
</tr>
<tr>
<td>$\tilde{G}_a = 1.7646 + 0.2953 \tilde{Q}$</td>
<td>0.8217</td>
</tr>
<tr>
<td>$\tilde{G}_a = -2.0313 + 0.5497 \tilde{Q} - 0.0036 \tilde{Q}^2$</td>
<td>0.8638</td>
</tr>
<tr>
<td>$\tilde{G}_a = -3.4378 + 0.7045 \tilde{Q} - 0.0084 \tilde{Q}^2 + 0.00004 \tilde{Q}^3$</td>
<td>0.8650</td>
</tr>
</tbody>
</table>

Note: $\tilde{Q}$ refers to the mean annual discharge for the station indicated by the subscript. See tables 3 and 4 for an explanation of the symbols.

observations, the mean gauge height for the year closely reflects mean discharge for that year. Inspection of the coefficients of determination for the hypotheses shows the following: (1) the data fit best at Shreveport, but the difference is not significant; (2) the linear hypotheses are acceptable because the increased determination coefficients are not significant.

If the mean discharge for a given year is known, the equations of table 7 may be used to predict the mean gauge reading. To analyze the behavior of stage through time, it is useful to assume that the river is attempting to
produce the predicted gauge value every year. When the river is "successful" the gauge reading will agree with the solution of the equation. When the actual mean gauge value does not correspond precisely to the predicted value, the river is said to have made an error.

The model may be expressed quantitatively by measuring the error in feet. A gauge reading in excess of that predicted by the equation may be called a positive error. When the gauge value is too small, the error is negative.

This model can be used to show the distribution of error through time at Shreveport by plotting gauge error against the calendar year (figure 7). The data for this station show no consistent upward or downward trend. The only notable effect is a decrease in the variability of the gauge height beginning in the early 1940's. This event appears to correspond in time with the closure of Denison Dam, which took place in October, 1943 (U. S. Geological Survey and Louisiana Department of Highways, 1964, p. 59).

Plotting the same phenomenon for Alexandria shows a different result (figure 8). In this case, no change in variability is evident, but there is a clear-cut downward trend through time.

The implication of this trend is that there has been a progressive change in the mean annual rating curve at Alexandria. This transformation may be illustrated by comparison of the extreme curves of gauge-discharge for
Figure 7. Gauge deviation as time series, Shreveport.
Figure 3. Gauge deviation as time series, Alexandria.
1928 and 1967 (figure 9). The disparity between these curves exceeds what would normally be expected and is interpreted as further evidence of progressive rating change.

To test the hypothesis of changing gauge error at Alexandria, a least square linear equation of the form

$$e = D_0 + D_1T$$

was fit to the data shown in figure 8. In this function, $e$ is the error of the gauge reading in feet, $T$ is the calendar year minus 1948, and the other terms are the constants producing the best fit.

The resulting equation is

$$e = -0.06511 - 0.13023 T . \quad (2)$$

If this time function is realistic, it is evident that the linear gauge on discharge regression equation for Alexandria (table 7) may be improved by the inclusion of equation (2).

The gauge-discharge relation for Alexandria may be written as

$$\bar{q} = 1.7646 + 0.2953 \bar{Q} + e .$$

Simplification results in the regression plane

$$\bar{q} = 1.6995 + 0.2953 \bar{Q} - 0.13023 T . \quad (3)$$
Figure 9. Rating curves of 1928 and 1967, Alexandria.
Before equation (3) may be utilized, it must be tested to determine how closely the theoretical gauge values fit the actual gauge observations.

It is convenient to consider the river as if it is attempting each year to produce a mean gauge height that corresponds to the solution to equation (3). When the river surface level exceeds the computed value, the error is positive. When the mean water level is less than calculated, a negative error results.

To test the realism of the equation, the error for each of the 40 years of record must be tabulated (table 8). For each year, the first column of the table gives the mean observed gauge reading, and the second column shows the value computed from equation (3). The third and fourth columns show, respectively, the error of the river and the square of the error.

Comparison of the observed and predicted gauge readings shows that the equation has considerable accuracy. Manipulation of the data in the table shows that the standard error amounts to 1.01 feet. The square of the standard error is 1.0281, and the variance of the observed gauge is 19.5961. It follows that the coefficient of determination for equation (3) amounts to

\[ R^2 = 0.9475. \]

This is a highly significant improvement over the original determination coefficient for Alexandria (table 7).
### TABLE 8

STANDARD ERROR OF ESTIMATE, GAUGE ON DISCHARGE AND TIME, RED RIVER AT ALEXANDRIA

<table>
<thead>
<tr>
<th>Year</th>
<th>Observed Gauge</th>
<th>Predicted Gauge</th>
<th>Error</th>
<th>Error Squared</th>
</tr>
</thead>
<tbody>
<tr>
<td>1928</td>
<td>12.76</td>
<td>11.81</td>
<td>0.95</td>
<td>0.9025</td>
</tr>
<tr>
<td>1929</td>
<td>14.74</td>
<td>13.12</td>
<td>1.62</td>
<td>2.6244</td>
</tr>
<tr>
<td>1930</td>
<td>14.12</td>
<td>13.17</td>
<td>0.95</td>
<td>0.9025</td>
</tr>
<tr>
<td>1931</td>
<td>9.03</td>
<td>8.93</td>
<td>0.10</td>
<td>0.0100</td>
</tr>
<tr>
<td>1932</td>
<td>13.52</td>
<td>15.89</td>
<td>-2.37</td>
<td>5.6169</td>
</tr>
<tr>
<td>1933</td>
<td>13.61</td>
<td>12.75</td>
<td>0.86</td>
<td>0.7398</td>
</tr>
<tr>
<td>1934</td>
<td>9.05</td>
<td>9.46</td>
<td>-0.41</td>
<td>0.1681</td>
</tr>
<tr>
<td>1935</td>
<td>16.65</td>
<td>16.21</td>
<td>0.44</td>
<td>0.1936</td>
</tr>
<tr>
<td>1936</td>
<td>4.57</td>
<td>6.48</td>
<td>-1.91</td>
<td>3.6481</td>
</tr>
<tr>
<td>1937</td>
<td>11.86</td>
<td>11.25</td>
<td>0.61</td>
<td>0.3721</td>
</tr>
<tr>
<td>1938</td>
<td>14.36</td>
<td>14.70</td>
<td>-0.34</td>
<td>0.1156</td>
</tr>
<tr>
<td>1939</td>
<td>9.33</td>
<td>8.87</td>
<td>0.46</td>
<td>0.2116</td>
</tr>
<tr>
<td>1940</td>
<td>11.74</td>
<td>11.01</td>
<td>0.73</td>
<td>0.5329</td>
</tr>
<tr>
<td>1941</td>
<td>18.57</td>
<td>17.05</td>
<td>1.52</td>
<td>2.3104</td>
</tr>
<tr>
<td>1942</td>
<td>13.98</td>
<td>13.44</td>
<td>0.54</td>
<td>0.2916</td>
</tr>
<tr>
<td>1943</td>
<td>7.67</td>
<td>7.40</td>
<td>0.27</td>
<td>0.0729</td>
</tr>
<tr>
<td>1944</td>
<td>12.45</td>
<td>11.94</td>
<td>0.51</td>
<td>0.2601</td>
</tr>
<tr>
<td>1945</td>
<td>19.85</td>
<td>22.05</td>
<td>-2.20</td>
<td>4.8400</td>
</tr>
<tr>
<td>1946</td>
<td>17.06</td>
<td>18.50</td>
<td>-1.44</td>
<td>2.0736</td>
</tr>
<tr>
<td>1947</td>
<td>11.53</td>
<td>12.58</td>
<td>-1.05</td>
<td>1.025</td>
</tr>
<tr>
<td>1948</td>
<td>9.56</td>
<td>10.68</td>
<td>-1.12</td>
<td>1.2544</td>
</tr>
<tr>
<td>1949</td>
<td>11.96</td>
<td>11.31</td>
<td>0.65</td>
<td>0.4225</td>
</tr>
<tr>
<td>1950</td>
<td>17.45</td>
<td>17.50</td>
<td>-0.05</td>
<td>0.0025</td>
</tr>
<tr>
<td>1951</td>
<td>10.42</td>
<td>9.73</td>
<td>0.69</td>
<td>0.4761</td>
</tr>
<tr>
<td>1952</td>
<td>8.51</td>
<td>7.85</td>
<td>0.66</td>
<td>0.4356</td>
</tr>
<tr>
<td>1953</td>
<td>10.89</td>
<td>11.00</td>
<td>-0.11</td>
<td>0.0121</td>
</tr>
<tr>
<td>1954</td>
<td>5.82</td>
<td>6.23</td>
<td>-0.41</td>
<td>0.1681</td>
</tr>
<tr>
<td>1955</td>
<td>6.68</td>
<td>6.69</td>
<td>-0.01</td>
<td>0.0001</td>
</tr>
<tr>
<td>1956</td>
<td>2.29</td>
<td>3.88</td>
<td>-1.59</td>
<td>2.5281</td>
</tr>
<tr>
<td>1957</td>
<td>16.55</td>
<td>18.25</td>
<td>-1.70</td>
<td>2.8900</td>
</tr>
<tr>
<td>1958</td>
<td>12.01</td>
<td>11.94</td>
<td>0.07</td>
<td>0.0049</td>
</tr>
<tr>
<td>1959</td>
<td>6.73</td>
<td>7.03</td>
<td>-0.30</td>
<td>0.0900</td>
</tr>
<tr>
<td>1960</td>
<td>8.21</td>
<td>8.23</td>
<td>-0.02</td>
<td>0.0004</td>
</tr>
<tr>
<td>1961</td>
<td>11.47</td>
<td>11.20</td>
<td>0.27</td>
<td>0.0729</td>
</tr>
<tr>
<td>1962</td>
<td>9.78</td>
<td>8.62</td>
<td>1.16</td>
<td>1.3456</td>
</tr>
<tr>
<td>1963</td>
<td>2.28</td>
<td>2.49</td>
<td>-0.21</td>
<td>0.0441</td>
</tr>
<tr>
<td>1964</td>
<td>4.15</td>
<td>3.84</td>
<td>0.31</td>
<td>0.0961</td>
</tr>
<tr>
<td>1965</td>
<td>5.02</td>
<td>4.45</td>
<td>0.57</td>
<td>0.3249</td>
</tr>
<tr>
<td>1966</td>
<td>6.71</td>
<td>5.94</td>
<td>0.77</td>
<td>0.5929</td>
</tr>
<tr>
<td>1967</td>
<td>5.78</td>
<td>5.25</td>
<td>0.53</td>
<td>0.2908</td>
</tr>
</tbody>
</table>

**Total** ......................................................... 38.0413

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Transformation of the equation accounts for 95 percent of the variation of the gauge. With a sample size of 40, it can be demonstrated that the coefficient of correlation of the universe lies between 0.929 and 0.990 (Arkin and Colton, 1963, pp. 16-18 and tables 15 and 16). These considerations show that equation (3) is realistic, and it is therefore accepted.

Attempts to fit a similar equation to the data for Shreveport produced an equation that showed no correlation improvement. At Shreveport the mean annual gauge reading is a simple linear function of the discharge.

In the case of Alexandria, if it is given that the discharge is constant, then equation (2) expresses the change in gauge through time. The slope of the line is the first derivative of that function,

\[ \frac{de}{dt} = -0.13023. \]  

(4)

This is the rate of change of stage in feet per year.

Equation (4) demonstrates that for a given discharge the river declines in height at a rate of 0.13 foot annually. Over the 40 years tested, the water surface elevation decreased 5.2 feet.

If long continued, the fall of the gauge at Alexandria would have an important morphological effect on Red River. From a geological perspective, a decline in elevation of 13 feet per century is very significant. Over the decades, there has undoubtedly been a
considerable increase in the valley slope between Shreveport and Alexandria.

