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ANALYSIS OF MAJOR PARAMETERS AFFECTING THE BEHAVIOR OF
THE MISSISSIPPI RIVER(U) ARMY ENGINEER DIV VICKSBURG MS
LOWER MISSISSIPPI VALLEY J R TUTTLE ET AL. DEC 82

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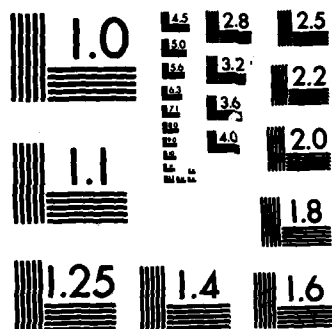
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US Army Corps
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Lower Mississippi
Valley Division

**ANALYSIS OF MAJOR PARAMETERS AFFECTING
THE BEHAVIOR OF THE MISSISSIPPI RIVER**

Potamology Program (P-I)

Report 4

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Prepared by

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Prepared for

**The President, Mississippi River Commission, and
The Division Commander, Lower Mississippi Valley Division**

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Report 4	2. GOVT ACCESSION NO. AD-A124 463	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ANALYSIS OF MAJOR PARAMETERS AFFECTING THE BEHAVIOR OF THE MISSISSIPPI RIVER		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) James R. Tuttle William Pinner		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Division, Lower Mississippi Valley, Potamology Branch P. O. Box 80, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Potamology Program (P-1)
11. CONTROLLING OFFICE NAME AND ADDRESS The President, Mississippi River Commission, and The Division Commander, Lower Mississippi Valley Division		12. REPORT DATE December 1982
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		13. NUMBER OF PAGES 67
		15. SECURITY CLASS. (of this report) Unclassified
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES Available from National Technical Information Service, 5285 Port Royal Road, Springfield, Va. 22151.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Mississippi River Potamology River engineering River regulation		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The present potamology program was initiated after the major flood of 1973, which confirmed that significant flood control capacity had been lost over a major portion of the lower Mississippi River. Objectives of the program are to obtain a better understanding of: the river's reaction to various parameters, why these reactions occur, and how to control these reactions and/or predict future changes resulting from them. (Continued)		

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20. ABSTRACT (Continued).

The studies described in this report consisted of detailed investigation of four major parameters: hydrology, sedimentation, channel geometry, and man-made modifications.

Hydrology of the Mississippi River is highly variable. Stages change daily, seasonally, and annually. These changes in stage continuously influence scour and fill patterns along the channel bed as well as the magnitude of hydraulic roughness, two variables that significantly affect the capacity of the channel to transport flow. It is important, therefore, that the effects of variable hydrology be recognized and understood and that flood control and channel improvement structures be designed and constructed to accommodate what nature provides.

Sediments are very important because they can accumulate in a manner that can seriously affect flood control capacity and navigation conditions. The most important sediments are those transported on and near the channel bed. The majority of these materials appear to be transported by a process called "trading" whereby material is scoured from one location, generally deep pools and point bars, and deposited at a location farther downstream, usually in crossings, during rising stages with the process reversing itself during falling stages.

Channel geometry and alignment of the Mississippi River are extremely variable. This discontinuity affects the capability of the channel to effectively transport flow and sediment, causing conditions that can affect flood flow lines and interfere with navigation.

Man-made modifications (levees, cutoffs, revetments, and dikes) have individually and collectively influenced river behavior. Some reaches of the river, although improved, continue to be problem areas in spite of considerable construction effort. It appears that present design concepts and criteria are generally adequate except in the more difficult reaches where development of alternative design concepts is needed.

Of the four parameters studied, effective management of the sediment parameter offers the greatest potential toward achievement of a stable, dependable channel for both flood control and navigation. The second most significant parameter, one interrelated with sediment transport and storage, is channel geometry and alignment.

Future potamology programs should focus primarily on the major objective of improving the balance between hydraulic parameters and sediment transport capabilities for a full range of flows, locally and throughout the middle and lower Mississippi River.

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PREFACE

This is an interim report of the Potamology Program (P-1) of the Lower Mississippi Valley Division. The Potamology Program is conducted under the direction of the Commander, Lower Mississippi Valley, and is a comprehensive study of physical forces which influence the flood carrying capacity and navigability of the lower Mississippi River. The purpose of the Potamology Program is to define cause-and-effect relationships that result in short-term and long-term changes in the lower Mississippi River's stage-discharge relationships and to develop improved design concepts and criteria for construction of channel stabilization works which will improve flood control and navigation along the lower Mississippi River.

This report briefly reviews the Potamology Program of the Lower Mississippi Valley Division and summarizes studies completed under the program since the major flood in 1973. Future studies under the program will concentrate on analysis of individual reaches of the river with emphasis on improved design concepts and criteria for construction of channel improvement works.

The studies reported herein were the responsibility of the four Lower Mississippi Valley Division District offices. Studies were conducted in the period 1976-1980.

ACKNOWLEDGMENTS

Analyses of the studies presented herein were made by or under the direction of Mr. Billy Garrett, New Orleans District; Mr. Brien Winkley, Vicksburg District; Mr. Andy Lowery, Memphis District; and Mr. Claude Strauser, St. Louis District. The report was prepared by Mr. James R. Tuttle and Mr. William Pinner, Potamology Branch, Lower Mississippi Valley Division.

SUMMARY

Potamology is that science in which principles derived from the study of alluvial river systems are applied to the design of works needed to control river behavior. In the Mississippi Valley, the need for these kinds of studies has grown with man's increasing occupation and development of the alluvial valley of the dangerous and unpredictable Mississippi River.

Since their beginnings in the early 1930's, the major thrust of potamology studies has changed to reflect the major design and construction problems in controlling the river. Earliest studies were used in defining the basic design parameters for efficient development of cutoffs. Subsequent studies were used in determining causes of failures in revetments, in developing improved revetment construction methods and materials, and in developing means to stabilize short troublesome reaches of the river with dikes.

The present potamology program was initiated after the major flood of 1973 which confirmed that significant flood control capacity had been lost over a major portion of the lower Mississippi River. Objectives of the program are to obtain a better understanding of: the river's reaction to various parameters, why these reactions occur, and how to control these reactions and/or predict future changes resulting from them.

The studies described in this report were conducted under the present potamology program and consisted of detailed investigation of four major parameters: hydrology, sedimentation, channel geometry, and man-made modifications. The following paragraphs briefly summarize results of the investigations:

Hydrology of the Mississippi River is highly variable. Stages change daily, seasonally, and annually. These changes in stage continuously influence scour and fill patterns along the channel bed as well as the magnitude of hydraulic roughness, two variables that significantly affect the capacity of the channel to transport flow. The ideal flow regime for the Mississippi River would be a steady non-varying flow. The Mississippi does not provide this type of flow regime, nor is it likely that the flow regime will change in this direction in the near future. It is important, therefore, that the effects of variable hydrology be recognized and understood and that

flood control and channel improvement structures be designed and constructed to accommodate what nature provides.

Sediments are very important because they can accumulate in a manner that can seriously affect flood control capacity and navigation conditions. The most important sediments are those transported on and near the channel bed which are primarily sand, commonly referred to as bed load, and believed to be the major channel molding material. The majority of these materials appear to be transported by a process called "trading" whereby material is scoured from one location, generally deep pools and point bars, and deposited at a location further downstream, usually in crossings, during rising stages with the process reversing itself during falling stages. In many reaches of the Mississippi the process is approximately balanced (amounts deposited during rising stages are scoured out and redeposited during falling stages). Some reaches are not balanced and the key variable appears to be channel geometry. These reaches are generally characterized by excessively wide channel widths which are usually associated with relatively straight channel alignment and/or a divided channel.

Channel geometry and alignment of the Mississippi River are extremely variable. Enormous variations exist in channel alignment varying from extreme sinuosity to straight reaches of negligible sinuosity. Channel widths and depths vary greatly throughout the river ranging from narrow, deep channel to very wide, shallow channels with middle bars, divided flows, and secondary channels or chutes. This discontinuity in geometry and alignment affects the capability of the channel to effectively transport flow and sediment causing conditions that can affect flood flow lines and interfere with navigation.

Man-made modifications (levees, cutoffs, revetments, and dikes) have individually and collectively influenced river behavior. Levees have confined flood flows to a more narrow floodplain causing stages to increase, concentrating greater magnitudes of flow in the channel area, affecting hydraulic parameters and sediment transport patterns during floods. Cutoffs constructed during the 1930's and 1940's in the section of river from a few miles downstream of Natchez, Miss., to about 55 miles downstream of Memphis, Tenn., significantly shortened that section of river causing stages to decrease sharply, particularly at Arkansas City, Ark., and Vicksburg, Miss. In the interim since the cutoffs, stages have slowly decreased upstream

of Arkansas City, Ark., to about Memphis, Tenn.; however, in the reach from Arkansas City, Ark. downstream to about Natchez, Miss., stages have increased severely impacting on flood control structures. These stage trends are viewed as adjustments by the river to the change in water surface slopes caused by lower stages in the vicinity of cutoffs. Revetments have successfully restricted and/or arrested lateral movement of banklines (caving) along the Mississippi. These structures encourage channel deepening at the riverward toe which affects channel geometry and alignment, particularly low water channel alignment. Dikes are designed to establish and maintain a channel trace approximately 2550 ft wide for flows up to about half bankfull. This component of the channel improvement program has successfully restored divided flow into a single efficient channel and contracted the low-water channel into an economically maintainable navigation channel in many locations. Some reaches of the river, however, although improved, continue to be problem areas in spite of considerable construction effort. It appears that present design concepts and criteria are generally adequate except in the more difficult reaches where development of alternative design concepts is needed.

The four parameters studied are not independent--they are interdependent. However, of the four parameters, effective management of the sediment parameter offers the greatest potential toward achievement of a stable, dependable channel for both flood control and navigation. Effective transport and storage of sediments, recognizing the "trading process," would significantly reduce the occurrence of middle bars, unstable channel alignment, and wide channel geometry beneficially impacting on flood flowlines and reducing annual maintenance dredging cost. Future channel improvement designs should give primary consideration to modifying existing channel geometry and alignment locally and throughout the river system to achieve a better balance between hydraulic parameters and sediment transport capabilities.

The second most significant parameter, one interrelated with sediment transport and storage, is channel geometry and alignment. It is readily apparent that random bar development and an unstable channel alignment are directly related to wide channel geometry. Existing wide geometry can be improved by improving sediment transport and storage capabilities by

construction of necessary channel improvement works. The major emphasis should be prevention of future additional wide geometry by timely construction of revetments and dikes.

Future potamology programs should focus primarily on the major objective of improving the balance between hydraulic parameters and sediment transport capabilities for a full range of flows, locally and throughout the middle and lower Mississippi River. Improvements would increase channel efficiency, minimize the potential for additional future increases in the project design flood flow line, reduce long-term channel improvement requirements, and reduce annual maintenance dredging requirements.

Potamology Investigations

Analysis of Major Parameters Affecting the Behavior of the Mississippi River

I. PURPOSE

This report provides a brief summary of the Lower Mississippi Valley Division and Mississippi River Commission (LMVD-MRC) Potamology Program prior to the major flood in 1973, a brief description of the events leading to a change in the direction of the LMVD/MRC Potamology Program in 1974, a brief description of the Potamology Program since the 1973 flood, a summary description of major parameters which potamology studies have shown to affect behavior of the Mississippi River, conclusions arrived at from the studies conducted, and recommended areas of concentration for future engineering studies.

II. INTRODUCTION

A. A DEFINITION OF POTAMOLGY.

The word "potamology" has its root in the Greek word "potamas" meaning river and is defined as the "science of rivers." In potamology principles derived from the study of alluvial river systems are applied to the design of works needed to control river behavior.

B. THE IMPORTANCE OF POTAMOLGY STUDIES.

The need for potamology studies of the lower Mississippi River arose when man first decided to occupy its alluvial valley. Early settlers tried to devise ways of protecting themselves and their property from the effects of the natural, uncontrolled river. Man still occupies the Mississippi's alluvial valley and still seeks ways to stabilize the river so that it maintains dependable flood profiles for use in designing flood protection structures, and so that it can provide a dependable and efficient low-water navigation channel to support the 400 million tons of commerce that moves annually on the river. To accomplish this objective requires a better knowledge of the river's reaction to various parameters, why these reactions occur, and how to control these reactions and/or predict future changes resulting from them. This is the purpose of the potamology program.