The fall of the water level at Alexandria has made obsolete the zero of the gauge at that station, which was defined some decades ago as mean low water. Small discharge values now produce negative gauge readings. Substitution of the mean low water of 1935-1967 for the actual gauge zero datum eliminated the necessity of dealing with imaginary numbers and division by zero in computations.

In the upper portion of the study area the elevation of the river surface is a simple linear function of the discharge. Farther downstream, the height of the water surface becomes a linear function of both discharge and time. The equations that define this relationship are quantitative proof of the degradational hypothesis of Fisk.

Friedkin (1945) has shown that valley slope is one of the fundamental variables controlling meander form. If depth has not changed, equation (1) shows that the result of increasing the gradient of the water surface would be to increase the tractive force exerted on the bottom.

In the absence of quantitative data ranging across several decades, it is not possible to make an assessment of the role of Red River sediment load over the past 130 years. It is known, however, that closure of Denison Dam
in October, 1943, caused drastic changes in sediment concentration in the upper part of the study area. Inasmuch as the data presented in the first chapter of this report show that changes in meander form were actively taking place subsequent to this event, it is imperative to consider in detail the impact of dam closure on these changes.

**Morphological Impact of Dam Closure**

From a hydraulic point of view, the impact of man on the meander morphology of a river cannot be considered as a simple independent variable. Human activities which affect streams are so diverse that they can be expressed quantitatively only in terms of the fundamental variables of meandering. Expansion of agriculture across flood plains might cause important changes in sediment load. Construction of revetments and other control structures of this type changes the local erodibility and flow resistance. Dam construction affects sediment and flow regimes. The end result is modification of the quantities of the independent variables. The diversity of effect is too complex to be categorized as a single distinct variable.

Dam closure on alluvial rivers is an excellent example of this complexity because it causes radical changes in several important variables. The effects pertinent to meander dimensions include the following: (1) deficiency in sediment load and (2) decrease in flow
variability. The former is the more important.

Sediment trapped in the reservoir causes radical decreases in the quantities of bed load and suspended load. The resulting degradation was noted by Lane (1934) and others, and the effect is so pronounced that attempts to devise a method of forecasting the degradation rate are an important aspect of contemporary hydraulic research (see, for example, Komura and Simmons, 1967).

Leopold et al. (1964, pp. 454-457) documented degradation below Denison Dam for the 16-year period following closure (1944-1960). Some 35,000 acre feet of sediment were eroded from a 100-mile reach below the dam. The mean rate of degradation was only 0.1 foot per annum, but in the 10-mile segment immediately below the structure it amounted to 5-7 feet during the 16 years.

Leopold et al. (1964) found that the total quantity of debris eroded from the channel periphery below the reservoir approximated the quantity of coarse material that had been lost by deposition. Some 77 million tons of sand accumulated in the reservoir (estimated to be about one-fifth of the total retained sediment), and this loss was compensated by erosion of an estimated 67 million tons of sediment downstream.

Other sources (U. S. Army Corps of Engineers, undated memorandum in files of the New Orleans District) report that sediment deficiencies have increased below Denison Dam with the passage of time. The report may be summarized
as follows: (1) During 1944-1948, mean annual suspended load at Fulton was almost 15 per cent lower than before closure; (2) during 1949-1953, mean annual suspended load at Fulton was nearly 30 percent below normal; (3) during 1954-1961, suspended sediment passing that station was 34 per cent less than before closure.

Leopold et al. (1964, p. 456) report that this downstream transition of sediment deficiency is due to a progressive armoring of the river bed. After the reach immediately downstream from the dam has been armored, the river is forced to regain sediment load farther downstream. With passage of time this condition migrates down the channel.

It may be significant that the file memorandum cited above (U. S. Army Corps of Engineers, no date) observed that only 18 per cent of the sediment in suspension at Fulton was clay in 1954 and that 36 per cent was sand (i.e., material retained by a 0.062-millimeter sieve). Schumm (1967 and 1969) referred to streams in which more than 11 per cent of the total load was sand (defined in his papers as materials retained by a 0.074-millimeter sieve) as bed load channels; he showed that this condition correlated with low sinuosity. Although there is some disparity in the definition of the sand-silt boundary, Schumm's observation is interpreted as evidence that the effects of Denison Dam on the study area are mainly expressed as a deficiency in total load.
The model experiments of Friedkin (1945) included tests with clear water which showed that even a total absence of sediment does not prevent the development of meandering (see, for example, Friedkin's Plate 11). The result observed was rapid erosion, especially of the banks, at the upper end of the channel. Sinuosity rapidly waxed downstream, developing as soon as sufficient load was attained by erosion to permit point bar deposition to commence. Presumably armoring through time would cause the point of sediment sufficiency to migrate downstream.

Paucity of sediment load prevents deposition of point bars, and excessive load culminates in excessive deposition and braiding. It appears likely that the presence of sufficient load for point bar deposition is a critical requirement. Even rivers that do not meander may display transverse oscillation at low water owing to the fact that bed load "collects in bars or shoals which tend to alternate in position along opposite shores" (Matthes, 1941, p. 633).

Laboratory flume studies with initially straight channels (Quraishy, 1944) have confirmed the development of these alternating shoals, which that author called "skew shoals." Continued flow produced continued shoal development, ultimately culminating in a sinuous flow pattern.

It is the opinion of this writer that, if other variables remain constant, there is some optimum sediment
load for production of a stable meander pattern. Within the limits of this optimum load, for a given sediment concentration there correspond a meander pattern and channel geometry that the river must ultimately attain, after which the pattern will remain stable despite downstream translation of individual bends.

Decreased variability of flow subsequent to dam closure has been considered important by some authors. Leopold et al. (1964, pp. 457-458) report that in some instances it has resulted in increased density of bank vegetation, effectively protecting the banks from erosion. The result was a deeper, narrower, and more sinuous channel. The present writer believed that this characteristic is probably confined to arid or semiarid regions and is not important in humid regions.

Matthes (1941) considered the magnitude and duration of discharge changes so critical that he defined his discharge variable in terms of variability. Inglis (1947, p. 7) believed that "meandering is essentially the outcome of varying flow conditions."

The latter conclusion is contrary to the available evidence (Leliavsky, 1966, p. 144). Laboratory investigations of Friedkin (1945) have demonstrated the fallacy of this generalization by producing meandering patterns in an initially straight channel under constant conditions of discharge, sediment concentration, valley slope, and other variables.
Variability of flow conditions alone is not a tenable hypothesis for the origin of meanders. The predominating processes on an alluvial river at a given time depend largely on the magnitude of the discharge being transmitted at that time. Russell (1958, p. 10) observed that flood discharges straighten the thread of maximum velocity, causing it to migrate from the vicinity of the cut bank to the point bar side of the river. Although it is true that initially this activity is a result of a steepening of slope resulting from downstream advance of the forward edge of the flood wave, the condition is maintained at high water because the meander dimensions are too small for the natural transverse oscillations of the enlarged mass of water.

This shows that the dimensions of the meanders and the meandering channel are not formed in response to the flood activity of the stream because at flood the equilibrium between meander form and the oscillating motion of the flowing water breaks down. Likewise, the relations between low water flow and channel morphology cannot be explained in terms of cause and effect. As Russell (1958, p. 10) observed,

If kept at low stage indefinitely, a river would continue to flow along whatever channel it happened to inherit, without ability to scour pools, build bars, or change its channel section appreciably.

It is evident that the form of a meandering channel is not the product of the extremes of flow.
Meander dimensions show a close correlation with mean discharge, as Schumm (1967 and 1969) has shown, and there appears to be no reason to believe that mean discharge is not a valid estimate of effective discharge. It is concluded that the impact of decreased variability of discharge is not significant compared to the effects that would follow any marked change in mean discharge and that the morphological consequences of dam construction in this case lie principally in the changes resulting from deficiency in total sediment load.

The rate of degradation appears to be a function of the degree of sediment deficiency; therefore, one result of the construction of Denison Dam has been a decrease in valley slope, which probably now extends some distance below Fulton. Although degradation may be taking place at Fulton, time series analysis has shown that the elevation of the water surface of the river has remained stable at Shreveport (figure 7). Thus flattening of the valley slope is restricted to the study area above Shreveport.

Friedkin (1945) correlated decreased valley slope with decreased sinuosity. Comparison of individual bends in the Fulton-Shreveport reach shows that this trend was not obvious in that locality until after 1938 (figure 3). It is therefore not clear whether channel straightening of this segment is a result of dam closure, upstream migration of some of the hydraulic tendencies prevalent
below Shreveport, or both.

The Fulton-Shreveport and Alexandria-Moncla reaches lack sufficient data for rigorous analysis of the valley slope variable; in each case one station fails to have records of adequate duration (Fulton and Moncla).

The Shreveport-Alexandria reach offers the best opportunity for correlation of hydraulic variables and meander morphology. Here the evidence of changing valley slope is clear-cut, and the equation derived previously permits quantification of hydraulic and valley slopes.

**Critical Variables of the Changing Red River**

Changing meander form has been expressed for the whole study area in terms of changes in mean meander dimensions. This approach was advantageous because these measures could be used for a statistical demonstration of the significance of the pattern transformations. However, for the purpose of correlation with the pertinent independent hydraulic variables, it is considerably more convenient to reduce the number of dependent variables to a single variable.

The ideal meandering variable should be simple to measure. It should be dimensionless so that rivers of different sizes can be compared. It should be sufficiently flexible to be utilized on any single-channel stream, regardless of meander symmetry. Finally, the variable must rigorously express the intensity of meandering.
Sinuosity satisfies all these requirements. It may be defined for any river segment as

\[ S = \frac{L_r}{L_v}, \]  

(5)

where \( S \) is the sinuosity, \( L_r \) is the length of the segment measured along the midchannel of the river, and \( L_v \) is the length of the segment measured along the axis of the river valley.

Sinuosity also relates the slope of the valley to the slope of the water surface. Should the river flow directly down the axis of the valley, river mileage would equal valley mileage and water surface slope would equal valley slope. Thus sinuosity has a minimum value of unity. As the tortuosity of the meanders increases, the disparity between river mileage and valley mileage (and also the disparity between valley slope and water surface slope) increases.

Thus sinuosity may also be defined as

\[ S = \frac{M_v}{M}, \]  

(6)

where \( M_v \) is the slope of the valley and \( M \) is the water surface slope.

Previous measurements may be used to summarize several segments of Red River (table 9). Inspection of sinuosity values of each segment for 1938 and 1957 shows that all segments reflect the general decline in tortu-
osity. The rate of decrease during this interval was least on the Alexandria-Moncla reach, where it declined so slowly that the Shreveport-Alexandria reach exceeded it in straightness by 1957. In general, however, sinuosity decreases downstream.

TABLE 9
SINUOSITY OF CHANNEL SEGMENTS, RED RIVER SURVEYS OF 1938 AND 1957

<table>
<thead>
<tr>
<th>Valley River Miles</th>
<th>Sinuosity 1938</th>
<th>Sinuosity 1957</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fulton-Shreveport</td>
<td>76 152.6 127.9</td>
<td>2.008 1.683</td>
</tr>
<tr>
<td>Shreveport-Grand Ecore</td>
<td>63 103.9 95.5</td>
<td>1.649 1.516</td>
</tr>
<tr>
<td>Grand Ecore-Alexandria</td>
<td>52 84.8 78.2</td>
<td>1.631 1.504</td>
</tr>
<tr>
<td>Alexandria-Moncla</td>
<td>25 39.8 38.2</td>
<td>1.592 1.528</td>
</tr>
<tr>
<td>Total</td>
<td>216 381.1 339.8</td>
<td>... ...</td>
</tr>
</tbody>
</table>

The overall sinuosity value of $S_{1938} = 1.764$ declined over the two decades between the surveys to $S_{1957} = 1.573$. Although the 1835-1838 channel survey was confined to the upstream end of the study area, that sample extended over 105.5 valley miles and 234.7 miles of continuous channel. The sinuosity was $S_{1838} = 2.225$, a considerably higher figure than the twentieth century values. Thus the available sinuosity measures reflect the changes documented previously.