C. THE NATURAL MISSISSIPPI RIVER.

The lower Mississippi River meandered freely across its alluvial valley until this century when man began preventing it from doing so. For instance, Figure 1 shows the river system as it is believed to have been over 3000 years ago when the Ohio joined the Mississippi below Natchez, Miss., and the Arkansas and Red Rivers had a separate outlet to the Gulf. Traces of former meander belts of the Mississippi River are evident across and along the floodplain of the lower river, indicating that no location in the alluvial valley was untouched by the river. The need to control this mighty river was recognized by early settlers who built the first, though ineffective, levee segments along the river. The flood control and navigation structures that exist today represent a continuation of man's early struggle against the river.

D. THE CHALLENGE--MANAGE THE RIVER.

The basic, continuing engineering challenge of the Mississippi River and Tributaries (MR&T) Project which was authorized in 1928 in the lower Mississippi and of the Regulating Works Project in the middle Mississippi River is to manage the river so that it maintains reasonably consistent flood profiles for use in designing flood control features throughout the valley and provides a dependable and efficient low-water navigation channel. The LMVD/MRC potamology program is designed to meet this challenge.

E. MEETING THE CHALLENGE--EARLY POTAMOLOGY STUDIES.

These studies began in the early 1930's. Their major thrust has changed over time to reflect the major design and construction problems in controlling the river.

During the period 1932 to 1945, the primary emphasis of potamology studies was to determine the local effects of cutoffs on water surface profiles and velocities, and to define the basic design parameters for the efficient development of cutoffs. This work contributed to the cutoff program of that period which successfully lowered flood profiles on the lower Mississippi.

During the period from 1946 to 1963, the emphasis was on studying the causes of revetment failures of the river's banks, and developing improved construction methods and materials for the revetment program. The results of this work are evident in the highly efficient and dependable articulated concrete mattress program of today.

During the period 1963 to 1972, the potamology studies became more comprehensive with respect to the river system, and were directed at defining the means for stabilizing short, troublesome reaches of the river. The results of this work contributed to the present ability to analyze such problem locations with the help of hydraulic models and to develop river alignment and dike systems for each location.

III. THE 1973 FLOOD—CONCERN WITH CHANGES IN CHANNEL CAPACITY

A. THE PROBLEM CONFIRMED.

Data collected during the 1973 flood indicated that the efficiency of the channel over a major section of the lower Mississippi had seriously diminished. The project flood flow line (design water surface elevation) and levee grades for the flood control project on the lower Mississippi River had been established based on stage-discharge relationships observed during the floods of 1945 and 1950. As the 1973 flood developed, it was apparent that stage-discharge relationships (Figure 2) were higher than those used to set the design flow line elevation and levee grades in the Mississippi for 250 miles both upstream and downstream from Vicksburg, Miss. Computations at the Vicksburg gaging station indicated that bankfull capacity was 18 percent (300,000 cfs) less than 1950 bankfull channel capacity. Similarly, at the peak stage of the 1973 flood with the river approximately 10 ft above bankfull stage, computations indicated that the capacity of the river was about 15 percent (350,000 cfs) less than the capacity under 1950 channel conditions. The loss of capacity of the river amounted to about a 4.5-ft upward shift of the 1973 stage-discharge relationship compared to the 1950 relationship.

B. A PANEL OF EXPERTS CONVENED.

In view of these circumstances, the President, MRC, convened a panel of experts representing various elements of the Corps and the academic world. Dr. Alvin Anderson, University of Minnesota, Dr. Vito Vanoni, California Institute of Technology, and Dr. Darrel Simons, Colorado State University, represented the academic world. The Corps of Engineers was represented by the Committee on Channel Stabilization, the Waterways Experiment Station (WES), the LMVD Potamology Board, and a representative from the Missouri River Division. The panel was briefed on the river conditions confirmed by data observed during the 1973 flood. The panel was then asked to make recommendations to MRC on the advisability of immediately initiating a major levee raising program and on the direction that potamology studies should

take. The panel concurred that the levee raising program was prudent and needed. It further recommended that studies should initially focus on a detailed, comprehensive review of the vast amount of data that had been collected over the years on the many varied aspects of the lower Mississippi River. This review would provide a strong and reliable basis for follow-on detailed studies of the river's reaction to various factors.

C. THE SUBSEQUENT POTAMOLOGY PROGRAM.

The subsequent potamology program was designed to follow the recommendations of the panel. Objectives of the program were to:

- (a) Review available prototype data.
- (b) Identify the major parameters that control the behavior of the lower Mississippi.
- (c) Determine how each parameter influences river behavior.
- (d) Analyze the relationships among parameters.
- (e) Recommend principles for designing the engineering works used to control the river.

The major geographical limits of the study area extended from St. Louis, Mo., to the Gulf of Mexico. The overall study area encompasses the entire river basin.

Review of prototype data was completed in FY 77. Data gathered and reviewed during this activity are stored in the large WES computer for convenient use in detailed studies.

The studies described in this report were initiated subsequent to the review of prototype data and included detailed study of four parameters as follows:

- (a) Hydrology
- (b) Sedimentation
- (c) Channel and Overbank Geometry
- (e) Man-made modifications.

Each study sought to identify the influence of each of the individual parameters on river behavior, to develop design concepts, and to recommend principles for designing channel improvement features.

IV. DISCUSSION OF MAJOR PARAMETERS AFFECTING RIVER BEHAVIOR

A. SELECTION OF MAJOR PARAMETERS.

Study of a river system the size of the Mississippi is a large undertaking involving a tremendous volume of prototype data. It was felt that the most efficient way of conducting such a study would be to break the task into parts or packages with each representing a major parameter affecting river behavior. In selecting the major parameters, consideration was given to type and comprehensiveness of available prototype data and the suitability of parameters for separate, individual analysis with a minimum of overlap with other parameters.

Hydrology was selected on the basis of stage and discharge data; sedimentation was an obvious parameter; channel and overbank geometry was selected on the basis of availability of hydrographic surveys, and man-made modifications was selected in order to group levees, cutoffs, revetments, dikes, diversions, and reservoirs under one heading.

Support for the above parameter selection can be found in several papers and texts on river engineering or related subjects. For example, Fisk⁽¹⁾ stated that slope, load, discharge, and the nature of bed material largely control river characteristics; Blench⁽²⁾ named average width, depth, slope, and meander size as major independent variables affecting river behavior; Leopold and Maddock⁽³⁾ named as chief variables mean velocity, depth, width, slope, quantity of sediment transport, and sediment size composition; and Shen⁽⁴⁾, in discussing variables influencing river morphology, stated that the engineer concerns himself with aspects of man-induced changes of hydrology, storm events, and the influence of modern channel morphology (width, depth, slope) on flow characteristics and sediment transport.

Although these references do not specifically cite the parameters selected, the variables named can easily be grouped under the first three: hydrology, sedimentation, and channel geometry. In regard to man-made modifications, three of the references cited (2-4) discuss man-made modifications at length and two (3 and 4) describe changes to river systems that have occurred as a result of man-made modifications. The Mississippi River has been transformed from a meandering, restless river to one of fixed alignment with a confined floodplain; therefore, the selection of man-made

modifications as a major parameter affecting river behavior is considered appropriate.

B. HYDROLOGY.

1. Influence of Water on Channel Geometry and Alignment.

Various investigations, both laboratory and field, have demonstrated that channel width and depth are related to the discharge of water through the channel (Lacey⁽⁵⁾, 1939; Friedkin⁽⁶⁾, 1945; Leopold and Maddock⁽³⁾, 1953 and Shen⁽⁴⁾, 1971). General relations developed from these investigations are usually presented in the form:

$$\text{width} = aQ^b \quad (\text{IV-1})$$

$$\text{depth} = aQ^b \quad (\text{IV-2})$$

where Q = water discharge in cubic feet per second, and a and b are numerical constants. From these relations, the greater the discharge of water that moves through a channel, the larger the cross section of the channel. Lesser discharges of water will produce an opposite effect. These relations are significant because they provide a basis of explanation for the highly mobile nature of channels in alluvial rivers such as the Mississippi.

Investigations have also established relations between water discharge and channel alignment or, more precisely, meander wavelength (Leopold and Wolman⁽⁷⁾, Dury⁽⁸⁾, and Carlston⁽⁹⁾). The general form of the relation is:

$$\lambda = aQ^b \quad (\text{IV-3})$$

where λ = wavelength in feet, Q = discharge of water in cubic feet per second, and a and b are numerical constants. This relation states that wavelength varies with discharge and while these relations are very general they confirm that hydrology influences river behavior.

2. Conditions Necessary for a Completely Stable River.

Considering only discharge, the ideal would be a steady, uniform flow daily, seasonally, and annually. This would provide, in accordance with relations IV-1, IV-2, and IV-3, a channel of given width and depth with uniform meander wavelength, assuming homogeneous material in the bed and banks and a given gradient. The Mississippi, due to the great size of its drainage basin and the rainfall and runoff patterns over it, does not have these characteristics.

3. Complex Mississippi River Basin Hydrology.

The drainage area of the Mississippi River basin, 1,246,000 square miles, is comprised of six major basins--Ohio, upper Mississippi, Missouri, Arkansas, White, and lower Mississippi--which contribute flow in varying amounts to the Mississippi. Average annual precipitation over the basin is 30.8 in., but it varies from 21.8 in. over the Missouri basin to 48.5 in. over the Lower Mississippi basin. Average annual runoff from the basin is 8.5 in. and varies from 2.38 in. in the arid Missouri basin to 17.97 in. in the humid Ohio basin. Table 1 shows average annual and average monthly runoff values from the major basins; these indicate that the Missouri and Arkansas River basins produce the least runoff.

Floods on the lower Mississippi usually originate in the Ohio basin and generally occur in early spring, while high flows from the Mississippi River above Cairo, Ill., usually occur in late spring and early summer and are significantly influenced by snowmelt. Table 2 shows average annual and average monthly flows at various major gaging stations on the Mississippi and its tributaries as well as average percent contribution by the Ohio and upper Mississippi River to the flows at Vicksburg, Miss. The percentage values show the Ohio as the largest contributor in January, February, March, April, May, November, and December with the Mississippi contributing the major flow in June, July, August, September, and October.

4. Variable Flows.

The magnitude of discharge in the lower Mississippi River varies substantially. This is illustrated by the graph shown in Figure 3 which was prepared from stage records between 1944 and 1980 at Vicksburg, Miss. The middle dashed line represents the average stage for each month. The upper and lower lines represent the maximum and minimum experienced stage in each month, respectively. The range in stage between the extremes varies from about 28 ft in October to about 50 ft in January, indicative of a highly variable flow regime. The following paragraphs address some specific types of variation that affect river behavior.

5. Effect of Variable Flows.

Major floods on the Lower Mississippi River can crest in any month from January to May. Table 3 lists major floods on the lower Mississippi, the dates they crested, and the average water temperature corresponding to the month in which the flood peaked. The significance of this is that water

temperature affects water viscosity and thus sediment transport capability (cold water--high transport, warm water--low transport) causing changes in the hydraulic efficiency of the river.

Extended durations of above or below normal flows affect channel capacity. Long durations of above normal flows tend to increase flow capacity, relative to the norm; and conversely, extended low flows tend to decrease channel capacity. Analysis of flow records at Vicksburg (Table 4) indicates that above normal flows preceded the 1950 flood while below normal flows preceded the 1973 flood.

Multicrested flood hydrographs cause loop effect (the phenomenon of alluvial rivers that causes the rising limb of a stage-discharge relationship to adjust upward when a secondary rise precedes the major rise). Figure 4 shows how the stage-discharge relationship is affected when the river rises to a crest, begins to recede, and rises to a second higher crest. The dashed portion of the loop rating curve represents the relationship for the first rise and the solid portion represents the second rise. The effect of this variation is to increase the stage above what it would have been if the rise had continued without a secondary crest. Figure 5 shows the stage-discharge relationship observed at Vicksburg in 1973.

The effects of varying magnitude of flow appear as annual fluctuations of stage for a given magnitude of water discharge. The graph in Figure 6 illustrates the short- and long-term fluctuations for a given discharge at Vicksburg. Because flows affect channel configurations which produce a range of stages for a given discharge, it is important from a design standpoint to define those flow conditions associated with upper and lower ranges of a stage.

6. Control of Hydrology.

As stated in section 2 above, the ideal would be a steady, uniform flow daily, seasonally, and annually. To date reservoirs, both single-purpose and multipurpose projects with 75,000 ac-ft and greater total storage capacity, control about 58 percent of the Mississippi River drainage basin. A quantitative analysis of the degree of control exerted by reservoirs is beyond the scope of studies conducted to date; however, the graphs in Figure 7 show an apparent decrease in peak flows and an increase in minimum flows, a trend indicative of reservoir operation. While the trend is favorable, its effect is not significant, and since it is unlikely that additional reservoirs will

be constructed, future design concepts will have to consider variable flows and their effects on channel conditions.

C. SEDIMENTATION.

1. Influence of Sedimentation on River Behavior.

Sedimentation is an important and complex parameter. Sediment transport is intricately related to flow of water and is therefore subject to the same variations as flow of water. Because of a highly varied flow and sediment regime and the heterogeneous nature of the riverbanks, the Mississippi River provides a channel which varies significantly relative to sediment transport capability. These variations in sediment transport capability, locally and throughout the river system, have a profound influence on river behavior.

2. Sediment Characteristics.

The types of sediment moved by flow include clays, silts, sands, gravels, and cobbles. Modes of transportation include suspension, saltation, and rolling and sliding, all of which occur simultaneously. "Bed load" is a term used to describe material moving on or near the bed. "Suspended load" is that portion of the total sediment load that is transported in suspension. Sediment can be classified by source as follows: "wash load" which is composed of silts and clays, and "bed sediment load" which is composed of materials in suspension that are also found in the channel bed, primarily sands. Both the bed sediment load and the wash load may move partially as bed load and partially as suspended load, although practically all the wash load is carried in suspension. "Total load" is comprised of suspended load and bed load.

3. Sediment Sources.

Sediments transported by the Mississippi River are a product of tributary inputs and scour of the bed and banks of the main stem channel.

Primary sources for the reach of river from St. Louis, Mo., to Cairo, Ill., are the Missouri and upper Mississippi Rivers. Early accounts described the Missouri River as being thick and muddy while the upper Mississippi was described as relatively clear with some locations colored to mildly turbid. Reservoir and bank stabilization construction has significantly affected sources in the Missouri River basin. The effect of similar construction in the upper Mississippi River basin has been much less pronounced.

Primary sources for the lower Mississippi River from Cairo, Ill., to the Gulf of Mexico are the Mississippi, Ohio, Arkansas-White, and Red-Ouachita Rivers, and bank caving and channel bed scouring on the main stem, particularly the +600 miles of river from Cairo, to Natchez, Miss. The natural Arkansas and Red Rivers transport significant quantities of suspended sediments. The Ohio and the smaller White and Ouachita Rivers are relatively clear flowing, similar to the upper Mississippi. Reservoir and bank stabilization construction has significantly affected sources on the Arkansas River and to a much lesser extent on the Ohio River. Bank stabilization construction has significantly affected bank caving volumes on the Mississippi River and is beginning to affect volumes on the Red River.

Bed-load sediment sources have been affected but in terms of location not volumes. Volumes of coarse material prevented from caving into the river by bank stabilization and/or being trapped by reservoir construction are replaced to the system by scour of channel bed and bars.

4. Measurement of Sediment Loads.

The portion of the total sediment load that can be measured with some degree of reliability is the suspended sediment load. Long-term records of measurements of suspended sediment loads, although scarce, are available for the Missouri, Arkansas, Red, and Atchafalaya Rivers and for two locations on the Mississippi River: St. Louis, Mo., and Red River Landing, La. Short-term records are available at Arkansas City, Ark., Vicksburg, Miss., and Natchez, Miss. Material moving in suspension near the riverbed and adjacent to the riverbed by rolling, sliding, or saltation cannot be measured; however, materials in the bed of the river are sampled to provide information on sediment size and gradation.

5. Sediment Supply.

Sediments have historically been supplied to the Mississippi River in varying magnitudes and composition by the tributaries and locally through bank caving. The long-term trend in the Mississippi River is a decrease in measured suspended sediment load. The decrease has occurred primarily in the loads supplied by the Missouri and Arkansas basins as shown in Figure 8. The tributary reductions plus reduction resulting from stabilization of caving banks along the main stem have resulted in a 46 percent reduction in annual

suspended sediment load at Tarbert Landing on the Mississippi and 30 percent at Simmesport on the Atchafalaya River.

While measured suspended sediment loads have decreased significantly, bed-load quantities in the Mississippi River are believed to be essentially unchanged. It is generally accepted that water discharge will transport quantities of bed-load material depending on availability and characteristics of the material and hydraulics of the system. For example, reaches immediately downstream of a newly constructed reservoir are subject to erosion of the channel bed as the river uses bed material to replace its bed load captured by the reservoir. In this sense then, bed-load transport is not materially affected in alluvial rivers with erodible channel beds unless the hydraulic characteristics of the system are changed or the magnitude of discharge modified. The hydraulic characteristics of the Mississippi River system have not changed materially in recent history and there is ample physical evidence (sandbars) that sufficient supply of coarse material is available; therefore, bed-load quantities are believed unchanged.

6. Sediment Transport.

Sediment technology has not clearly defined the physical laws governing the transportation of sediment, nor has it advanced to the point that bed-load sediments can be reliably measured; therefore, it is necessary to study the changes in sediment transport by analyzing changing shape, size, and location of sandbars and scouring and shoaling of the channel bed. Hydrographic surveys, aerial photography, maintenance dredging records, and field observations provide the data necessary for studies.

Sandbars are common features of alluvial rivers. Properly located, they serve an important function relative to sediment transport processes. The proper location of sandbars, based on subreaches which are not troublesome, is a geometrical pattern of alternate point bars, uniformly spaced. Disruption of point bar spacing with random middle bars which migrate and change size denotes an imbalance in sediment transport capability. It is this kind of activity that can interfere with navigation and adversely affect flood conveyance. Many reaches of the Mississippi formerly having unstable middle bars have been improved, but a number of subreaches, although somewhat improved, continue to have less than desirable sediment transport capabilities.

Scour and fill of the channel bed are also common in rivers with erodible beds. On the Mississippi River, it is known that crossings fill during rising stages and scour during falling stages. The reverse process occurs in bendways. This process is directly related to channel alignment and functions best in a sinuous channel with point bars. The process is disrupted and distorted by wide channel widths, divided channels, and long straight reaches. The consequences are raised flood flow lines and interference with navigation.

Prior to intensive construction of channel improvement features, much of the channel of the Mississippi River from St. Louis, Mo., to the vicinity of Natchez, Miss., was characterized by distorted channel geometry and numerous middle bars. Many of the reaches have been improved and are now satisfactory. This has been accomplished by training and contracting the river channel to achieve better sediment transport capabilities. Some reaches, however, continue to be troublesome although improved. These reaches are characterized by straight channel alignment and/or wide shallow cross section. Figure 9 illustrates a straight reach. Divided channels are also not conducive to efficient sediment transport because bed-load sediments generally do not divide in proportion to flow.

The task of future designs is to provide better transport capabilities locally and throughout the river system. Engineering works must be designed to minimize deposition and maximize scour. This can be accomplished through realignment of the channel, greater contraction of channel width, concentration of flow to one primary channel, and contraction of flows at higher elevations. Some reaches may be improved by one of the above modifications or it may require combinations of works. The primary principle is to reduce the magnitude of deposition during rising stages and increase the scouring capability of the river during falling stages.

D. CHANNEL AND OVERBANK GEOMETRY

1. Relation to River Behavior.

Theoretically, a river channel will develop stable geometric parameters for the ideal hydrologic and sediment conditions previously described. Laboratory research has demonstrated that unique geometric channel parameters of sinuosity (ratio of channel length to valley length), width, depth, and cross section will develop and remain stable for a uniform rate of discharge

and fixed slope. The Mississippi River is, however, far from that ideal configuration.

Enormous variations exist in channel sinuosity varying from the extreme sinuosity of the Togo reach located about 22 miles downstream of Vicksburg, Miss., to straight reaches of negligible sinuosity, such as the Kate Aubrey reach, located just upstream from Osceola, Ark. Channel widths and depths vary greatly throughout the river exhibiting very wide, shallow channels with middle bars, divided flows, and secondary chutes. These channel conditions affect overall channel roughness and significantly affect river behavior. Causes for these undesirable channel conditions are partly natural and partly man's influence.

2. Natural Influences.

Much of the existing alignment and general channel geometry of the lower Mississippi River is a function of natural processes. Exceptions are the reach of river from St. Louis, Mo., to Cairo, Ill., which has experienced significant changes in geometry as a result of the channel stabilization program and the middle reach of the lower Mississippi which was significantly shortened as a result of the cutoff program. Natural factors that affect alignment and geometry include: geology of the valley (bluff lines, depth to tertiary deposits, fault zones, etc.), subsurface soils (gravel deposits, clay plugs, point bar deposits, etc.), and variable hydrology.

3. Man-made Modifications.

Man-made modifications to the river channel have indirectly affected channel geometry and alignment. In the reach of river between Cairo, Ill., and St. Louis, Mo., channel stabilization construction initiated about 1888 has caused a significant decrease in average channel widths and an increase in channel depths. In the lower Mississippi River, a program of bendway cutoffs designed to reduce flood flow line elevations significantly reduced channel length from near Old River, La., to near Memphis, Tenn. Subsequent adjustments by the river, to the instability produced by the cutoffs, have produced a wider channel which is hydraulically rougher causing a loss in flood flow capacity.

4. Geometrical Characteristics of the Mississippi Channel.

Data from five historic hydrographic surveys have been analyzed to determine how average geometrical elements of the river (width, depth, and

cross-sectional area) have changed over time. Dates of complete surveys available for analysis were 1889, 1921, 1946, 1959, and 1977 for the reach St. Louis to Cairo, and 1878-1890, 1913-1915, 1948-1951, 1962-1964, and 1975 from Cairo, Ill. to the Gulf. Average elements for bankfull and low flow for the St. Louis District (Miles 0 to 195 above Cairo, Ill.) are shown in Table 5. Results of the analysis clearly indicate the degree of change that has taken place and the time period in which changes occurred. In regard to the low-water channel, average width decreased about 20 percent from 1889 to 1921 and has remained fairly consistent since. Initial dike construction between 1880 and 1910 was apparently successful in closing off secondary channels causing the development of a deeper, narrower, better defined channel. In regard to the bankfull channel, channel width from 1889 to 1921 decreased almost 40 percent but regained an increment between the 1921 and 1946 surveys. The cause for the increase in width between 1921 and 1946 is not clear, but it is possible that the 1927 flood, a major flood, could have destroyed much of the former dike work causing the channel to widen. Subsequent contraction activities have generally maintained average geometrical elements since 1946.

Channel geometry in the Memphis District (Mile 973 to 515 AHP) has not changed significantly in recent history. The greatest change has been in the low-water channel which has shown an increase in cross-sectional area of about 20 percent.

Geometrical elements in the Vicksburg District (Mile 595 to 320 AHP) show a significant increase in average width and cross-sectional area from 1948-1951 to 1975. Table 6 shows average geometrical values for the District indicating a 16.4 percent increase in width, 13.7 percent increase in cross-sectional area, and 5.0-ft average increase in hydraulic radius. The area/width ratio, which yields an average depth assuming a rectangular channel shape, indicates virtually no change. These values represent changes in channel geometry at an elevation 40 ft above the low-water reference plane (LWRP) which is about bankfull. Reaches experiencing the greatest increase in width are Mile 530 to 500 AHP (approximately 2000-ft increase) and Mile 430 to 400 AHP (approximately 2000-ft increase). One reach (Mile 490 to 470 AHP) experienced a decrease in average width (approximately 450 ft).

The channel in the New Orleans District from Old River Control, Mile 314, to about Mile 200 AHP has experienced a reduction in cross-sectional area of about 15 percent with a corresponding decrease in hydraulic radius of almost 20 percent. Most of the reduction appears to have occurred since 1950; however, earlier surveys do indicate some loss prior to 1950. The decrease is primarily caused by the diversion of a portion of the Mississippi River flow to the Atchafalaya River via Old River. The percentage of flow diverted has, however, remained about the same since 1950 indicating that channel adjustment to reduced flow in the Mississippi is lagging the timing of diversion magnitudes or other factors are involved. Studies have not adequately solved the question. The channel below about Mile 200 AHP is unchanged over the past 40 years.