During 1938 and 1957 (table 9) absolute decreases
in tortuosity have been most rapid toward the upstream end of the study area. From table 9 percentage decreases in sinuosity were calculated for each river segment (table 10).

### TABLE 10

PERCENTAGE DECREASE IN SINUOSITY OF RED RIVER REACHES, 1938-1957

<table>
<thead>
<tr>
<th>Segment</th>
<th>Percentage Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fulton-Shreveport</td>
<td>19</td>
</tr>
<tr>
<td>Shreveport-Grand Ecore</td>
<td>8</td>
</tr>
<tr>
<td>Grand Ecore-Alexandria</td>
<td>8</td>
</tr>
<tr>
<td>Alexandria-Moncla</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 10 also shows that maximum rates of channel straightening have been restricted to the northern portion of the river. Mean sinuosity decrease between Fulton and Shreveport over this period amounted to 1 per cent per annum, a value considerably greater than is evident southward.

Because the remnant channel of 1835-1838 has 72 per cent of its valley mileage within the Fulton-Shreveport reach, it is comparable to that segment. The total sinuosity decline there during 1838-1938 amounted to only 10 per cent, a rate of 0.1 per cent per annum. The rate after 1938 was 10 times greater than this; it is evident that the rate of channel straightening has greatly
accelerated in recent decades.

The 8 per cent sinuosity decline between Shreveport and Alexandria took place in 20 years, during which the valley slope of that reach was actively increasing. Because the available data do not suggest significant change in other variables here, the relation between valley slope and sinuosity is taken to be an example of cause and effect.

The critical variable is the rate of fall of the gauge level at Alexandria. Although it was documented only for the 40-year period 1928-1967, Fisk discerned physiographic evidence of this phenomenon as early as 1935-1937, indicating that it must already have been in progress. Presumably the decline of water level at that station is still occurring.

The usual geological interpretation would postulate river entrenchment at Alexandria resulting from some event which lowered base level. Thus Fisk correlated the onset of entrenchment with diversion into the present channel segment from Echo to Moncla. Steepening of the gradient below Echo lowered base level for all stations along the Red River, the effect being transmitted upstream as a knickpoint. The decline of the water surface as measured at Alexandria appears to indicate that the knickpoint has passed that point, whereas the stability of the Shreveport gauge suggests that it is still in the process of migrating toward that station.
Powell (1875, p. 203) originally defined base level as a limiting datum for erosion by running water. In his original definition he envisioned base levels as being controlled by the level of the sea, the elevations of the beds of trunk streams, or the elevations of resistant rock layers across stream channels. In reality, his conception of base level was a surface composed of valley slopes. Powell indicated this in the following explanation:

What I have called base level would, in fact, be an imaginary surface, inclining slightly in all its parts toward the lower end of the principal stream draining the area through which the level is supposed to extend, or having the inclination of its parts varied in direction as determined by tributary streams.

Thus base level was defined as a surface composed of one or more minimum valley slopes, and the elevation of the surface was regarded as a function of the elevation of the lower end of the stream, or stream segment.

Powell referred to sea level as the "grand base level, below which the dry lands cannot be eroded." In addition, there are local and temporary base levels determined by "the levels of the beds of the principal streams which carry away the products of erosion."

For the purposes of this paper it is necessary to modify this traditional conception into a form that is amenable to precise measurement. The difficulty is that the limiting depth of erosion of any large alluvial river is only partially controlled by the level of the sea or master stream. Other variables play an important role.
The mean elevation of the bed of a river is a function of the combination of hydraulic variables peculiar to that stream. In a given river segment, the bed height of the downstream end of the channel may not exert significant control on depths encountered some distance upstream. Depending on the local variables, portions of the segment may be broad and shoal or relatively deep and narrow. The limiting depth of erosion at any river cross section depends on the specific hydraulic environment of that section; scour pools and inflection points (or pools and riffles) produce maximum and minimum depths, respectively.

Although mean channel thalweg elevation could be used as a mean local base level for erosion, extensive hydrographic surveys conducted over a wide range of flow conditions would be necessary to estimate such a datum accurately. Furthermore, detection of long-term changes in base level would require the existence of such surveys over several decades at frequent intervals. It is doubtful that such comprehensive measures are available over any sizeable river segment anywhere.

Even if such data were obtainable, the mean channel thalweg elevation would usually have only extremely localized value as a mean erosional base level. Inasmuch as accordance of bed levels between tributaries and the master stream at points of conjunction is not inevitable, such a base level might well have meaning only for the main river channel.
From the standpoint of fluvial dynamics, a more fundamental level is mean water surface elevation. Processes on a given river reach are to a degree controlled by the water surface elevation of the downstream end of the river segment. To distinguish the resulting datum from the base level of Powell (1875), the term hydraulic base level will be used in this paper.

Two aspects of this distinction are notable. First, lowering of the mean water surface level of the downstream end of a reach lowers the hydraulic base level of the river segment. To the master stream and its tributaries it does not matter whether the channel bottom has degraded, because they are nonetheless obliged to degrade their water surface levels toward the hydraulic base level. This phenomenon will be referred to as hydraulic degradation to distinguish it from the usage of the geologist.

Secondly, the accomplishment of this hydraulic degradation does not necessarily imply geological degradation. The river may lower its water surface by widening and shoaling its cross section. For instance, the level of the water surface of Red River at Alexandria is known to be lower than previously, but it is not known whether this is the result of degradation of the river bed, change in width-depth ratio, or both.

The valley slope most relevant to the hydraulics of a river segment is not the slope of the surface of the
alluvium, which is usually given in geological investigations, but rather is the slope determined by the actual height of the water surface at each end of the reach. Slopes measured along natural levees may be relics of conditions that no longer control the form of the channel.

The water surface slope is a function of the valley slope and the sinuosity, as shown by equation (6). The fundamental importance of water surface slope is illustrated by equation (1), the tractive force equation. Like valley slope, the slope of the river surface is simple to calculate when gauge elevations are known.

The accumulation of gauge and discharge data on major streams over several decades, especially when combined with frequent discharge measurements by field parties, presents a unique opportunity for geomorphological analysis. Owing to the great quantity of field data currently being collected by agencies such as the U. S. Army Corps of Engineers, the U. S. Geological Survey, and others, investigations of unprecedented exactitude into the behavior of natural streams will be possible in the near future. At present, a particularly promising approach includes regression studies of the relation between valley slope and sinuosity, or water surface slope.

**Changing Hydraulic Slopes, Shreveport-Alexandria**

In cases where all variables other than slope have remained constant, it is not unreasonable to conceive of
meandering as a slope adjustment phenomenon. The definition of sinuosity, as given in equation (6), illustrates this succinctly.

It is necessary to begin with a precise definition of the variables. The hydraulic elements pertinent to valley and water surface slopes across a reach are the water surface elevations at either end of the segment. In this paper the mean annual gauge level is defined as the gauge elevation which corresponds to the mean annual discharge.

During 1929-1967 the mean annual discharge at Shreveport was 23.86 thousand cusecs. Using this sample mean as an estimate for the population, gauge height in feet above the mean low water of 1935-1967 may be calculated by solving the linear gauge on discharge equation for Shreveport (table 7). Addition of the mean low water elevation (135.83 feet above mean sea level) results in the value \( G_s = 142.18 \) feet, the mean annual gauge for Shreveport.

During 1928-1967 the mean annual discharge at Alexandria was 30.32 thousand cusecs, whereas the survey years of 1938 and 1957 correspond to \( T \) values of -10 and 9, respectively. Solving equation (3) for these quantities and adding the mean low water elevation (44.63 feet) shows that \( G_a(38) = 56.59 \) feet was the gauge elevation for Alexandria in 1938, but the 1957 value declined to
\(G_{a(\gamma)} = 54.11\) feet. Thus the gauge elevation of the water surface for mean discharge at Alexandria declined 2.48 feet over the two decades between the surveys.

Mean head is defined in this paper as the difference between water surface elevations at each end of the river segment during periods of mean discharge. Thus, in 1938 the mean head between Shreveport and Alexandria was
\[
G_s - G_{a(38)} = 142.18\text{ feet} - 56.59\text{ feet}, \quad \text{or} \quad H_{1938} = 85.59\text{ feet},
\]
where \(H\) is the mean head for the year of subscript.

Using the same method, \(H_{1957} = 88.07\) feet. It is now possible to compute valley slope for both years of survey.

Mean valley slope may be defined as the mean head divided by valley length. It may be written
\[
M_v = \frac{\bar{H}}{L_v}, \quad (7)
\]
where \(M_v\) is the mean valley slope in feet per mile, \(\bar{H}\) is mean head in feet, and \(L_v\) is valley mileage. Valley mileage values from table 9 may be used to find mean valley slope (table 11).

Equation (2) shows that the deviation of gauge height at Alexandria is a linear function of time. Considerations that follow from equations (3) and (7) indicate that valley slope is also a linear function of time, given that discharge and valley mileage have remained constant.

Thus a linear relation exists between an independent
time variable and a dependent mean valley slope variable. This function may be defined as the line uniting the points \((T, \bar{M}_v)\), the variables being defined as before. The surveys of 1938 and 1957 (table 11) provide two points on that line, namely \((-10, 0.74427)\) and \((9, 0.76579)\). Substitution of these values in the function \(\bar{M}_v = E_0 + E_1 T\), where \(E_0\) and \(E_1\) are constants, will produce the desired results. Thus mean valley slope in feet per mile is

\[
\bar{M}_v = 0.755596 + 0.0011326 T .
\]  

This function gives quantitative expression to the increase in valley slope through time, consequent to the decline of the gauge at Alexandria.

While valley slope increased across the Shreveport-Alexandria reach, sinuosity declined. Equation (6) shows that sinuosity is the ratio of valley slope to water surface slope.

Changes in meander intensity produce changes in the slope of the water surface. Given a constant valley slope,
an increase in sinuosity would flatten the slope of the water; a decrease in sinuosity would steepen that slope. On the reach under consideration, steepening of the valley slope coincided with channel straightening, resulting in a great increase in the water surface slope.

Mean water surface slope may be defined as

\[ \bar{M} = \frac{H}{L_r} \]  

where \( \bar{M} \) is the hydraulic slope, \( H \) is mean head, and \( L_r \) is river mileage (from table 9). The results for the survey years of 1938 and 1957 are given in table 12.

**TABLE 12**

WATER SURFACE SLOPE, SHREVEPORT-ALEXANDRIA REACH OF RED RIVER

<table>
<thead>
<tr>
<th>Year of Survey</th>
<th>Feet per Mile</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>1938</td>
<td>0.45358</td>
<td>0.000086</td>
</tr>
<tr>
<td>1957</td>
<td>0.50700</td>
<td>0.000096</td>
</tr>
</tbody>
</table>

Comparison of the data of tables 11 and 12 reveals a remarkable contrast in the rate of change of slope. During the 19 years between the surveys, valley slope increased less than 3 per cent, whereas the slope of the water surface increased almost 12 per cent. In view of the drastic rate of increase of the hydraulic slope, it is hardly surprising that fundamental changes in the fluvial dynamics.
of the river are taking place.

**Sinuosity and Valley Slope**

Based on his model investigations, Friedkin (1945, Plate 16) correlated increasing valley slope with waxing sinuosity. The present writer believes that this result is due to a tendency for the model rivers to retain some approximation of the original water surface slope by increasing tortuosity.

The reaction of Red River to increasing valley slope is in contradiction to the conclusions of Friedkin (1945). It is possible that this disparity resulted from the vast differences in scale between Red River and the laboratory model stream. Mean discharge of Red River at Alexandria is 200,000 times the maximum discharge of the model, and the laboratory valley slopes were some 40 times steeper than the Shreveport-Alexandria valley slope. However, there are striking parallels between the behavior of Red River and the results attained in some model tests.

Although the valley slope-sinuosity curve of Friedkin (1945) shows a positive correlation, the function is not linear (figure 10). It is significant that the curve is concave downward, so that the rate of sinuosity increase declines markedly toward the upper end of the curve.

The morphology of Friedkin's curve suggests the existence of an upper limit for sinuosity. Furthermore, there is experimental confirmation for the conclusion
Figure 10. Valley slope-sinuosity (Friedkin, 1945).
that, should valley slope increase beyond some critical value, sinuosity will begin to decline.

Although the latter was not plotted on his formal curve (figure 10), Friedkin (1945, p. 14) alluded to this situation in his text. After noting that "increasing the velocities by increasing the slope resulted in increasing the size of bends," he added:

The more rapid the rate of bank erosion, the shallower were the cross sections. Thus the tendency to increase velocities by increasing the slope was opposed by the decrease in hydraulic radius which tended to reduce velocities. The effects of shallowing of cross sections with increase in discharge or slope are indicated by the flattening of the curves showing relationship between discharge and slope, and width of bends . . . . The end point of this tendency and counter tendency is an extremely wide and shallow stream which does not erode its banks and does not meander. This resulting condition occurred in several tests and is found in natural rivers in wide shoaled reaches and in braided rivers. (Emphasis added.)

This condition had previously been suggested by Matthes (1941, p. 633):

If a river flowing in an erodable [sic] channel could coordinate velocity with bed-resistance by simply adjusting its width, then, theoretically it could maintain a straight, but wide and shallow, channel down the axis of the valley. The hydraulic gradients would then equal the valley-slope and its bed-load would travel over the full width of a very flat bed. Extraordinary as such a condition would be, it is in rare instances met with in nature in a small way, as for instance in channels descending debris cones and alluvial fans. Such channels, however, are unstable and usually short-lived.

It is possible that the results outlined by Friedkin were omitted from his formal graph because they were then believed to be "extraordinary" and "rare."
There is also theoretical justification for this concept of sinuosity. Given that other variables remain constant, then meandering is a slope adjustment phenomenon: the increase of sinuosity with the onset of waxing valley slope maintains a water surface slope of equilibrium. As long as that equilibrium slope may be approximated, the tractive force equation shows that shear will remain nearly constant (equation (1)).

Once the equilibrium is destroyed (by cutoffs on natural rivers), the precipitous increase of hydraulic slope increases tractive force toward the point of channel destruction. In the face of channel straightening aggravated by continuing increases in valley slope, the equilibrium between the tractive force exerted by the flowing water and the erosional resistance of the channel perimeter may be maintained only by shoaling (equation (1)).

Although it is not presently possible to draw the entire curve of valley slope-sinuosity, some aspects of its morphology appear evident (figure 11). Once channel straightening resulting from steep valley slope approximates the minimum sinuosity of unity, no further straightening may occur. Hence the right limb of the curve is the line

\[ S = 1 \] (approximately).

If the scale of Friedkin's model does not preclude comparison with natural rivers, then his graph (figure 10) is acceptable as an approximation of the left limb. Mathé-
Mathematical analysis of Friedkin's curve shows that it fits the parabola

\[ S = -0.38 + 363.3 m - 20,000 m^2, \]

where \( m \) is the dimensionless slope of the valley. Derivative analysis shows that this plot of points \((m, S)\) has a sinuosity maximum at \((0.009, 1.27)\), which is where Friedkin (1945) ended the curve.

A sinuosity of 1.27 is too small to be comparable to the sinuosities of natural meandering rivers. This disparity may have resulted from the unique dimensions of the model. If so, then the points that compose the valley slope-sinuosity curve of a stream of given hydraulic dimensions may be different from the points for other streams of differing dimensions. It is therefore tentatively concluded that the universal plot of valley slope-sinuosity is a family of curves.

The region of the curve between the positive slope left limb and the linear right limb is exemplified by Red River. Because the exact morphology of this portion of the curve is not known, it is shown by dashed lines (figure 11). Model experiments and the future behavior of Red River (or another natural stream) may clarify the nature of the valley slope-sinuosity function in the future.

If the left limb and central portion of the curve is not a parabola of the form...
\[ S = F_0 + F_1 M_v + F_2 M_v^2, \]  
(10)

where \( F_0 \), \( F_1 \), and \( F_2 \) are constants that give the curve a downward concavity, then it must be a curve with some of the characteristics of such a parabola.

**Future Pattern Changes, Shreveport-Alexandria**

Because the precise form of the negative slope part of the curve is unknown, only the simplest assumptions are justifiable. Calculations of the changes in valley slope and water surface slope during 1938-1957 have shown that water surface slope across this reach has been waxing at a greater rate than valley slope. The simplest possible assumption is that there is a linear relationship between valley slope and water surface slope, or that the actual relationship will be very closely approximated by a linear function.

Analysis of alternative possibilities indicates that this procedure should yield a conservative estimate of the probable increase in hydraulic slope. Because the waxing of valley slope appears to be linear through time, the adjustment of the river could take the following forms: (1) sinuosity can decline in a linear fashion; (2) sinuosity can decrease in a parabolic fashion, as suggested by Fried-kin's curve; (3) the valley slope-sinuosity curve may be neither linear nor parabolic, but may be a more complex function. The last possibility cannot be rejected because the exact mathematical form of the response is unknown.
However, the simpler hypotheses are preferable.

If sinuosity declines in a linear fashion beyond the point of maximum sinuosity, it would have the form

$$ S = G_0 + G_1 M_v, $$

where $G_0$ and $G_1$ are constants that give the line a negative slope. Substitution of this value in equation (6) shows that

$$ M = \frac{M_v}{G_0 + G_1 M_v} $$

expresses water surface slope as a function of valley slope.

Since this linear sinuosity equation must have a negative slope, the constant $G_1$ is negative. Hence the denominator will decrease in value through time, as the numerator increases. It follows that the rate of increase of the water surface slope would exceed the prediction of a simple linear function.

If the parabolic form of equation (10) is the real form of the valley slope-sinuosity curve, then the equation would be

$$ M = \frac{M_v}{F_0 + F_1 M_v + F_2 M_v^2}. $$

As before, the numerator will increase in a linear manner through time, and the denominator will be decreasing at a progressively faster rate. Thus, if either hypothesis is
correct, the river surface slope \( M \) will increase at a greater than linear rate.

It should be borne in mind that the linear assumption of the following calculation will tend to underestimate the increase of water surface slope if the valley slope-sinuosity curve is a simple linear or parabolic function. The amount of error will be negligible, however, if the extrapolation is not projected excessively.

The linear hypothesis states that the relation between valley slope and water surface slope can be written

\[
M = H_0 + H_1 M_v ,
\]  

(11)

where \( H_0 \) and \( H_1 \) are constants.

The calculated valley slopes and river surface slopes for the survey years 1938 and 1957 (tables 11 and 12) provide the two points, \( M \) and \( M_v \), which determine the line. Simultaneous solution shows that, for the Shreveport-Alexandria river reach, the relation is

\[
M = -1.39395 + 2.48234 M_v .
\]

This may be converted into a time series equation by substituting the time series function of valley slope, equation (8), for \( M_v \). If river surface slope is desired in feet per mile, the resulting function is

\[
M = 0.48170 + 0.0028115 T .
\]

(12)
To complete the first approximation of future pattern changes, mean head must be computed. Mean head, expressed in feet, and river surface slope, in feet per mile, can be utilized to extrapolate river mileage with the equation

\[ L_r = \frac{H}{M}, \]  

(13)

where \( L_r \) is the length of the river in miles. The resulting sinuosity is calculated by dividing the river length, \( L_r \), by the constant valley length of 115 miles. The estimated river dimensions are summarized (table 13).

Table 13 is believed to be a conservative approximation of the expected changes on the Shreveport-Alexandria river segment. Future surveys of the river will confirm the model on which the table is based or will indicate the necessity for a revision. The foregoing considerations suggest, however, that deviations from the predicted hydraulic slope probably will be toward an increased, rather than a decreased, water surface slope.

It is interesting that even the conservative forecast of the table indicated that the water surface slope of the year 2008 will exceed that of 1938 by more than 40 per cent. It is estimated that the current (1970) hydraulic slope is greater than the late nineteenth century slope by at least 70 per cent. By the close of this century the hydraulic slope will exceed the nineteenth century value by nearly 100 per cent. The first derivative of
### TABLE 13

**EXTRAPOLATED RED RIVER DIMENSIONS, SHREVEPORT-ALEXANDRIA, 1938-2008**

<table>
<thead>
<tr>
<th>Year</th>
<th>Water Surface Slope*</th>
<th>Mean Head*</th>
<th>River Miles</th>
<th>Sinuosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1938</td>
<td>0.453580</td>
<td>85.59109</td>
<td>188.70</td>
<td>1.64</td>
</tr>
<tr>
<td>1948</td>
<td>0.481695</td>
<td>86.89336</td>
<td>180.39</td>
<td>1.57</td>
</tr>
<tr>
<td>1958</td>
<td>0.509810</td>
<td>88.19563</td>
<td>173.00</td>
<td>1.50</td>
</tr>
<tr>
<td>1968</td>
<td>0.537925</td>
<td>89.49790</td>
<td>166.38</td>
<td>1.45</td>
</tr>
<tr>
<td>1978</td>
<td>0.566040</td>
<td>90.80017</td>
<td>160.41</td>
<td>1.39</td>
</tr>
<tr>
<td>1988</td>
<td>0.594155</td>
<td>92.10244</td>
<td>155.01</td>
<td>1.35</td>
</tr>
<tr>
<td>1998</td>
<td>0.622270</td>
<td>93.40471</td>
<td>150.10</td>
<td>1.31</td>
</tr>
<tr>
<td>2008</td>
<td>0.650385</td>
<td>94.70698</td>
<td>145.62</td>
<td>1.27</td>
</tr>
</tbody>
</table>

*Water surface slope is in feet per mile, mean head is in feet.*

Equation (12) shows that the rate of water surface slope increase measured during 1938-1957 amounts to 0.28 foot per mile per century.

Because they are based on regression analysis of 40 years of data, the calculated values for mean head are believed to be accurate. Only in the event that the gauge level is artificially stabilized, that the water level decline is arrested by attainment of a limiting minimum slope below that station, or that impingement against a resistant rock unit slows erosion is it considered likely that this 40-year trend will be terminated. As long as the mean gauge level at Alexandria continues to fall, while stages at Shreveport remain stable, progressive changes in river form and dynamics will take place.
The extrapolated river mileage, computed from equation (13), is included because it will provide a ready check on the accuracy of the model in the future. Any marked deviation from the mileage forecast by the table would indicate the necessity of revision. Such comparisons will shed considerable light on the real nature of the relations between the independent variable (valley slope) and the dependent variables (water surface slope and sinuosity).

The computed sinuosity values reflect the continuous channel straightening that may be expected. The measured sinuosity of the river fragment of 1835-1838 was 2.225, a figure considerably greater than the values of the table. In the 1830's, valley slope exceeded the water surface slope by a ratio of 2.225 to 1, despite the fact that the slope of the valley at that time must have been much flatter than at present. Extrapolation of the table clearly shows that the river slope today is rapidly approaching the steepness of the valley.

Leopold et al. (1964, p. 281) have proposed that a sinuosity of 1.5 should be considered a minimum value for a meandering channel. This definition is satisfactory for the purposes of this paper.

Inspection of the table shows that this minimum value was reached in 1958. This date is not an extended extrapolation inasmuch as it was only one year after the survey of 1957. The time at which the river attained the minimum
sinuosity for meandering so closely followed the survey year that it scarcely admits doubt, even if the hypothesis on which the table was calculated should prove to be inexact.

Thus the Shreveport-Alexandria reach of the Red River of today no longer displays a meandering pattern. However, several excellent examples of meander loops may still be observed on the river. These meandering segments are separated by considerable stretches of straight or gently undulating channel. Well-developed meander loops have become the exception rather than the rule.

**Conclusion**

The independent variables of meander dimensions include the following: (1) valley slope, (2) bed load ratio, (3) total load, (4) discharge, (5) resistance to erosion, (6) climate, (7) time, and (8) preexisting morphology.