5. Undesirable Geometry and Alignment.

Undesirable geometry and alignment is defined as any geometry and alignment that disrupts hydraulic parameters and sediment transport capabilities, hinders navigation, and/or acts as an impediment to conveyance of flood flows. It has already been noted that existing Mississippi River geometry and alignment deviates significantly from that of a river with uniform sinuosity and geometry; however, it is apparent that sinuosity and geometry are not extremely sensitive in that satisfactory performance has been achieved throughout most of the river with the aid of strategically placed channel improvement features. Locations that have been the most difficult to improve, requiring excessive improvement features, are straight reaches, divided channels, and excessively wide cross sections.

In a river with a significant bed-load movement such as the Mississippi, the hydraulic and geometry characteristics of the channel must accommodate all flows and provide storage for high-flow sediments in periods of low flow. Nature does this by building a sinuous channel that is efficient for all stages and provides conditions to accommodate sediment loads transported by the river. Anding⁽¹⁰⁾ indicates that the meandering reach, because of its energy slope variations, does a better job of maintaining itself than a straight reach (Figure 10). A sinuous river can adjust its slope by adjusting its path of flow; thus, it can effectively balance the movement of sediments. Dredging records and dike construction records for a sinuous reach

and for a relatively straight reach have been compared to illustrate the difference in effort necessary to maintain navigation.

Figure 11 shows the location and general alignment of the two reaches, Ozark-Eutaw and Baleshed-Ben Lomond. Figures 12 and 13 show channel alignment developments in the two reaches over an extended period of time. Table 7 compares certain statistics for the two reaches including: sinuosity, top bank width, total length of dikes constructed, and total yards of maintenance dredging required over a given time period. It is quite apparent that the Baleshed-Ben Lomond reach suffers from severe sediment deposition during the passage of a flow hydrograph. Analysis of stage, discharge, slope, and velocity data reveals significant differences in hydraulic parameters for the two reaches. For example, water surface slopes increase with stage through Ozark-Eutaw and decrease with stage through Baleshed-Ben Lomond. Velocities in Ozark-Eutaw average about 7.0 ft per second at about bankfull compared to about 4.8 ft per second at Baleshed-Ben Lomond.

The importance of consistency of channel geometry and alignment, locally and throughout, is illustrated by the above example. However, it is impractical to remold existing geometry and alignment to achieve consistency; therefore, future designs must concentrate on development of channel improvement structures capable of modifying hydraulic parameters in those reaches that are significantly out of phase.

A program of physical model studies to optimize channel alignment and geometry, considering both flood control and navigation purpose, should be conducted. The most troublesome reaches include: Greenville reach (Miles 535 to 545 AHP); Baleshed-Ben Lomond (Miles 480 to 490); Cottonwood Bar (Miles 466 to 473); Racetrack Bar (Miles 427 to 434); Togo Island (Miles 412 to 420); and Middle Ground Bar (Miles 405 to 410).

E. MAN-MADE MODIFICATIONS.

Because of his desire to live in the river's alluvial valley, man has modified and attempted to control the river to prevent flooding and provide safe dependable navigation. Major man-made works utilized to accomplish this goal include: flood protection levees, cutoffs to reduce flood profiles, revetments to stabilize banks and prevent channel meandering, dikes to contract the low-water channel and encourage development of a desirable alignment, dredging to remove undesirable shoal areas in the channel and make

desirable realignments of the channel in specific locations, and tributary improvements which include all or most of the same features utilized on the Mississippi.

These modifications have collectively and individually affected river behavior and its characteristics in varying degrees. Collectively, they have raised overbank stages by confining flood flows (levees); confined the river channel to one alignment (revetments and dikes); shortened the river and reduced stages in the middle portion of the lower Mississippi River (cutoffs); contracted the low-water channel encouraging enlargement of the navigation channel (dikes); and reduced suspended sediment loads (bank stabilization and reservoir regulation). Effects of some of these works offset or compensate for the effects of others.

For example, stage increases (levees) cause more of the flow to be confined to the channel area, and if levees alone are used over an extended period, changes in channel alignment and geometry can be expected. But bank stabilization and channel alignment control by revetments and dikes tends to offset this effect. Additionally, cutoffs have significantly lowered stages in some reaches reducing the frequency and duration of overbank flows, and the effect of levee confinement. Finally reservoir regulation reduces the crest of flood hydrographs reducing frequency and duration of overbank flows, and thus, also reducing the effect of levee confinement.

Another example is the cutoffs which reduced stages but also shortened the river inducing instability. The natural reaction of the river was to meander and recapture lost length, but the bank stabilization program prevented this and forced the river to make other adjustments to reduce or absorb the excess energy created by the shorter river length. The river has apparently reduced some of the energy excess by adjusting slopes above the point of the majority of the cutoffs (stages at Helena and Memphis have decreased). It has also done this by producing less efficient channel geometry through the reach where most of the cutoffs are located (Natchez to about Greenville), as evidenced by the fact that stages have increased with respect to those in 1950 at Natchez, Vicksburg, and Lake Providence but not at Arkansas City which represents a pivot point between the two major reaches.

The following sections will briefly discuss effects of individual works.

1. Levees.

Levees confine overbank discharges to a relatively narrow floodway compared to natural conditions and thus cause stages to increase. Figure 14 shows annual peak stages at Natchez, Miss., from the 1800's to the present. Prior to 1890, peak stages did not exceed bankfull stage appreciably indicating significant overbank flow capacity. Beginning about 1890, a noticeable increase above bankfull is evident, and by 1930 stages almost 10 ft above the bankfull reference line were occurring. Evolution of average levee height is superimposed in Figure 14 for reference. Similar graphs were prepared for Arkansas City, Memphis, and St. Louis to show effects at other locations along the river. These graphs are shown in Figures 15-17. The long record of stages and their consistent pattern, plus the fact that no other major alteration of the river took place prior to 1890, support the conclusion that the increase in stages was attributable to confinement of the floodplain by levees. The effect of levee confinement is less pronounced in the reach Cairo, Ill., to St. Louis, Mo., because capacity of the overbank has been less affected.

Confining overbank discharges confines suspended sediment loads. Those sediments that ordinarily passed into the overbank and possibly were deposited under unconfined conditions apparently must be transported under confined conditions. Consideration of this fact has led some engineers to conclude that confinement would result in aggradation of the channel, believing that the confined sediment load would be in excess of the river's transport capability. Whether or not confinement caused aggradation due to an excessive load cannot be confirmed. The cutoff program, to be discussed in a subsequent section, certainly interrupted the process if it were active, and suspended sediment loads in the river are about 50 percent of loads 30 years ago. Therefore, the effects of levees on suspended sediment loads and their subsequent effect on river behavior are considered negligible, particularly in regard to future conditions.

Another aspect of levee confinement is the effect of variable widths between levees and/or between levee and bluff line on hydraulic parameters during flood flows when a portion of the flow is transported by the

overbank. The degree of confinement varies significantly, particularly from Baton Rouge, La., upstream. Minimum widths are about 3200 ft between levees, primarily downstream of Baton Rouge, ranging to a maximum of about 15 miles at various locations. A potential for significant effect is recognized; however, studies have not revealed prototype conditions that could confidently be identified as a product of variation in overbank flows, a possible reason being that overbank flow occurrences have been relatively infrequent over the past 30 years. While variations of confinement could be a significant parameter, particularly in the case of an extended cycle of frequent overbank occurrences, it is impractical to relocate levee segments to obtain more uniformity of confinement; therefore, future designs will have to accommodate conditions as they exist.

2. The Cutoff Program.

The element that probably has had the greatest effect of any man-made feature on the channel capacity of the main channel was the series of cutoffs that were constructed in the middle portion of the lower Mississippi River between 1932 and 1942. A total of 16 cutoffs were developed in that period within the section of river from about 20 miles downstream from Natchez, Miss., to about 55 miles downstream from Memphis, Tenn. The locations of the cutoffs are shown on Figure 18 and statistics on individual cutoffs are presented in Table 8.

The basic purpose of the cutoffs was to increase the flood carrying capacity of the river and thus avoid the necessity of constructing protection levees to heights considered extreme. The cutoff program was a success in that it produced the lowest stages experienced in modern times in the section of river affected. But the cutoffs also induced instability causing the river to react and seek to reestablish its pre-cutoff hydraulic regime.

Initial effect of the cutoffs on stages varied depending on the relative locations of cutoffs to major gaging stations. The greatest lowering of stage, 16 ft, occurred at the Arkansas City gaging station, located just upstream from the Greenville Bend cutoffs. The Vicksburg gaging station experienced the next largest lowering, 10 to 12 ft. The direct effect of cutoffs at the Natchez, Helena, and Memphis gaging stations was much less significant. Figure 19 is a time series plot of the average annual stage for

a specific discharge at the Natchez, Vicksburg, Arkansas City, Helena, and Memphis gaging stations.

Lane⁽¹¹⁾ states: "The changes which take place in erodible channels due to cutting off bends may be divided into two classes: (a) immediate changes, and (b) long-period changes."

Immediate changes are seen in the reduction of stages. Long-term changes are more complex. Theoretical changes, associated with a single cutoff, are bed lowering upstream of the cutoff and bed raising downstream of the cutoff. The number of cutoffs made and their close proximity to each other in most cases prevent verification of the scour and fill concept. It is noted, however, that stages at Helena and Memphis show a long-term decreasing trend which could be interpreted as the scour component. It is also noted that stages at Vicksburg, Natchez, and Red River Landing show a long-term increasing trend which could relate to the fill component. The channel has not, however, experienced fill. Hydrographic surveys in the reach Arkansas City, Ark., downstream to Red River Landing show an increase in average channel cross-sectional area, rather than a decrease. This means that the increase in stage is caused by changes in channel geometry and alignment, changes that cause the channel to be less efficient. The changes are seen in the form of increased number and size of sandbars, increase in size of divided flow subreaches, and increase in average channel width which affects hydraulic parameters and sediment transport capabilities. The significance of the changes in channel morphology is that the river is seeking to reestablish its pre-cutoff hydraulic regime through adjustment in channel geometry. The objective of these adjustments is to increase hydraulic roughness and develop features (divided channels, etc.) that interfere with flood flow capacity. Future designs must recognize the potential for development of undesirable channel geometry and alignment in individual reaches, and structures designed to minimize and/or arrest these conditions should be constructed in a timely manner.

3. Revetments.

Bank stabilization is an essential component of the Channel Improvement Program. The wandering tendency of the Mississippi River is well documented. Without stable, erosion resistant bank lines to arrest lateral movement, no location in the valley would be safe from the river's destructive forces.

Revetment construction has successfully restricted the meandering tendencies of the river, but it has not yet succeeded in stabilizing either the alignment or the cross section of the river sufficiently to preclude the development of wide, undesirable geometry that has affected hydraulic performance of the river and caused flow-lines to raise. The revetment program should be completed as rapidly as possible. Top bank control is essential to providing a dependable, stable channel for flood control and navigation. In the reach of river from St. Louis to the vicinity of Baton Rouge, La., control of channel width is essential to providing stable, dependable channel alignment and geometry. From the vicinity of Baton Rouge downstream, control of top bank is essential to safety of flood control structures, primarily protection levees.

Annual monitoring of bank caving activities is used to determine average annual and maximum bank caving rates at specific locations throughout the 300 miles of river from approximately Red River Landing, La., to the Gulf. A similar program should be developed and executed for the remaining section of river upstream to St. Louis, Mo.

Currently the most active caving bank lines, excluding some localized situations, are located downstream of Natchez, Miss. Top bank width is increasing in this section of river and could, if allowed to continue at the present rate, cause other changes in the channel. These changes could result in development of additional undesirable channel geometry and alignment causing further increases in flood flow-lines in that section of river.

4. Dikes.

Dikes are designed and used extensively throughout the section of river from St. Louis, Mo., to Red River Landing to develop and maintain a desirable low-water channel alignment. These structures serve three basic purposes: (a) to contract the low-water channel sufficiently to cause the river to scour and maintain a dependable navigation depth; (b) to close off secondary channels by encouraging sediment deposition to provide and maintain a single channel; and (c) to develop and maintain an alignment improving the balance between hydraulic parameters and sediment transport capabilities and providing areas for temporary storage of excess sediments. The program to date has been successful in meeting these purposes; however, some reaches, although improved, continue to be problem areas in spite of considerable construction effort. In the St. Louis District three particular areas fall into this

category: Mile 50, Mile 96, and Mile 117 above Cairo, Ill. In the Memphis District, two areas continue to be problem reaches: Kate Aubrey reach (Mile 785 to 800 AHP) and Buck Island reach (Mile 695 to 705 AHP). The Vicksburg District also has two areas: Greenville reach (Mile 535 to 545 AHP) and Lake Providence reach (Mile 480 to 495 AHP).