Comparison of the results of the model studies of Friedkin (1945) with the behavior of Red River has suggested a first approximation of the form of the curve of valley slope-sinuosity (figure 11). It is believed that this is the general form for a family of curves that would describe the behavior of streams of differing hydraulic dimensions. It is hoped that future studies will clarify the quantitative nature of this generalization.
CHAPTER IV

CONTEMPORARY HYDRAULIC REGIME

Introduction

The results of 216 discharge measurements at Alexandria, performed during 1963-1967, were punched on computer cards and subjected to multiple regression analysis. This analysis, still in progress, will eventually be the core of a more detailed investigation of the hydraulics of the river. The results presented in the present study were computed using the General Foods Multiple Regression Package, Revised for S360 from MRP 45/31 for IBM 1620, March, 1968. The program includes an automatic deletion feature which eliminates the least significant variable after each regression step.

Although positive results were obtained, it is important to bear in mind the limitations of the data available for analysis, which include the following:

1. **Bed load.** No measures of bed load were attempted; no practical method for realistic bed load measurement on a large river exists. A solution to this problem would be a major contribution (Leopold et al., 1964, p. 185).

2. **Suspended load.** All sediment measures pre-
sented in this chapter are referred to as suspended load. The values given are the computed means of sediment concentrations sampled along three to five verticals in the cross section, from the surface to the bottom. Although all measurements were conducted in conformity with standard engineering procedures, theoretical considerations suggest that the sediment concentrations measured by such methods do not accurately reflect the static sediment concentration, which is the critical concentration for morphological processes (Leopold et al., 1964, pp. 185-188).

3. Composition of the bottom. Available samples of the composition of the river bed were too few for significant statistical manipulation. They were therefore omitted.

4. Environment of measured cross section. The results obtained by measurements of scour and fill in a single cross section may not typify the scour and fill activity in other environments of the river (Leopold et al., p. 233). The specific environment of the cross section measured is near the upstream end of a straight segment some two and one-half miles in length (Murray Street Bridge, Alexandria). Probably some distortion in cross-sectional geometry has resulted from a revetment located on the right (cut) bank.
The measured channel section is believed to be somewhat deeper and narrower than the average Red River channel.

The site may be described as being located near the upstream end of the scour pool associated with a meander of very slight intensity (long wave length and low sinuosity).

The variables measured, the symbols used in the following pages to represent the variables, and the units of measure are summarized in table 14. Although most of the variables are self-explanatory, the following require special attention:

1. **State of discharge.** This variable is a measure of the mean rate at which discharge was changing during the 48 hours surrounding the time of measurement. These values, computed from published tables of daily discharge, were obtained by averaging the discharge changes recorded for the day preceding and the day following the time of discharge observation. Waxing discharges have positive values, waning discharges are negative, and no change has a value of zero.

2. **State of stage.** This variable is a measure of the mean rate of change of stage per day, based on the 48 hours surrounding the time of discharge observation. The method of computation is the same as that used to calculate the state of
TABLE 14
MEASURED HYDRAULIC VARIABLES, RED RIVER AT ALEXANDRIA, 1963-1967

<table>
<thead>
<tr>
<th>Variable Name*</th>
<th>Unit of Measure</th>
<th>Variable Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge</td>
<td>1000 Cusecs</td>
<td>Q</td>
</tr>
<tr>
<td>Stage</td>
<td>Feet above Gauge Zero</td>
<td>S</td>
</tr>
<tr>
<td>Width</td>
<td>Feet</td>
<td>W</td>
</tr>
<tr>
<td>Maximum Depth</td>
<td>Feet</td>
<td>D</td>
</tr>
<tr>
<td>Cross-Sectional Area</td>
<td>100 Square Feet</td>
<td>A</td>
</tr>
<tr>
<td>Water Temperature</td>
<td>Degrees Fahrenheit</td>
<td>T</td>
</tr>
<tr>
<td>Mean Velocity</td>
<td>Feet per Second</td>
<td>V</td>
</tr>
<tr>
<td>Maximum Velocity</td>
<td>Feet per Second</td>
<td>V</td>
</tr>
<tr>
<td>Suspended Sand</td>
<td>Parts per Million</td>
<td>Sₐ</td>
</tr>
<tr>
<td>Suspended Silt</td>
<td>Parts per Million</td>
<td>Sᵢ</td>
</tr>
<tr>
<td>Suspended Total</td>
<td>Parts per Million</td>
<td>Sₐ+i</td>
</tr>
<tr>
<td>Thalweg Depth</td>
<td>Feet below Gauge Zero</td>
<td>Dₜ</td>
</tr>
<tr>
<td>State of Discharge</td>
<td>1000 Cusecs per Day</td>
<td>dQ</td>
</tr>
<tr>
<td>State of Stage</td>
<td>Feet per Day</td>
<td>dS</td>
</tr>
</tbody>
</table>

*Sand is defined as the material retained in a 0.062 millimeter sieve, and silt is all material passing through that sieve.

discharge variable.

All other variables are defined as they are commonly used in the literature or as they have been defined in preceding pages of this report.

The computer analysis included measures of central tendency and dispersion for each variable (table 15). These measures define the hydraulic dimensions of the Red River at Alexandria for 1963-1967.

Certain parameters displayed a remarkable degree of variability. These variables are as follows:

1. **State of stage.** The rate of change of water

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### TABLE 15

MEASURED HYDRAULIC DIMENSIONS OF RED RIVER AT ALEXANDRIA, 1963-1967

<table>
<thead>
<tr>
<th>Variable Symbol</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Variation Coefficient</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>18.6</td>
<td>25.0</td>
<td>1.34</td>
<td>1.5</td>
<td>165.0</td>
</tr>
<tr>
<td>S</td>
<td>5.8</td>
<td>6.9</td>
<td>1.19</td>
<td>-2.4</td>
<td>35.4</td>
</tr>
<tr>
<td>W</td>
<td>496</td>
<td>64</td>
<td>0.13</td>
<td>394</td>
<td>694</td>
</tr>
<tr>
<td>D</td>
<td>25</td>
<td>8</td>
<td>0.34</td>
<td>13</td>
<td>59</td>
</tr>
<tr>
<td>A</td>
<td>73.2</td>
<td>31.2</td>
<td>0.43</td>
<td>26.2</td>
<td>266.0</td>
</tr>
<tr>
<td>T</td>
<td>69</td>
<td>15</td>
<td>0.21</td>
<td>37</td>
<td>90</td>
</tr>
<tr>
<td>V</td>
<td>1.96</td>
<td>1.10</td>
<td>0.56</td>
<td>0.57</td>
<td>6.30</td>
</tr>
<tr>
<td>Vs</td>
<td>3.0</td>
<td>1.6</td>
<td>0.54</td>
<td>0.8</td>
<td>9.2</td>
</tr>
<tr>
<td>Sa</td>
<td>109</td>
<td>129</td>
<td>1.19</td>
<td>4</td>
<td>751</td>
</tr>
<tr>
<td>St</td>
<td>376</td>
<td>519</td>
<td>1.38</td>
<td>22</td>
<td>3200</td>
</tr>
<tr>
<td>Sna+1</td>
<td>485</td>
<td>621</td>
<td>1.28</td>
<td>28</td>
<td>3783</td>
</tr>
<tr>
<td>Ds</td>
<td>19</td>
<td>3</td>
<td>0.15</td>
<td>14</td>
<td>34</td>
</tr>
<tr>
<td>dQ</td>
<td>-0.06</td>
<td>2.86</td>
<td>45.82</td>
<td>-11.5</td>
<td>22.5</td>
</tr>
<tr>
<td>dS</td>
<td>-0.003</td>
<td>0.838</td>
<td>299.18</td>
<td>-2.0</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Note: These values were calculated from 216 discharge measurements at Murray Street Bridge, Alexandria. The field observations were made by field parties of the U. S. Army Corps of Engineers, New Orleans District.

*Variable symbols and units of measure are defined by table 14.

Surface elevation per day is extremely conspicuous. The coefficient of variation is on the order of 30,000 per cent, and increases in stage as great as 6.7 feet per day were experienced.

2. **State of discharge.** The rate of change of discharge per day is also highly variable, the coefficient of variation amounting to nearly 4,600 per cent. Decreases in discharge...
as great as 11,500 cusecs per day and increases of 22,500 cusecs per day were experienced.

3. **Discharge and stage.** Both variables displayed coefficients of variation exceeding 100 per cent. Discharge extremes ranging from 1,500 cusecs to 165,000 cusecs were measured. The negative value of the minimum stage shows the effect of progressive decline of water surface elevation at Alexandria.

4. **Suspended sediment.** Suspended sand, silt, and the total suspended load all display coefficients of variation in excess of 100 per cent.

5. **Channel geometry and velocity.** The variables of width, maximum depth, cross-sectional area, and thalweg depth are all remarkable for the relatively small values of their variation coefficients. Changes in discharge at this station are accommodated mainly by changes in stage, and, to a much lesser degree, by changes in velocity (coefficient of variation = 56 per cent), cross-sectional area (coefficient of variation = 43 per cent), and depth of flow (coefficient of variation = 34 per cent). Although thalweg depth has only a small degree of variability (coefficient of variation = 15 per cent), it is noteworthy that a thalweg depth of 3/4 feet below gauge zero has been
observed, a value 5 standard deviations beyond the mean.

Although the river responds to increased discharge mainly by increasing water surface elevation, observations of unusual thalweg depths show that sometimes this response is partly achieved by scouring of the bottom.

**Current Concept of Scour and Fill**

Contemporary documents, consultations with engineering personnel familiar with the Red River, and field observations suggest a concept of river regime somewhat at variance with the usual model presented in the literature. The most comprehensive document dealing with the scour and fill activity of the Red River is a file memorandum by Mr. George A. Price, Chief, Hydrologic Investigations Section, New Orleans District (U. S. Army Corps of Engineers, 1964). This document summarizes the regime as follows:

1. The bed of Red River from Fulton to Alexandria is subject to rapid and erratic scour and fill, amounting to 8 to 12 feet above and below the average bed, and as much as 10 feet in a single week.

2. There is a trend of similarity in the variations of bed elevation, water surface, velocity, cross-sectional area, discharge and sediment, all of which tend to change simultaneously in the same direction. On the other hand, the depth of flow changes more slowly and sometimes remains nearly constant while the other variables are changing by several hundred percent. Under these conditions, it is difficult to attribute cause and effect to the various observed variables.

3. The following is believed to be a reasonable explanation of what occurs. It at least offers
good agreement with observed conditions.

4. The independent variable is discharge. Changes in discharge may be large and rapid. With an increase in discharge the river partly overflows the next upstream point bar, scouring from it the material to fill up the channel below. As the bed rises so does the water surface, the area increasing because the channel is wider at the higher elevation. The velocity then adjusts to a new value consistent with the discharge and cross-section at which the new channel is stable.

5. With a decrease in discharge, the immediate consequence is lower water surface and restricted cross-section. Thereafter the channel adjusts to a lower bed with narrower width.

6. Evidence of increasing (scouring) velocity with bed degradation is lacking. Indeed there is actually a correlation between degradation and depth + velocity.

7. No scheme for quantitative forecasting is apparent.

3. It is believed that most of the sediment movement occurs as bedload.

The next section of this report will verify some of these observations and modify some of them.

Scour and Fill Regime

Numerous regression hypotheses were tested using the data and procedure outlined in the introduction to this chapter. Variable symbols and units of measure of the equations presented in this section are defined in table 14.

In the following pages the elementary relations between hydraulic geometry, independent variables, and sediment behavior will be summarized. The presentation will define these relations with three expressions: (1) the regression equation, (2) the coefficient of determination
of the function \(R^2\), (3) the coefficient of determination for the universe.

The latter was calculated using procedures outlined by Arkin and Colton (1963, pp. 16-17 and table 23). It defines the determination coefficient \(R^2\) by a range. The true determination coefficient is somewhere within the boundaries of this range, at an 0.0001 significance level. Thus the odds that the true determination coefficient for the universe is a value within this range are 9,999 to 1.