The problem in three of the four areas in the Memphis and Vicksburg Districts (Kate Aubrey, Greenville, and Lake Providence) is basically their lack of sinuosity and their wide, shallow geometry. In the fourth area, Buck Island, the problem is excessive sinuosity (alternate bars spaced too closely) and wide geometry. All four reaches have a long history of maintenance dredging. The three areas in the St. Louis District are primarily characterized by wide cross sections and at Mile 50 a divided flow situation. Maintenance dredging is required almost annually to provide project depth and width. The low-water channel widths at Miles 50, 96, and 117 above Cairo are 6000, 2080, and 2950 ft, respectively. At bankfull, the channel widths are 10,570, 6410, and 7715 ft, respectively. The average width of the low-water and bankfull channel for the St. Louis Reach is 2,100 and 4,620 ft, respectively. These bankfull widths are significantly greater than the 4620-ft width for the St. Louis reach. The fact that the bankfull channel width at these locations significantly exceeds the average value creates the potential for excessive deposition, and transport capability at higher stages of the subject locations is not adequate to evacuate these depositions as the river recedes to low water. This type of river behavior is common to many locations where excessively wide banks occur. A desirable design for this type of situation would be one that would modify hydraulic parameters to cause the river to begin scouring the deposited material at higher stages than would normally occur in order to move excess material out of the reach before stages approached low water.

Dikes are designed to establish and maintain a midbank and low-water trace approximately 2500 ft wide within the confines of the major bank lines. Laboratory modeling has been conducted to determine best dike configuration individually and in systems. Such efforts have included consideration of spacing, angle to flow, and crest elevations individually and with respect to each other. A major concept is to attract fill within the dike system to effect better, more uniform contraction. While past and present design concepts and criteria have proven satisfactory in the majority of cases, additional considerations are warranted.

Dike design concepts should be broadened to take into account the total sediment transport process, modifying the process where feasible to improve channel conditions from a flood control as well as a navigation standpoint. Reaches where there is excessive deposition of sediments during rising stages could possibly be improved by contracting the channel at higher elevations, thus reducing the magnitude of deposition and initiating scouring of crossings at higher elevations and allowing more time for the river to excavate the material. This concept would be site-specific, with use of mathematical and physical models necessary to optimize dike configurations. Additionally, each reach should be investigated to identify loss of flow to overbank areas through low swales, in obscure abandoned channel segments, etc. The maximum amount of flow possible should be confined to the main channel.

Completion of the dike component of the Channel Improvement Program will require a significant number of structures at many sites along the river. Sequence of construction as reflected by the annual construction program is considered important. Annual construction effort should be concentrated, without regard to District boundaries, at those sites where the greatest potential for significant shift in channel alignment exists. Shifts could cause an imminent threat to a flood control structure and/or adversely affect hydraulic parameters and sediment transport capabilities. Each reach requiring additional structures should be evaluated in relation to all reaches requiring structures, and determination made on the basis of consequences of delaying construction for 1 year. For example, delaying construction of works in the Kate Aubrey reach would not result in loss of control in that reach. The Reid Bedford reach is a different case. This reach is showing strong indications of a significant change in channel alignment and geometry. Delay of structures in this reach could allow the river to develop a situation that could take several years and significant funds to stabilize. Annual construction programs should include all reaches determined to have a consequence and reaches with greatest consequence should make up the program. Significant consequences are defined, in order of decreasing importance, as: threat to a flood control structure; strong indication of adverse change in channel alignment and geometry; excessive sediment deposition interfering with flood control and navigation; repetitive maintenance dredging with a minimal probability of adverse change in channel alignment; and occasional maintenance dredging.

V. CONCLUSIONS

The four major parameters studied--hydrology, sedimentation, channel geometry, and man-made modifications--individually and collectively are the major influences on river behavior.

The increase in flood flow line, revealed by the 1973 flood, is the result of changes in channel alignment (increased severity of curvature in bendways), increases in channel width (causing a decrease in effective transport of bed-load sediments), and development and enlargement of sandbars. The combined effect of these causes is an overall increase (form roughness and bed form roughness) in the hydraulic roughness of the river channel.

Large variations in the magnitude of flow cause variations in sediment scour and fill patterns, variations of hydraulic roughness, and the phenomenon of loop effect. The effect of these variables is annual fluctuations of stage-discharge relationships such that different stages can be observed for the same magnitude of discharge.

Reservoir regulation has favorably altered flows for design of flood control and navigation improvements; however, natural runoff from uncontrolled areas rather than releases from reservoir storage dominates flow variations on the Mississippi River. Since it appears unlikely that additional reservoirs will be constructed, designs will have to accommodate such variations.

The bed of the Mississippi River continues to be highly mobile daily, seasonally, and annually indicating that bed-load quantities have not changed appreciably although measured suspended sediment loads have reduced 50 percent since 1950.

The capacity of the Mississippi River to transport bed-load sediment varies from reach to reach according to variations in channel alignment and geometry. Reaches with deficient transport capability develop sandbars, divided channels, and excessive shoaling, all of which decrease the river's hydraulic efficiency causing flow line raises, and create alignment problems which interfere with river navigation.

The revetment program has successfully prevented the river from meandering, but it has not prevented the development of inefficient channel alignment and geometry. Control of top bank widths through effective and efficient use of revetments, supplemented by other works where necessary, is

essential to the safety of flood control structures and to providing a stable channel for flood control and navigation.

Existing dike systems have generally improved channel alignment and stabilized hydraulic conveyance at selected locations; however, several of these systems have not provided the degree of improvement and dependability desired. Additional study is needed to enhance and/or develop concepts and criteria capable of modifying hydraulic parameters sufficiently to achieve more efficient bed-load sediment transport in a particular reach.

Reaches that are currently experiencing active bank caving (concave and/or convex banks, chute channels, back channels, etc.) represent the greatest potential for future additional losses in channel efficiency. The section of river currently experiencing the most active bank caving, with the exception of the Mississippi River below Baton Rouge, La., is located between Natchez, Miss., and Red River Landing, La.

Design of dike systems, excluding some of the more troublesome reaches that have been model tested, is governed partly by general guidelines established from physical model testing and partly by experience and observation. Although this concept has generally proven satisfactory over the years, there is a need for development of more definitive relationships, established by engineering studies, between hydraulic parameters and bed-load transport capabilities for various channel alignments and geometries.

Delay in construction of channel improvement works in a particular reach that is undergoing changes in alignment and geometry in order to "determine the course the river desires" can result in additional channel improvement works over and above what would have been required if a correctly designed construction had been initiated earlier.

The section of river from St. Louis, Mo., to the Gulf of Mexico is composed of a series of individual reaches, varying in length, exhibiting varying channel alignment and geometry, sediment transport capabilities, and constructed channel improvement features. Additional needs of individual reaches vary from zero improvement to substantial improvement. Types of problems, and therefore solutions, also vary from reach to reach.

Distinction of sediment transport capabilities from reach to reach is primarily based on visual observation and experience. There is a need for a mathematical modeling capability to develop an engineering basis for evaluating transport capabilities of individual reaches. There is also a need

for physical modeling capability to develop more effective design criteria for improvement of reaches with poor transport capability.

There is a need to obtain data on scour and fill patterns during the passage of a flow hydrograph. These data are needed to supplement studies of alternative measures of maximizing scour and minimizing fill activities at specific locations.

VI. RECOMMENDATIONS

Future designs for stabilizing the river must give primary consideration to modifying existing channel alignment and configuration to achieve a better balance between hydraulic parameters and sediment transport capabilities, locally and throughout the river system. It is recommended that designs focus on the concept of minimizing the magnitude of fill during rising stages and maximizing the magnitude of scour during falling stages. Development and utilization of physical and mathematical models are considered necessary to establishing new or improved design criteria for channel improvement structures.

Dike systems that have been active for an adequate period of time and that have not provided a stable, dependable channel should be reevaluated relative to hydraulic parameters and sediment transport capabilities. Future studies should include the following reaches: Baleshec-Ben Lomond (Mile 485 AHP), Greenville (Mile 540 AHP), Buck Island (Mile 695 AHP), Kate Aubrey (Mile 790 AHP), and Robinson Bayou (Mile 855 AHP) and Cape Bend (Mile 50), Potato Bend (Mile 96), and Ellis Grove Landing (Mile 117 above Cairo, Ill.)

Future studies should investigate the feasibility of improving the hydraulic efficiency of reaches which interfere with flood flows. Such reaches include: Middle Ground Bar (Mile 409 AHP), Togo Island (Mile 415 AHP), and Cottonwood Bar (Mile 470 AHP). Active bank caving is occurring in Dead Mans Bend (Mile 338 AHP), and in Graham Bend (Mile 30) and Palmetto Bend (Mile 325 above Cairo). This section of river should be investigated to determine how much future, additional channel widening can be allowed before channel alignment and geometry are adversely affected.

Future additional dikes and dike systems should continue to be constructed to the minimum crest elevation necessary to provide project dimensions for navigation. Exceptions are those reaches where mathematical and physical models determine that sediment transport capabilities can be improved by increasing dike elevations without impacting on flood flow lines. Most

probable locations for exception include the Greenville reach (Mile 535 to 545 AHP) and the Baleshed-Ben Lomond reach (Mile 480 to 495 AHP).

Control of channel width through effective and efficient use of revetments supplemented by other works, particularly in the reach of river from St. Louis, Mo., to the vicinity of Baton Rouge, La., is essential to providing a stable, dependable channel for flood control and navigation. Control of top bank from the vicinity of Baton Rouge, La., to the Gulf is essential for protection of flood control structures, primarily protection levees.

The revetment program should be completed as rapidly as possible. A program of annual monitoring of bank caving activities should be formulated and implemented for the entire reach of river from St. Louis, Mo., to the Gulf. The existing monitoring program by the New Orleans District is noted.

Sequence of construction of channel improvement features is important. Development of annual channel improvement construction programs should consider, in order, the following factors at each loation needing improvement:

- (a) Threat to flood control structures.
- (b) Control of top bank width.
- (c) Control of channel alignment.
- (d) Improved balance between hydraulic parameters and sediment transport.

A threat to a flood control structure should be determined by evaluating annual bank caving rates. Caving bank lines capable of encroaching on the stability control line in 1 to 2 years, using maximum experienced bank caving rates, should receive top priority. Descending priorities should be assigned to other reaches based on estimated encroachment time using maximum caving rates.

Decisions on control of top bank widths should be governed by consequences of no action. Reaches determined to have a high potential for short-term excessive increase in top bank width, increases which would cause the development of undesirable channel alignment and geometry, should be programmed for stabilization at the earliest possible time. "Short-term potential" is defined as 3 to 5 years. Reaches rated as having long-term potential should be assigned lesser priorities.

Decisions on control of channel alignment should also be governed by consequences of no action. Reaches determined to have a high potential for

significant (undesirable) change in channel alignment should be programmed for stabilization immediately. The Reid Bedford and Cottonwood Bar reaches are in this category. Each reach should be rated in terms of potential and the effect of a change on construction quantities and priorities set accordingly.

Decisions on improvement of the balance between hydraulic parameters and sediment transport capabilities reach to reach should be governed by consideration of flood control and navigation. Reaches exhibiting significant imbalance between hydraulic parameters and sediment transport capabilities should receive the highest priority in this category. "Exhibiting significant imbalance" describes reaches that have been difficult to stabilize, experience excessive sediment deposition, continue to be troublesome, and require annual maintenance dredging. These reaches include: Ellis Grove Landing (Mile 117), Potato Bend (Mile 96), and Cape Bend (Mile 50 above Cairo), and Robinson Bayou (Mile 852 AHP), Kate Aurey (Mile 785 AHP), Buck Island (Mile 695 AHP), Greenville (Mile 535 AHP), Baleshed-Ben Lomond (Mile 485 AHP), and Reid Bedford (Mile 428 AHP). Reaches exhibiting lesser degrees of imbalance should receive descending priority ratings.

The section of river from St. Louis, Mo., to the Gulf of Mexico should be subdivided into individual reaches, the length of each determined by consistence of channel alignment and geometry and/or stabilization. Each reach should be described in terms of bank stability, channel characteristics, sediment transport, maintenance dredging, etc. A master file of those reaches requiring improvement should be compiled and updated annually. Each reach in the master file should provide a list of needs, special design considerations, status of completion, and maximum allowable timetable for individual structures (revetment and/or dikes).

VII. THE FUTURE POTAMOLGY PROGRAM

The future program should focus primarily on the major objective of improving the balance between hydraulic parameters and sediment transport capabilities for a full range of flows, locally and throughout the middle and lower Mississippi River. Improvements would increse channel efficiency, minimize the potential for additional, future increases in the project design flood flow line, reduce long-term channel improvement requirements, and reduce annual maintenance dredging requirements. Components of the program include:

(a) Data collection:

- (1) Data storage and retrieval system.
- (2) Scour and fill patterns for various channel alignment and geometry conditions.
- (3) Hydraulic variables for significantly differing channel alignment and geometry cross sections (velocity and slope profiles).
- (4) Bed sediment size as needed and bed-load transport rates.

(b) Development of mathematical and physical models:

- (1) One-dimensional flow-sediment model (mathematical).
- (2) Two-dimensional flow-sediment model (mathematical).
- (3) Steady-state backwater model (mathematical).
- (4) Fixed-bed and moveable-bed physical models with capability to model overbank flows, divided flow, etc., for special reaches.

(c) Detailed analysis of individual reaches:

- (1) Identify basic problem of individual reach (channel alignment, excessive loss of flow from the main channel, excessive width, divided channel, excessive amount of flow in overbank, etc.).
- (2) Establish existing hydraulic parameters and sediment transport capabilities, subject reach, upstream reach, and downstream reach (mathematical and/or physical model).
- (3) Investigate alternative designs (improved alignment, structure modifications, and/or both).

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TABLE 1

AVERAGE ANNUAL AND AVERAGE MONTHLY RUNOFF
IN INCHES

BASIN	ANNUAL	MONTH											
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MISSOURI RIVER HERMANN, MO. 528,200 Sq. Mi.	2.38	.68	.10	.18	.23	.22	.25	.21	.13	.13	.13	.12	.09
MISS. RIVER ALTON, ILL. 171,500 Sq. Mi.	7.85	.43	.48	.87	1.19	1.11	.91	.72	.45	.41	.44	.45	.39
OHIO RIVER METROPOLIS, ILL. 203,000 Sq. Mi.	17.98	2.22	2.54	2.98	2.55	1.82	1.12	.83	.66	.49	.50	.79	1.47
WHITE RIVER CLARENDON, ARK. 25,500 Sq. Mi.	15.76	1.65	1.79	2.11	2.25	2.22	1.45	.83	.62	.51	.52	.72	1.09
ARKANSAS RIVER LITTLE ROCK, ARK. 157,000 Sq. Mi.	3.37	.25	.28	.34	.43	.57	.41	.26	.14	.19	.18	.20	.12
RED RIVER ALEXANDRIA, LA. 67,000 Sq. Mi.	6.37	.65	.71	.84	.79	1.05	.67	.32	.18	.17	.23	.31	.47

TABLE 2

AVERAGE ANNUAL AND AVERAGE MONTHLY

DISCHARGE IN 1000 CFS
(1930-1975)

BASIN	ANNUAL	MONTH											
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
MISSOURI RIVER HERMANN, MO.	72	38	51	81	109	100	119	96	58	60	60	55	39
UPPER MISS. RIVER ALTON, ILL.	98	64	78	129	181	163	138	107	66	62	66	68	58
UPPER MISS RIVER ⁽³⁾ ST. LOUIS, MO.	173	104	130	210	293	266	258	208	127	124	129	126	99
OHIO RIVER ⁽²⁾ METROPOLIS, ILL.	266	388	487	520	460	318	202	145	116	89	88	142	257
LOWER MISS. RIVER MEMPHIS, TENN.	456	494	630	743	808	638	492	394	268	214	217	257	336
WHITE RIVER ⁽⁴⁾ CLARENDON, ARK.	29	36	43	46	50	49	33	18	14	12	11	16	24
ARKANSAS RIVER ⁽⁵⁾ LITTLE ROCK, ARK.	39	33	41	46	60	78	57	36	19	20	26	25	27
LOWER MISS. RIVER ⁽¹⁾ VICKSBURG, MISS.	552	571	731	854	948	825	619	490	335	261	271	311	421
RED RIVER ALEXANDRIA, LA.	31	38	46	47	47	61	40	19	11	10	14	19	27
ATCHAFALAYA RIVER SIMMESPORT, LA.	174	175	222	270	303	289	216	154	98	72	77	88	129
LOWER MISS. RIVER RED RIVER LANDING, LA.	453	473	597	702	763	702	526	398	270	209	219	244	342
% CONTRIBUTION (2) ÷ (1)	48.3	48.1	66.7	60.8	48.5	38.5	32.7	29.7	34.6	34.2	32.3	45.7	61.1
% CONTRIBUTION (3) ÷ (1)	31.3	18.2	17.8	24.6	30.9	32.3	41.7	42.5	37.9	47.6	47.5	40.5	23.5
SUM % (2) and (3)	79.6	86.3	84.5	85.4	79.4	70.8	74.4	72.2	72.5	81.8	79.8	86.2	84.6
% CONTRIBUTION (4) and (5) ÷ (1)	10.5	12.1	11.5	10.8	11.6	15.4	14.5	11.0	9.8	12.3	13.7	13.2	11.6

TABLE 3

MAJOR FLOODS

LOWER MISSISSIPPI RIVER

VICKSBURG, MISS., GAGING STATION

FLOOD YEAR	PEAK STAGE FT	PEAK DISCHARGE 1000 CFS	DATE OF CREST	WATER TEMP, °F	DAYS ABOVE BANKFULL STAGE	*DAYS TO PEAK	*DAYS TO FALL
1927	58.4	2278	May 1	62.0	175	231	81
1929	55.2	1730	Jun 6	72.0	118	95	55
1937	53.2	2080	Feb 17	42.0	43	39	52
1945	47.4	1922	Apr 9	49.0	46	46	102
1950	44.9	1876	Feb 23	43.0	29	65	136
1961	44.9	1578	May 30	70.0	12	92	32
1973	53.1	1962	May 12	65.0	89	188	64
1975	49.8	1839	Apr 13	60.0	41	123	80
1979	47.9	1690	Apr 27	61.0	52	60	54

* Estimated

** Number of days above an arbitrarily selected base discharge of 600,000 cfs.

TABLE 4

AVERAGE ANNUAL DISCHARGES
VICKSBURG, MISS., GAGING STATION

YEAR	ANNUAL DISCHARGE 1000 CFS	DEVIATION FROM LONG-TERM AVERAGE 100 CFS
1930	451	-122
1931	317	-256
1932	577	+ 4
1933	589	+ 16
1934	312	-261
1935	682	+109
1936	404	-169
1937	622	+ 49
1938	583	+ 10
1939	545	- 28
1940	347	-226
1941	409	-164
1942	568	- 5
1943	637	+ 64
1944	555	- 18
1945	817	+244
1946	620	+ 47
1947	587	+ 14
1948	592	+ 19
1949	691	+118
1950	872	+299
1951	804	+231
1952	604	+ 31
1953	440	-133
1954	327	-246
1955	449	-124
1956	419	-154
1957	662	+ 89
1958	596	+ 23
1959	484	- 89
1960	525	- 48
1961	652	+ 79
1962	618	+ 45
1963	369	-204
1964	430	-143
1965	553	- 20
1966	456	-117
1967	523	- 50
1968	568	- 5
1969	609	+ 36
1970	593	+ 20
1971	521	- 52
1972	645	+ 72
1973	980	+407
1974	814	+241
1975	775	+202
1976	477	- 96
1977	488	- 85
1978	621	+ 48
1979	853	+280

TABLE 5

CHANNEL GEOMETRICAL ELEMENTS
MISSISSIPPI RIVER ABOVE CAIRO, ILL.
MILES 195-0

Overall Average Values (Bankfull)

<u>YEARS</u>	<u>WIDTH (W) FT</u>	<u>HYDRAULIC RADIUS (R) FT</u>	<u>AREA (A) SQ FT</u>	<u>A/W FT</u>	<u>AR 2/3 CU FT</u>
1884-89	6440	20.3	115,800	20.3	839,200
1920-24	3950	26.1	95,600	26.1	827,300
1946-47	4550	24.5	97,200	24.5	797,000
1959-67	4560	25.0	99,600	25.0	824,100
1976-78	4620	24.7	99,900	24.8	820,500

Overall Average Values (Low Flow)

1884-89	2615	8.5	17,100	8.5	77,300
1920-24	2055	9.6	16,400	9.6	75,700
1946-47	1925	10.7	18,000	10.7	88,300
1959-67	2090	10.9	19,500	11.0	97,000
1976-78	2100	10.9	19,800	10.9	98,500

TABLE 6

CHANNEL GEOMETRICAL ELEMENTS
MISSISSIPPI RIVER BELOW CAIRO, ILL.
MILES 320-595 AHP (1962)

Overall Average Values (+40 ft Above LWRP)*

<u>YEAR(S)</u>	<u>WIDTH (W) FT</u>	<u>HYDRAULIC RADIUS (R) FT</u>	<u>AREA (A) SQ FT</u>	<u>A/W FT</u>	<u>AR 2/3 CU FT</u>
1975	5440	68	244,200	45	4,000,000
1962-64	4870	64	216,600	44	3,400,000
1948-51	4550	63	210,600	46	3,300,000

Overall Average Values (0 ft Above LWRP)

1975	2964	38	70,415	24	800,000
1962-64	2684	35	56,626	21	600,000
1948-51	2598	35	54,988	21	600,000

* Values represent averages below a reference plane which is 40 ft above (+40) the low-water reference plane (LWRP).

TABLE 7
STRAIGHT* VS. SINUOUS** REACHES
PERTINENT STATISTICS

<u>REACH TYPE</u>	<u>SINUOSITY</u>	<u>TOP BANK WIDTH+ FT</u>	<u>LENGTH OF DIKES CONSTRUCTED++ FT</u>	<u>MAINTENANCE DREDGING# CU YD</u>
STRAIGHT	1.10	6870	51,309	36,000,000
SINUOUS	1.46	5476	9530	0

* STRAIGHT REACH - BALESSED-BEN LOMOND (Mile 480 to 494).

** SINUOUS REACH - OZARK-EUTAW (Miles 565 to 580).

+ 1973-1975 Hydrographic Survey.

++ Through 1977.

1962 to 1975.

TABLE 8

MAN-MADE NECK CUTOFFS, 1932-1942

<u>RIVER MILE LOCATION ON 1975 MAPS</u>	<u>YEAR OPENED</u>	<u>BENDWAY MILES</u>	<u>CUTOFF DISTANCE MILES</u>	<u>DISTANCE RIVER SHORTENED MILES</u>
678 HARDIN	1942	18.8	1.9	16.9
628 JACKSON	1941	11.1	2.4	8.7
625 SUNFLOWER	1942	12.9	2.5	10.4
575 CAULK	1937	17.2	2.0	15.2
549 ASHBROOK	1935	13.3	1.9	11.4
541 TARPLEY	1935	12.2	3.6	8.6
589 LELAND*	1933	11.2	1.4	9.8
514 WORTHINGTON	1933	8.1	3.8	4.3
504 SARAH	1936	8.5	3.2	5.3
463 WILLOW	1934	12.4	4.7	7.7
448 MARSHALL	1934	7.3	3.1	4.2
424 DIAMOND	1933	14.6	2.6	12.0
388 RODNEY	1936	10.0	4.1	5.8
366 GILES	1933	14.0	2.9	11.1
343 GLASSCOOK	1933	15.6	4.8	10.8
TOTALS		187.2	44.9	142.3

* Natural cutoff.