In agreement with the current concept of Red River behavior, discharge was found to be the fundamental independent variable controlling channel geometry. A simple linear hypothesis relating cross-sectional area and discharge produced the equation

\[
A = 43.57 + 1.589Q
\]

in which case the coefficient of determination \(R^2 = 0.926\).

It was subsequently found that superior results were obtained by transforming the discharge variable to its square root. The relation then became

\[
A = 0.3871 + 19.298Q^{\frac{1}{2}}
\]

in which case \(R^2 = 0.971\).

The significance of this transformation is appreciable because the determination coefficient of the latter function is 6.9 standard errors above the coefficient of the
former equation. The statistical tables cited above show that the probability of occurrence of such a marked departure in the value of the coefficient of determination lies in the interval between 0.0000002 and 0.00000000026. The odds against the occurrence of an accidental disparity of this magnitude exceed 500,000,000 to 1.

The determination coefficient for the universe lies between $R^2 = 0.951$ and $R^2 = 0.983$; so the odds that the true coefficient of determination is within this interval are 9,999 to 1. The area of the channel cross section at Alexandria appears to be a linear function of the square root of the discharge.

There is some correlation between the square root of the discharge and the channel width. The equation

$$W = 392.70 + 27.38 Q^{\frac{1}{2}}$$

has a coefficient of determination of $R^2 = 0.804$, which is considerably less significant than the relation for cross-sectional area. The coefficient for the universe is in the interval between $R^2 = 0.688$ and $R^2 = 0.880$. Although it is necessary to conclude that there is some degree of correlation (it is highly unlikely that the determination coefficient is zero), the relationship does not fit the data as well as might be desired.

The maximum depth of flow also displays correlation with the square root of discharge. The equation
\[ D = 10.15 + 3.84 Q^{0.57} \]

has a coefficient of \( R^2 = 0.917 \) and must be within the interval between \( R^2 = 0.863 \) and \( R^2 = 0.951 \). Although the fit is somewhat better for depth than for width, both functions are inferior to the cross-sectional area equation.

These equations show that the Red River at Alexandria adjusts its channel geometry to the prevailing discharge by altering the cross-sectional area as a linear function of the square root of the discharge, or as some function that is at least very close numerically to that quantity.

Leopold et al. (1964, p. 219) relate the elements of channel geometry to discharge as power functions (functions that plot as straight lines on logarithm paper). Averaging the results measured at 158 gauge stations, those authors derived the function

\[ A = I \sqrt{Q} \]

where \( I \) is a constant. It has become standard practice in hydraulic studies to assume that relations between variables are best expressed by equations obtained from logarithmic plots of measured data.

There are, however, certain drawbacks with such a procedure. Logarithmic plots tend to mask sizable deviations from the theoretical curves, especially toward the upper right-hand corner of the graph (where large numbers
are involved). In some cases the logarithmic assumption may obscure rather than clarify relatively simple relations.

The routine assumption of logarithmic distribution cannot be justified in cases where less complex functions produce results of indubitable significance. The significance of the power function of Leopold et al. was not given and hence is not available for comparison. It may be significant, however, that an impartial attempt to fit the data from 158 cross sections to discharge resulted in an exponential average value of 0.57, since this only slightly exceeds one-half. It appears probable that, for many discharge values, the numerical solution to the power function equation may closely approximate the square root of discharge, plus a constant. It is possible that the exponential value derived by Leopold et al. resulted because some of the measured river cross sections also have areas that are functions of the square root of discharge.

Finally, the power function of Leopold et al. predicts that the cross-sectional area of the river would become zero should discharge cease as a result of diversion or the temporary effects of dam closure upstream. The continuing existence of numerous former Red River channels shows that this is wholly unrealistic. A linear square root function has the virtue of predicting a remnant channel of finite dimensions, although of reduced
size. The exact predicted area may be suspect because no discharges of zero were included, but the range of discharges was extreme (table 15).

If the function

$$A = J + K Q^{\frac{1}{2}},$$ (14)

where J and K are the constants appropriate to a given river cross section, is useful at other stations, it would have considerable value. The determination of the coefficients for a station would permit a very close estimate of the discharge by computation from a measurement of the area of channel cross section. Although the measurement procedure would be more laborious than the use of a rating curve based on stage, it might produce superior results at stations (such as Alexandria) where the rating curve is erratic. This method might also have utility in cases where the direct measurement of discharge is impractical or impossible.

The close relation between the area of channel cross section and the square root of discharge suggests that the constant shift in rating results from the apparently irregular behavior of the river bed. Since channel geometry alone does not clarify the scour and fill regime, it is necessary to consider the variables responsible for thalweg depth.

Numerous regression tests have shown that there is no simple correlation between discharge in any form and
thalweg depth and that there is no simple correlation relating the elements of channel geometry to the depth of the thalweg. A typical result was obtained in the case of the regression of thalweg depth on cross-sectional area, which produced a determination coefficient of 

\[ R^2 = 0.213. \]

Because the determination coefficient for the universe is in the interval 

\[ R^2 = 0.055 \text{ to } R^2 = 0.421, \]

and the former is almost zero, it follows that no relation is probable.

Although channel geometry and thalweg depth do not directly correlate, they do exhibit similar patterns of behavior during flood passage. These patterns have been described by Leopold et al. (1964, p. 230):

Study of the hydraulic geometry shows that the mean bed elevation at a river cross section depends not only on water discharge but is intimately related to changes in width, depth, velocity, and sediment load during the passage of the flood. During a flood passage, each of these parameters executes a hysteresis loop, usually in such a sense that at a given discharge the rising limb of the hydrograph is characterized by a larger sediment load, a higher velocity, and a smaller depth than the same discharge on the falling limb of the hydrograph. Similarly, mean bed elevation executes a hysteresis loop, the minimum bed elevation not necessarily being associated with maximum discharge during the flood passage.

Flood passages on Red River conform to this pattern.

An excellent example is offered by the largest flood that occurred during the period of observation, that of late April and May, 1966 (table 16). During this flood identical discharges of 153,000 cusecs were observed preceding and following the peak discharge. Comparison of
<table>
<thead>
<tr>
<th>Date</th>
<th>Discharge</th>
<th>Suspended Load</th>
<th>Velocity</th>
<th>Stage</th>
<th>Area</th>
<th>Width</th>
<th>Depth</th>
<th>Thalweg</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 20</td>
<td>7,500</td>
<td>183</td>
<td>1.4</td>
<td>2.2</td>
<td>5,250</td>
<td>489</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>April 27</td>
<td>46,900</td>
<td>3,575</td>
<td>4.1</td>
<td>14.2</td>
<td>11,500</td>
<td>544</td>
<td>36</td>
<td>22</td>
</tr>
<tr>
<td>May 5</td>
<td>153,000</td>
<td>3,783</td>
<td>6.3</td>
<td>33.2</td>
<td>24,300</td>
<td>680</td>
<td>54</td>
<td>21</td>
</tr>
<tr>
<td>May 9</td>
<td>165,000</td>
<td>2,750</td>
<td>6.2</td>
<td>35.4</td>
<td>26,500</td>
<td>694</td>
<td>59</td>
<td>24</td>
</tr>
<tr>
<td>May 11</td>
<td>153,000</td>
<td>2,087</td>
<td>5.8</td>
<td>35.2</td>
<td>26,600</td>
<td>693</td>
<td>58</td>
<td>23</td>
</tr>
<tr>
<td>May 18</td>
<td>96,600</td>
<td>1,100</td>
<td>4.6</td>
<td>28.1</td>
<td>21,000</td>
<td>643</td>
<td>48</td>
<td>20</td>
</tr>
<tr>
<td>May 25</td>
<td>52,100</td>
<td>894</td>
<td>3.4</td>
<td>19.0</td>
<td>15,200</td>
<td>594</td>
<td>40</td>
<td>21</td>
</tr>
</tbody>
</table>

Note: Field measurements executed by personnel of the U. S. Army Corps of Engineers. Units of measure are as follows: discharge in cusecs, suspended load in parts per million, velocity in feet per second, stage in feet, area of cross section in square feet, width and depth in feet, and thalweg depth in feet below gauge zero. Velocity is the mean value, and depth is the maximum for the cross section.
data measured during these times of identical discharge shows a larger sediment load, higher velocity, and a lesser depth at the time of waxing discharge. All channel dimensions were smaller before peak discharge than afterward, necessitating higher velocity to accommodate discharge.

The behavior of the suspended load variable is of particular interest because the maximum observed sediment concentration preceded the maximum observed discharge. Although it is possible that the measurements of May 9 were made slightly after the actual peak discharge, the fact remains that the remarkably high sediment concentration of April 27, when discharge was only 46,900 cusecs, is in contrast to the much smaller loads accompanying higher discharges after the flood peak. The tendency for maximum sediment concentrations to precede maximum discharge was noted by Hjulstrom (1935) and has subsequently been established as a general rule (see, for instance, Morisawa, 1968, p. 62 and Fig. 4.11).

The original data from which table 14 was generalized show that the silt and sand fractions peaked at different times. The greatest measured silt concentration occurred on April 27 (3,200 parts per million), preceding the greatest observed water discharge by 12 days. On May 5, the silt concentration had declined to 3,032 parts per million, although the total sediment load in suspension had reached an apparent maximum. At the time of maximum water discharge the silt concentration had fallen to only
2,100 parts per million. The precipitous decrease in silt content continued as the discharge waned.

When the silt concentration reached an apparent maximum (April 27), the sand concentration was still increasing, having attained 375 parts per million. The next observation (May 5) showed that the sand content had doubled, reaching 751 parts per million. The spectacular increase in suspended sand was largely responsible for the occurrence of the maximum observed total suspended load. Thereafter the suspended sand concentration decreased, being only 650 parts per million during the discharge peak of May 9. It continued to decline as discharge waned.

Only mean velocity appeared to peak at the same time as the suspended total load and suspended sand. The hypothesis that suspended load is a function of mean velocity was therefore tested with regression. The results failed to produce satisfactory determination coefficients.

The cause of this failure was the production of a determination coefficient of $R^2 = 0.570$ by the equation relating the sand fraction of the suspended load to velocity. The true coefficient is in the interval $R^2 = 0.379$ and $R^2 = 0.721$. The probability that there is no significant relation cannot be overlooked, and it was concluded that these variables do not correlate.

Substitution of the unaltered velocity with the mean velocity squared resulted in a radical improvement, mainly owing to a drastic increase in the determination coefficient.
for the sand fraction. The relation found was

\[ S_{a+1} = 45.33 + 36.75 \, v^2 \]

in which case \( R^2 = 0.315 \). The universal coefficient is in the range \( R^2 = 0.705 \) and \( R^2 = 0.887 \), which is interpreted as a satisfactory correlation. No other variable or combination of variables (including discharge in any form) displayed any significant correlation with suspended load.

There is some theoretical justification for this hypothesis. Leliavsky (1966, p. 46) has noted that tractive force (equation (1) of this study) is numerically very close to the square of velocity, so that the one might serve as an approximation of the other. Russell (1967, p. 46) observed that "in general, it is believed that turbulence increases at a rate that somewhat exceeds the square of the current velocity." It is therefore tentatively concluded that suspended load is a function of mean velocity squared.

Unlike suspended load, the behavior of the thalweg depth variable during the flood passage of April-May, 1966 (table 16), does not suggest the existence of any correlation with velocity. The maximum measured thalweg depth occurred shortly after the time of the greatest observed velocity and during the maximum discharge. The behavior of the thalweg during the period April 27-May 5 appears anomalous inasmuch as it shoaled slightly while the velocity increased 226 per cent.
The behavior of the river bed may be clarified by transformation of selected variables from Table 16. Mean depth of flow (Table 17) was calculated by dividing the area of cross section by the channel width. The mean depth of the bottom was obtained by subtracting stage from mean depth of flow, the result being the mean depth of the river bed in feet below gauge zero. Dates of observation, discharge values, mean velocities, and thalweg depths were taken from Table 16.