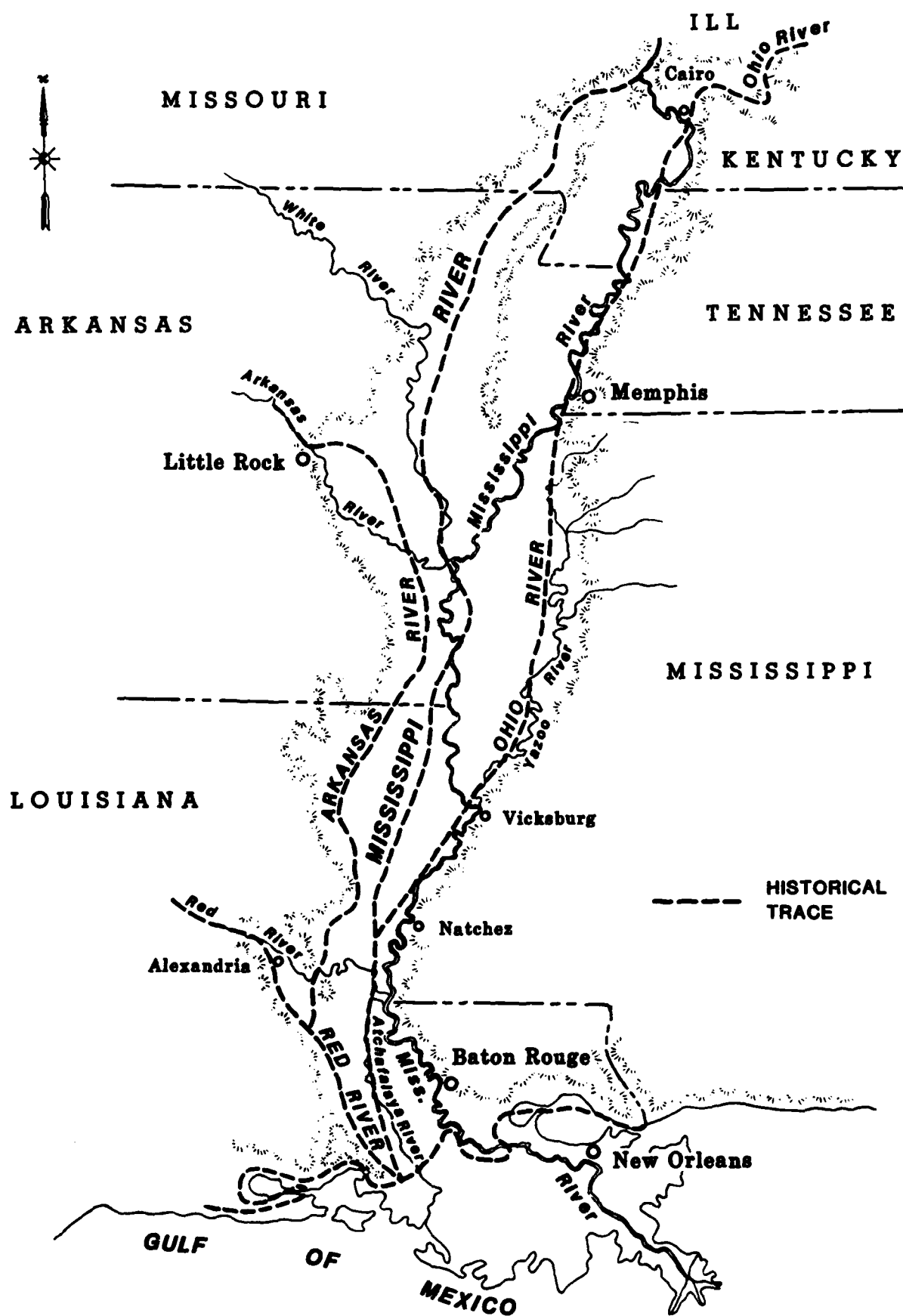
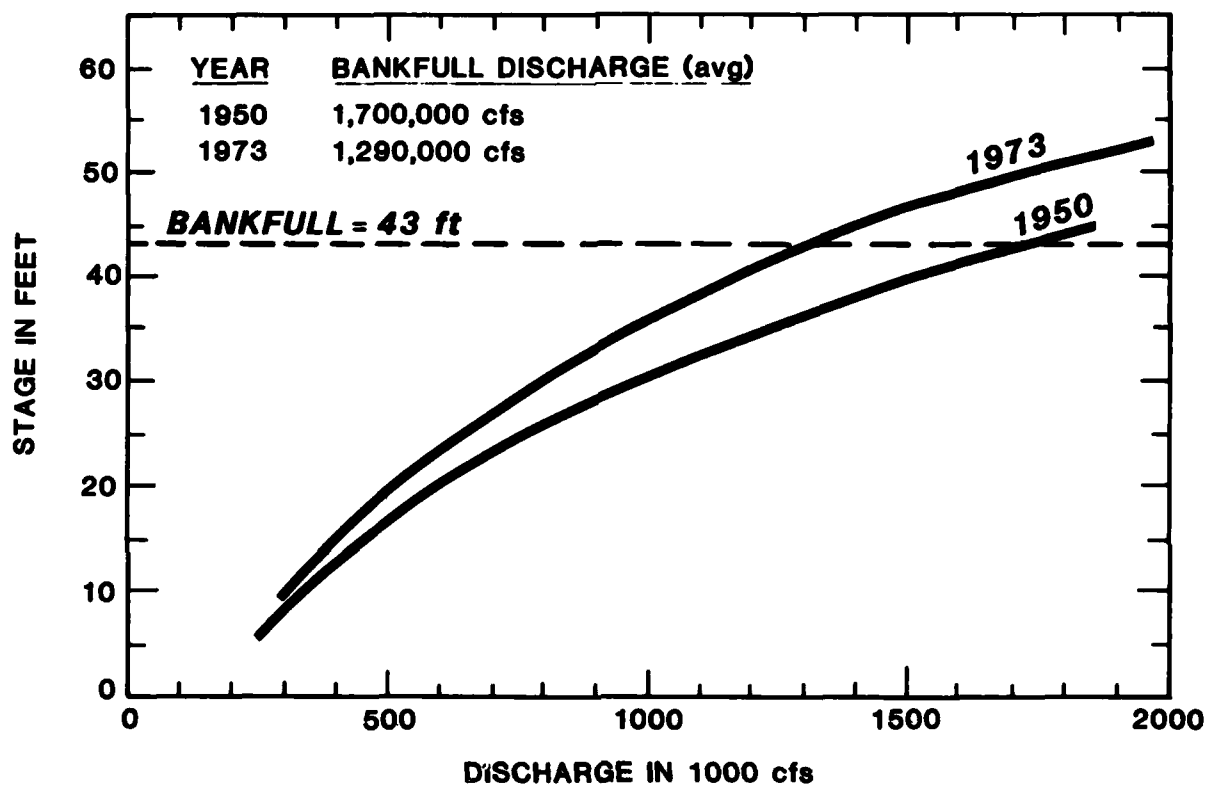


FIGURE 1. HISTORICAL TRACE OF THE LOWER MISSISSIPPI RIVER



**FIGURE 2. STAGE-DISCHARGE RELATION, 1950 AND 1973
AT VICKSBURG, MISS.**

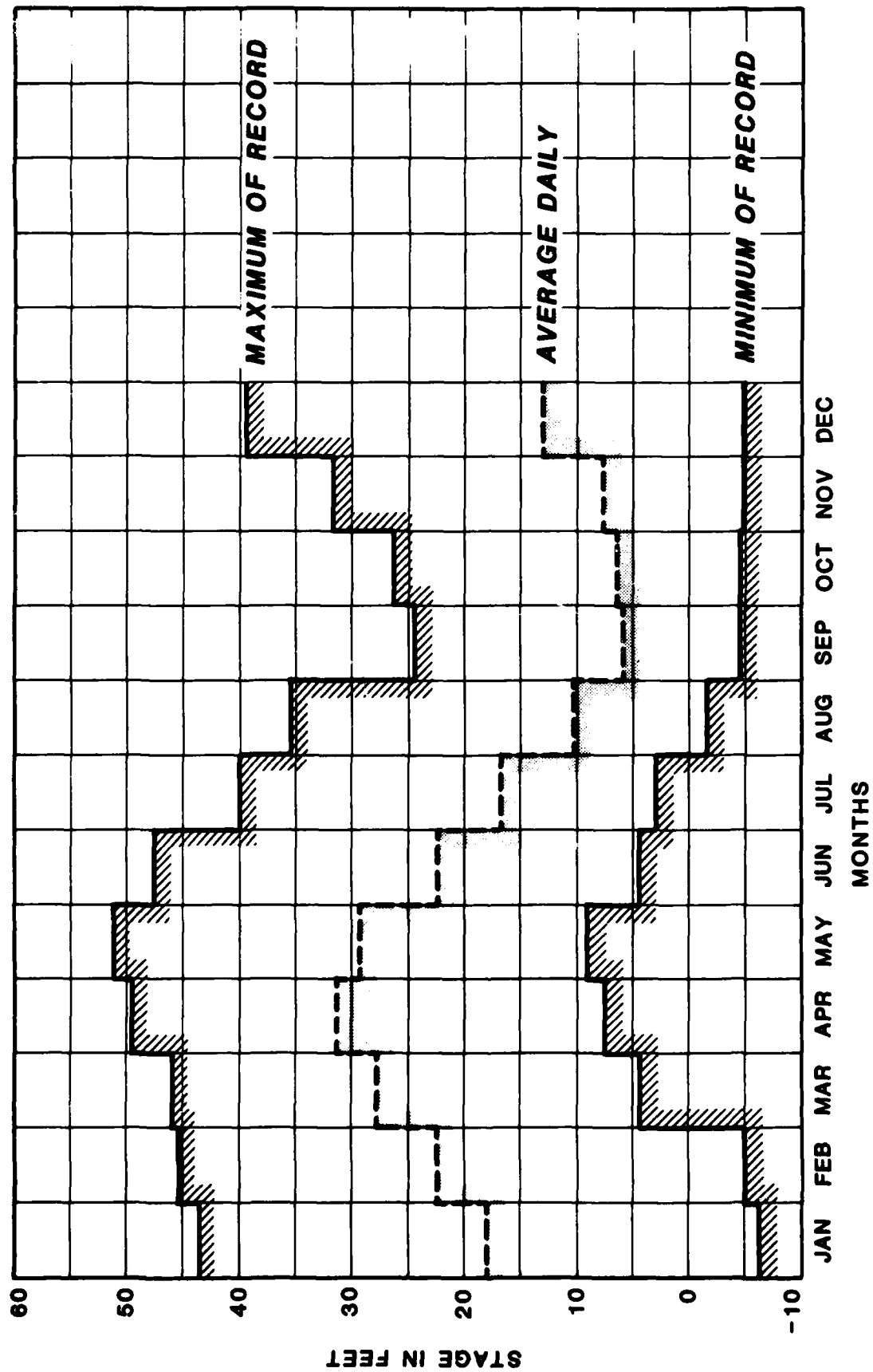


FIGURE 3. MONTHLY SUMMARY OF DAILY STAGES, 1944 TO 1980, VICKSBURG, MISS.