**TABLE 17**

OBSERVED DISCHARGES, VELOCITIES, AND CHANNEL DEPTHS DURING FLOOD PASSAGE, RED RIVER AT ALEXANDRIA, APRIL-MAY, 1966

<table>
<thead>
<tr>
<th>Date</th>
<th>Discharge</th>
<th>Velocity</th>
<th>Mean Flow Depth</th>
<th>Mean Bottom Depth</th>
<th>Thalweg Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>April 20</td>
<td>7,500</td>
<td>1.4</td>
<td>10.7</td>
<td>8.5</td>
<td>16</td>
</tr>
<tr>
<td>April 27</td>
<td>46,900</td>
<td>4.1</td>
<td>21.1</td>
<td>6.9</td>
<td>22</td>
</tr>
<tr>
<td>May 5</td>
<td>153,000</td>
<td>6.3</td>
<td>35.7</td>
<td>2.5</td>
<td>21</td>
</tr>
<tr>
<td>May 9</td>
<td>165,000</td>
<td>6.2</td>
<td>38.2</td>
<td>2.8</td>
<td>24</td>
</tr>
<tr>
<td>May 11</td>
<td>153,000</td>
<td>5.8</td>
<td>38.4</td>
<td>3.2</td>
<td>23</td>
</tr>
<tr>
<td>May 18</td>
<td>96,600</td>
<td>4.6</td>
<td>32.7</td>
<td>4.6</td>
<td>20</td>
</tr>
<tr>
<td>May 25</td>
<td>52,100</td>
<td>3.4</td>
<td>25.6</td>
<td>6.6</td>
<td>21</td>
</tr>
</tbody>
</table>

Note: Field measurements executed by personnel of the U.S. Army Corps of Engineers. Units of measure are as follows: discharge in cusecs, velocity in feet per second, flow depth in feet, bottom and thalweg depths in feet below gauge zero.

The results show that mean depth of flow displays the same general pattern during flood passage as maximum depth and the other elements of channel geometry. As
Leopold et al. (1964) observed, depths during waxing discharge are more shoal than during waning discharge. The time of greatest mean depth did not coincide with maximum discharge but was shortly thereafter. There is a lag between the occurrence of a given discharge and the adjustment of channel geometry to dimensions appropriate to that discharge. Area of cross section (table 16) displayed the same pattern.

Mean bottom depth is the most remarkable of the variables of table 17. The average depth of the river bed decreased markedly during the period of rapidly waxing discharge. The greatest observed bed elevation occurred on May 5, when the bottom averaged only 2.5 feet below gauge zero. This day also produced the maximum observed velocity, maximum suspended sand concentration, and maximum total suspended load. All preceded the occurrence of maximum discharge.

The behavior of the mean bottom depth variable appears to confirm the qualitative model of Red River scour and fill (U. S. Army Corps of Engineers, 1964). The memorandum stated that increases in discharge produced erosion of point bar deposits, the materials thus derived being deposited downstream. Locations downstream from point bars would therefore shoal with waxing discharge. Then, as the bed elevation increases, "so does the water surface, the area increasing because the channel is wider at the higher elevation." Thus increases in discharge should
correlate with filling and decreases should correlate with scouring.

Comparison of thalweg depth with mean bottom depth, however, shows that this concept is inaccurate. The behavior of the thalweg depth variable proves that during the overall period of waxing discharge (April 20-May 9) the general result was erosion of the thalweg from the original 16 feet to 24 feet below gauge zero. Despite a temporary shoaling between April 27 and May 5, the ultimate effect was a 50 per cent increase in thalweg depth. The apparent filling of the bed did not occur.

During April 20-May 5 channel width increased markedly (table 16). Although the increase was only 39 per cent, channel width was enlarged 191 feet. In turn, this greatly augmented the surface area of the channel bottom. The increased surface area accounts for the shoal nature of mean bottom depth. The original river bed was deeper than previously but was flanked by broad zones of shoal overflow waters. Hence the variable pertinent to scour and fill is not the mean elevation of the bed, but the elevation of the thalweg.

The fact that neither discharge nor velocity alone is the dominant variable in determining thalweg depth may be readily demonstrated. This is indicated by the flood passage of May-June, 1965 (table 18), which produced record thalweg depths for the 5-year period. The maximum value was observed on June 3, when a depth of 34 feet below gauge
<table>
<thead>
<tr>
<th>Date</th>
<th>Discharge</th>
<th>Suspended Load</th>
<th>Velocity</th>
<th>Stage</th>
<th>Area</th>
<th>Width</th>
<th>Depth</th>
<th>Thalweg</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 12</td>
<td>5,000</td>
<td>154</td>
<td>1.0</td>
<td>1.6</td>
<td>4,920</td>
<td>481</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>May 19</td>
<td>39,500</td>
<td>1,449</td>
<td>3.5</td>
<td>12.8</td>
<td>11,300</td>
<td>562</td>
<td>43</td>
<td>30</td>
</tr>
<tr>
<td>May 26</td>
<td>28,000</td>
<td>518</td>
<td>2.9</td>
<td>9.7</td>
<td>9,580</td>
<td>535</td>
<td>42</td>
<td>32</td>
</tr>
<tr>
<td>June 3</td>
<td>42,400</td>
<td>1,425</td>
<td>3.7</td>
<td>12.4</td>
<td>11,400</td>
<td>559</td>
<td>46</td>
<td>34</td>
</tr>
<tr>
<td>June 9</td>
<td>26,200</td>
<td>665</td>
<td>2.9</td>
<td>9.1</td>
<td>9,010</td>
<td>535</td>
<td>41</td>
<td>32</td>
</tr>
<tr>
<td>June 30</td>
<td>12,900</td>
<td>165</td>
<td>2.1</td>
<td>4.4</td>
<td>6,150</td>
<td>492</td>
<td>25</td>
<td>21</td>
</tr>
</tbody>
</table>

Note: Field measurements executed by personnel of the U. S. Army Corps of Engineers. Units of measure are as follows: discharge in cubic feet per second, suspended load in parts per million, velocity in feet per second, stage in feet, area of cross section in square feet, width and depth in feet, and thalweg depth in feet below gauge zero. Velocity is the mean value, and depth is the maximum for the cross section.
zero was attained (5 standard deviations beyond the mean). May 12-June 3 is notable for 14 feet of thalweg degrada-
tion, which was unequaled by any other flood passage during 1963-1967. Also notable was May 12-May 19, when the thal-
weg declined 10 feet in a single week.

Comparison of this flood with the flood of maximum discharge (tables 16 and 17) demonstrates that the vari-
ables of either discharge or velocity alone have little effect on thalweg depth. The sole evidence for the hypothe-
sis that depth of thalweg is a function of discharge is that, in each case, the maximum observed thalweg occurred at the time of maximum observed discharge. The disparity in quan-
titative results, however, is extreme.

Discharge of 42,400 cusecs in 1965 produced erosion to a depth of 34 feet below gauge zero, but in 1966 a dis-
charge of 165,000 cusecs could achieve only 24 feet depth. The 1966 flood was accompanied by mean velocities as high as 6.3 feet per second (maximum = 9.2 feet per second), whereas the 1965 passage was characterized by a maximum observed mean velocity of only 3.7 feet per second (maximum = 5.4 feet per second). The quantity of thalweg deepening cannot be a direct, simple function of either variable.

Regression studies show the accuracy of this conclu-
sion. Determination coefficients in all cases showed little significant relationship between velocity and thalweg depth and between discharge and thalweg depth.

Comparison of total suspended load values for each
flood indicates that, in general, the 1965 flood passage was characterized by lesser sediment concentrations (for example, contrast June 3, 1965, with the comparable discharge day of April 27, 1966). This suggests that moderate discharge combined with sediment deficiency might produce thalweg erosion, thus increasing sediment load toward capacity. However, sediment concentration on Red River is a function of the square of velocity, and the latter does not show any satisfactory correlation with thalweg depth. Regression has also indicated that sediment concentration, alone or in combination with other variables, has no significant relation to thalweg depth.

The maximum flood of 1966 was also marked by larger channel dimensions and higher stages. Thus none of these variables appears to offer any explanation for the excessive thalweg depths in 1965.

Because cold water has greater viscosity than warm water (see, for example, Giles, 1962, tables 1(C) and 2), it is possible that water temperature played some part. Temperature changes are known to affect settling velocities of sediment particles (Leliavsky, 1966, p. 187), and a correlation between low water temperatures and high sediment concentrations has been demonstrated on the Colorado River (Lane, Carlson, and Manson, 1949).

The mean water temperature during the highly erosive 1965 flood passage, 81.7 degrees Fahrenheit, varied from 78 to 86. The flood of 1966 occurred when water tempera-
tures averaged 73.7 degrees Fahrenheit, ranging from 70 to 78. The viscosity of the water alone (ignoring the effect of sediment suspension) was therefore greater in the latter case. Although it is true that sediment concentrations were much greater during the 1966 flood (in apparent conformity with the above concept), the inability of that passage to erode the bottom more deeply suggests that water viscosity variation resulting from temperature alone was not significant for thalweg depth.

Investigation of the data did not produce evidence favoring concepts of the efficacy of the water temperature variable. Graphs plotting velocity against suspended sand, suspended silt, and total suspended load were made, and points were labeled with water temperature. The results failed to produce any indication that larger sediment loads should correlate with lower temperatures.

Water temperatures during the period of observation ranged from 37 degrees Fahrenheit to 90 degrees, but even extreme temperature differences appeared to have no effect. Attempts to transform the variable (for example, by using the reciprocal of the temperature) produced no improvement. Multiple regression of Red River data shows that temperature is insignificant even for the silt fraction of the suspended load (that is, particles finer than 0.062 millimeter). Water temperature has no significance in determining sediment concentration in the Red River at Alexandria, the effects (presumably) being totally masked by
other variables.

Because of the tendency for sediment concentrations to be greater during waxing discharges of flood passages, it is reasonable to suspect that times of rapidly increasing discharge might correlate with enhanced suspended sediment concentration and/or rapid thalweg erosion. Regression studies, however, show no significant relation. Attempts to find valid correlations for functions in which the state of discharge was combined with other variables were likewise unsuccessful.

Similarly, stage, and the rate at which it is changing, means little in regard to sediment concentration and depth of thalweg. Like the elements of channel geometry (width, maximum depth, cross-sectional area), there is a correlation solely with discharge.

Only two variables showed a significant correlation with thalweg depth. The square root of discharge and maximum depth of flow are related by the function

\[ D_{t} = 7.11 - 3.03 Q^{0.5} + 0.94 D, \]

which showed a determination coefficient of \( R^2 = 0.818 \). The universal determination coefficient for this relationship is in the interval \( R^2 = 0.709 \) to \( R^2 = 0.889 \).

It was initially believed that this correlation was spurious. It seemed probable that the high value of the determination coefficient resulted from a close relation between maximum depth and thalweg depth. However, depth
of flow correlates with the square root of discharge, and thalweg depth does not. Deletion of the discharge variable (the least significant variable) from the thalweg equation causes the coefficient of determination to decline to $R^2 = 0.411$. The coefficient for the universe is between $R^2 = 0.208$ and $R^2 = 0.597$. Hence the hypothesis that there is a close relation between maximum depth and thalweg depth is rejected.

It was therefore tentatively concluded that thalweg depth (at least at Alexandria) may be approximated from an equation of the general form

$$D_t = L - M Q^{\frac{1}{2}} + N D,$$  \hspace{1cm} (15)

where $L$, $M$, and $N$ are constants. Whether this function should be considered to be a cause-and-effect relation is problematical.

The pertinence of depth of flow to bottom erosion has some theoretical justification because depth of flow is a variable in the tractive force equation. Given an approximately constant water surface slope, it is reasonable to expect that the magnitude of the shear exerted on the thalweg bed by the flow of a natural river should have a positive correlation with the maximum depth of flow. Variation in water surface slope should normally be relatively small compared to variation in depth.

The negative sign of the square root of discharge variable is remarkable. At a given discharge the thalweg
depth is wholly a function of the depth of water flowing over it. Given a constant maximum depth, large discharges are associated with thalweg shoalness, and small discharges appear to produce maximum thalweg depths.

Acceptance of the hypothesis of the thalweg depth equation (as a first approximation) appears to clarify the anomalous results observed during flood passages of 1965 and 1966 (tables 16, 17, and 18). Large discharges are not necessarily associated with extreme thalweg depths. Although times of waxing discharge tend to coincide with thalweg erosion, this is largely because such times are also characterized by greatly enhanced water depths.

An example of the apparent interplay between discharge and depth of flow is offered by the channel changes which occurred during April 27-May 5, 1966 (table 16). Although maximum depth increased from 36 to 54 feet, the thalweg shoaled slightly inasmuch as the increased depth was offset by the greater discharge. This shoaling is only comprehensible in light of the thalweg depth function.

Computations show that the equation predicts thalweg depths for the flood passages of 1965 and 1966 which conform very closely to the actual measured values, a fact that may be readily confirmed from the data of tables 16 and 18. The regression function appears valid even for extreme cases.

Although the equation does not initially appear theoretically satisfying and may not be the final solution
to the scour and fill problem, it is nonetheless important. Equation (15) shows that discharge is not the sole determining variable.

**Channel Geometry and Meander Dimensions**

Regression studies of meandering channels, ranging in scale from laboratory models to the Lower Mississippi River, appear to have established useful correlations between the dimensions of a channel and the dimensions of the meanders produced by that channel. These results indicate that it is probable that changes in channel depth have accompanied changes in meander pattern.

Direct regression of meander dimensions on depth has rarely been attempted, mainly because measurements of depth are often not available. However, Inglis (1947) and Leopold and Wolman (1960) have established a positive correlation between channel width and meander wave length.

Using a logarithmic assumption, these investigators derived the relation

\[ L = 0 W^P , \]

where \( L \) is meander wave length, \( W \) is channel width, and \( 0 \) and \( P \) are constants. In both studies the value of \( P \) very closely approximated unity. Thus Inglis (1947, p. 10), utilizing data previously measured by Jefferson (1902), computed \( P \) as 0.995. Leopold and Wolman (1960, p. 772, table 1, and Fig. 2) found that \( P \) was 1.01. These studies concluded that the actual exponents are unity, so that the
equation is linear rather than geometric.

There was considerable disparity in the values attributed to the coefficient 0. Leopold and Wolman (1960, p. 772), for example, state that "meander length ranges from 7 to 10 times the channel width," but they attribute a value of 10.9 to the coefficient 0 (this is repeated in Leopold et al., 1964, p. 297). Inglis (1947, p. 10) calculated that 0 is 6.06.

Since the equation is linear, it may be written

\[ W = \frac{L}{0}, \]  

(16)

where \( L \) and \( W \) are as defined above and 0 is (presumably) a constant of unknown value. The equation shows that increases in Red River meander wave length should have been accompanied by increasing channel width.

Because the area of cross section is the product of width and depth and a function of discharge, and because discharge did not change appreciably during 1928-1967, cross-sectional area is believed to have remained constant. It follows that depth must have declined to compensate for progressive increases in width. This appears to be confirmed by Schumm (1960), who has shown that high width-depth ratios correlate with low sinuosities on 47 alluvial rivers of the Great Plains.

This conforms to the concept of a river in the process of transition from a meandering to a braided stream pattern. Equation (15) shows that, given a constant dis-
charge and a declining depth of flow, the thalweg depth will decrease. Thus the fact that Red River is no longer navigable is a direct result of a channel metamorphosis that has gradually taken place across the decades. The extremely shoal Red River of today has little in common with the navigable stream that was Red River 100 years ago.

Conclusion

The square root of discharge explains 97 per cent of the variation of cross-sectional area of Red River at Alexandria. The square of velocity, which is numerically close to tractive force and turbulence, accounts for 82 per cent of the variation of suspended sediment. Depth of flow minus the square root of discharge accounts for 82 per cent of the variation of thalweg depth. It is believed that Red River has shoaled and widened its channel while it has straightened its meanders, a transformation interpreted as toward a braided pattern.
CHAPTER V

CONCLUSION

Synthesis

Channel metamorphosis has transformed Red River from a narrow and deep meandering stream to a wide and shoal, relatively straight river. Over a considerable portion of the river this transformation appears to be a result of increased valley slope consequent to diversion.

Fisk (1940, p. 19) summarized the morphology and origin of the typical flood plain of aggradation as follows:

The lowlands parallel the meander belt of a river for great distances and are utilized first for storage of flood waters and then as avenues for their release as the stream subsides. This type of linear lowland becomes the new stream course when crevassing of a natural levee diverts the full flow of a stream from the old channel. After it is established in its new course, the stream constructs new levees and forms new lowlands by smothering pre-existent flood-plain irregularities with natural levee and lowland sediment. The fact that the new levee systems soon reach heights in excess of those which mark the former course of the river can be easily demonstrated on contour maps of the Mississippi and Red River alluvial valleys and supports the thesis of a constant aggradational process.

The morphology of the flood plain of contemporary Red River does not conform to this description.

Map studies of the alluvial plain south of Boyce

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(Boyce, Alexandria, LeCompte, and Marksville quadrangles, in pocket) show that the flood plain is dominated by two prominent ridges: (1) an eastern ridge, which is composed of the natural levees of contemporary Red River, and (2) a western ridge, composed of natural levees flanking an earlier Red River channel defined by bayous Jean de Jean, Rapides, Robert, and Boeuf.

Below Boyce the older channel is bounded by natural levees that are higher, wider, and more continuous than the levees flanking the present course. This disparity in development and the decline of water surface elevation at Alexandria is evidence of the continuing hydraulic entrenchment of Red River.

North of the latitude of Boyce evidence of entrenchment is too subtle to be discerned from inspection of topographic quadrangles (Campti quadrangle, in pocket). The observer on the ground, however, may note that the descent from the general level of the flood plain surface to the water's edge is achieved by traversing a series of steplike microterraces. This phenomenon is especially evident on the point bar of Kateland Plantation (W. 1/2 sec. 34, T. 6 N., R. 3 W., Boyce quadrangle).

Transformation of flood plain morphology has been accompanied by development of braiding tendencies. The latter has resulted in deposition in the river channel of numerous islands that are especially apparent at low water. These may be seen from the Red River bridge at Grand Ecore.
(sec. 51, T. 10 N., R. 7 W., Campti quadrangle) and at other localities.

Changes in fluvial behavior have accompanied morphological transformation. During the nineteenth century bank failure was most commonly observed during periods of declining stage after a flood. Engineers familiar with the contemporary Red River believe that bank erosion is most intense during rising stages today (oral communication with personnel, New Orleans District, U. S. Army Corps of Engineers).

Comparison of Red River metamorphosis with laboratory studies (Friedkin, 1945) has resulted in formulation of a first approximation of the function of valley slope-sinuosity (figure 11). The universal plot of this relation is believed to be a family of curves, each member of which has a general form resembling this figure. The points composing this curve for an individual river are believed to be functions of the hydraulic dimensions of that river.

Conclusion

Morphometric study of fluvial phenomena is not original to this report, but some conclusions which have emerged from past studies of this type have been unrealistic. The origin of this lack of realism has been failure to appreciate the fact that meanders on natural rivers commonly fail to conform with the smooth, flowing patterns seen in textbooks and displayed by distorted models.

This approach has resulted in attempts to measure
meander dimensions using criteria applicable only to special cases. The utilization of radius of curvature as a measure of meander intensity is an excellent example. Field evidence shows that great numbers of rivers, including the classical Meander (Buyuk Menderes) River of Anatolia (Lane, 1957, Fig. 5), possess bends of such marked asymmetry that radius of curvature is impossible to measure. Insistence upon the retention of this unit of meander intensity resulted in the suggestion that, to be considered a meander, some degree of symmetry must be present in a bend (Leopold et al., 1964, p. 295).

Further, utilization of this criterion has led to the formulation of conclusions based on data which do not typify the real morphology of the rivers studied. Thus selection of Red River meanders with sufficient symmetry for radius of curvature measurements resulted in a sample which reflected the observer's bias toward an idealized form, but not reality. Sweeping conclusions have been based on meanders that are anomalous rather than typical.

For dimensional analysis of natural rivers it is necessary to employ different criteria. Wave length, bending ratio, and sinuosity are not the only possible and perhaps realistic measures of meander intensity, but they do possess the virtues of high statistical significance, versatility, and simplicity.

The slope relation aspect of bending ratio and sinuosity is especially pertinent inasmuch as meandering may
be conceived as a slope adjustment phenomenon. Geological investigations commonly include measurements of alluvial slopes, but usually they are based on the slopes of alluvial plains or natural levees. The slopes pertinent to meandering are the valley and water surface slopes. In the case of Red River, the slope of the flood plain is a relict of conditions prevalent prior to the Moncla Gap diversion.

River slopes are best computed from analysis of gauge-discharge data in combination with simple map measurements. Accuracy of results obtained from utilization of the extensive daily gauge records far exceeds what may be gleaned from mapped data or even aerial photographs. Mean slopes may be calculated for times of mean discharge at each end of the reach, thus expressing the average prevailing condition with unique exactitude. Time series procedures may then be used to test hypotheses of changing hydraulic slopes. The vast quantity of gauge-discharge data that have been carefully measured and recorded through the years constitutes a much neglected resource for detailed investigations in alluvial morphology.

Recent studies of Schumm (1969) and others have stressed the theme of river metamorphosis. Detailed investigations of rivers that are actively changing pattern will provide new insights into roles played by the pertinent variables. The complex aspects of pattern metamorphosis cannot be adequately explained for all cases.
using only one or two variables. Even in the relatively clear-cut case of Red River it is necessary to consider the probability that changing sediment loads may have contributed to the observed results.

Red River metamorphosis in the study area is largely the result of a complex entrenchment that was produced by rejuvenation of the southern portion of the study area. This event lowered the hydraulic base level of the river, producing channel metamorphosis.

It is interesting to contrast the conclusions of this study with inferences drawn from recent laboratory model experiments with knickpoints in noncohesive materials. Extending their experimental results to natural rivers using principles of hydraulic similitude, Brush and Wolman (1960, p. 70) believe that they have discovered that

a knickpoint probably would not be recognizable more than several miles upstream from its initial position unless the original fall was extremely high; it would be most unlikely to travel the entire length of a natural stream.

The evidence of Red River contradicts this conclusion.

Numerous historic documents refer to the former existence of the Rapides above Alexandria, more than 25 miles beyond Moncla (where the river debouched onto the flood plain of the Lower Mississippi River). Even today, records of the gauge-discharge relation at Alexandria indicate that water levels at that station are declining 13 feet per
century. The terraced, entrenched nature of the flood plain is visible in the field even farther upstream, notably on the southern side of the point bar of Kateland Meander. The entrenchment of the alluvial plain is so evident for 40 valley miles above Moncla that it is discernible on topographic quadrangles with 20-foot contour intervals. Channel metamorphosis on Red River, in the form of a transition toward braiding, now extends more than 200 valley miles beyond the original fall at Moncla. All of these evidences show that the various phenomena which accompany knickpoint migration are effective for great distances upstream on natural rivers.
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Oscar Douglas Abington was born on March 3, 1963, in Alexandria, Virginia. He received a Bachelor of Arts degree in English in 1961 from Louisiana State University at Baton Rouge. He received a Master of Science degree in physical geography from the same university in January of 1964. In January of 1968 he was granted a graduate fellowship by the New Orleans District, U. S. Army Corps of Engineers.
EXAMINATION AND THESIS REPORT

Candidate: Oscar Douglas Abington
Major Field: Geography
Title of Thesis: Changing Meander Morphology and Hydraulics, Red River, Arkansas and Louisiana

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Date of Examination:

April 16, 1973
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Light-duty
Medium-duty
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U S Route
State Route

BOYCE, LA.