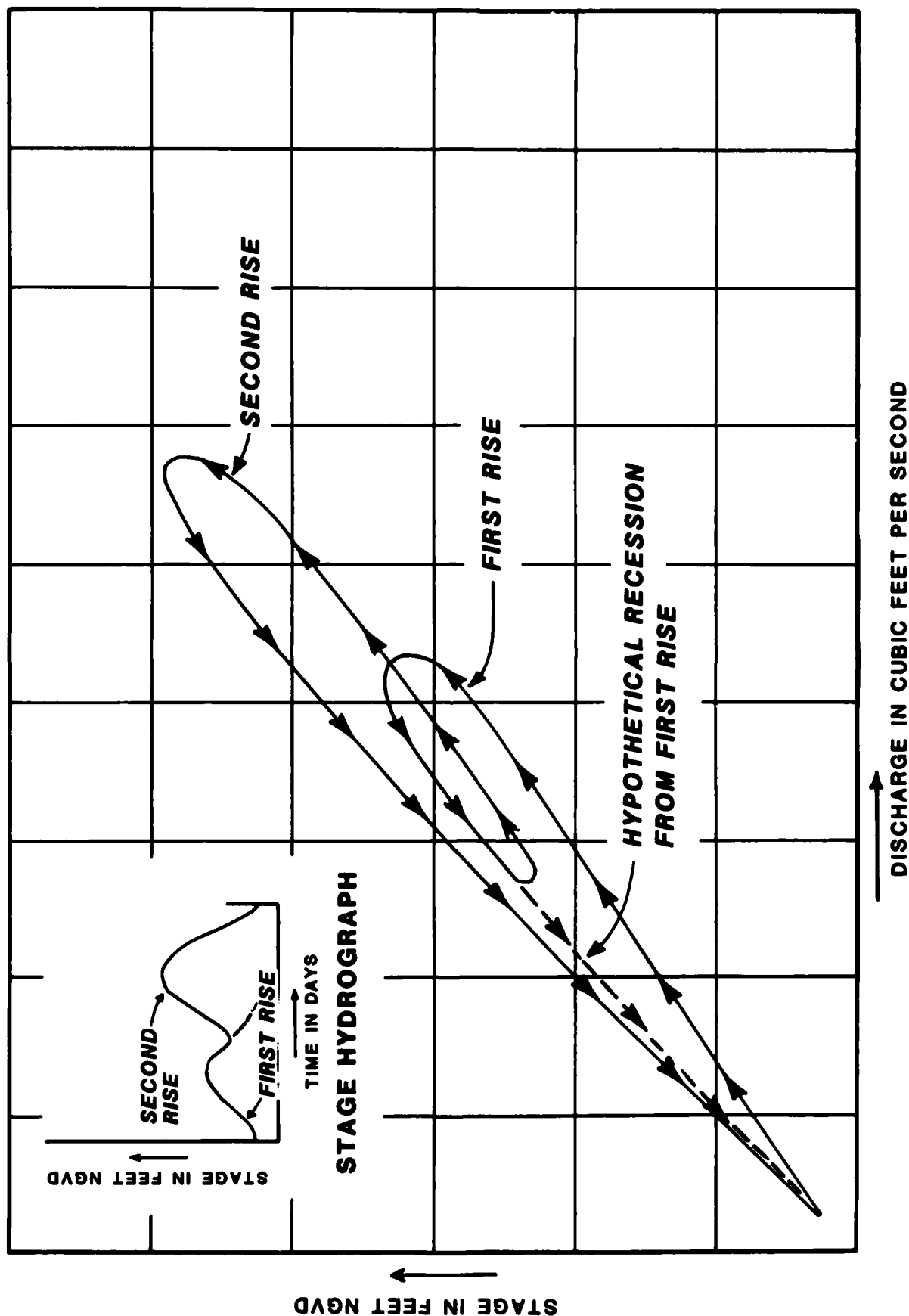


FIGURE 4. TYPICAL STAGE - DISCHARGE LOOP RATING CURVE, MISSISSIPPI RIVER

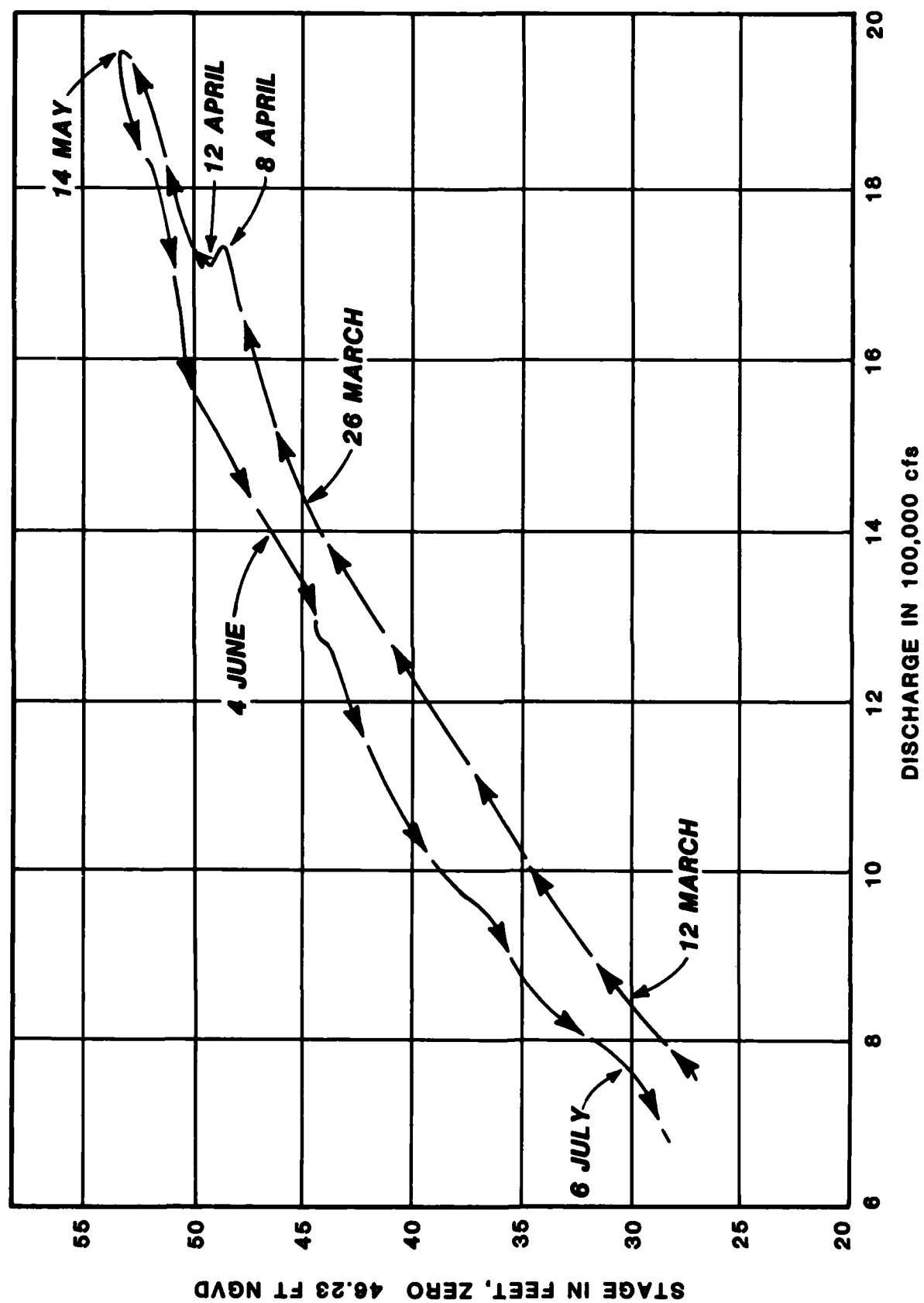
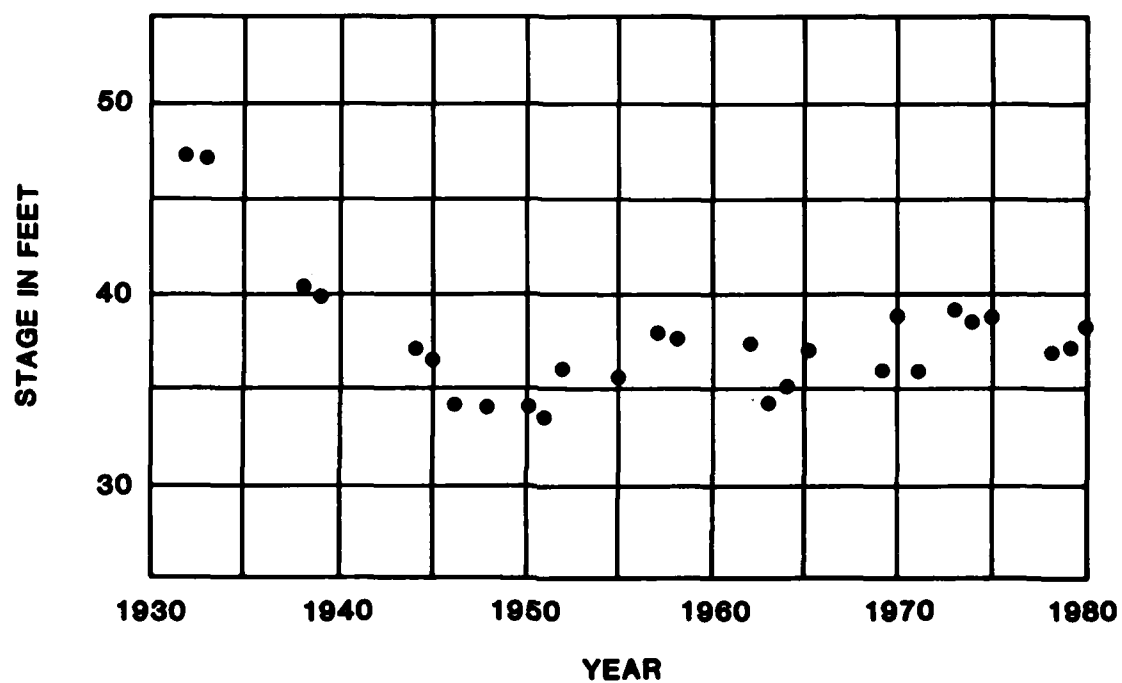
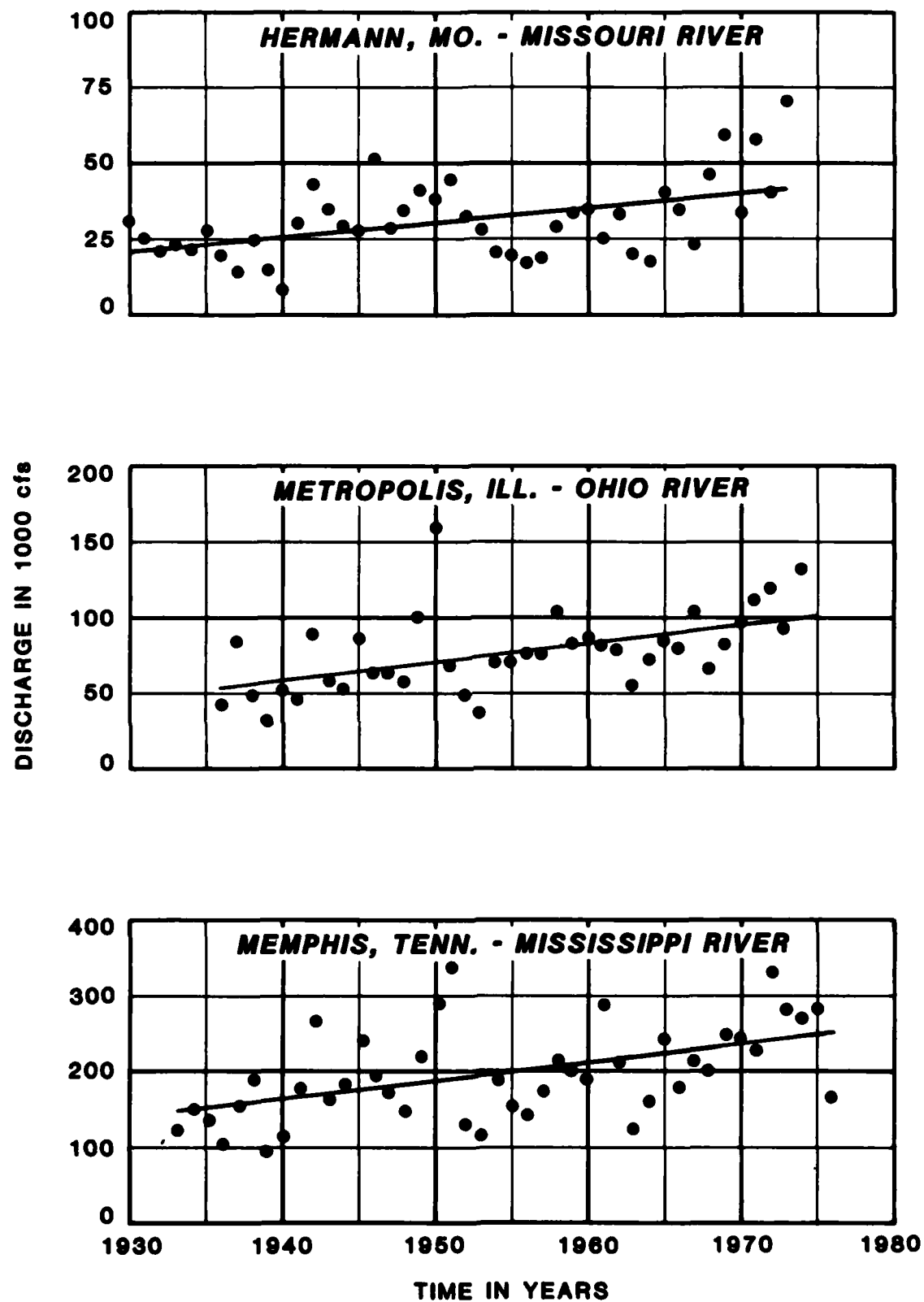


FIGURE 5. 1973 LOOP RATING CURVE FOR MISSISSIPPI RIVER AT VICKSBURG, MISS.



**FIGURE 6. AVERAGE STAGE FOR A DISCHARGE OF 1,200,000 cfs
AT VICKSBURG, MISS.**



**FIGURE 7. ANNUAL 60-DAY MINIMUM DISCHARGE
AT KEY LOCATIONS**

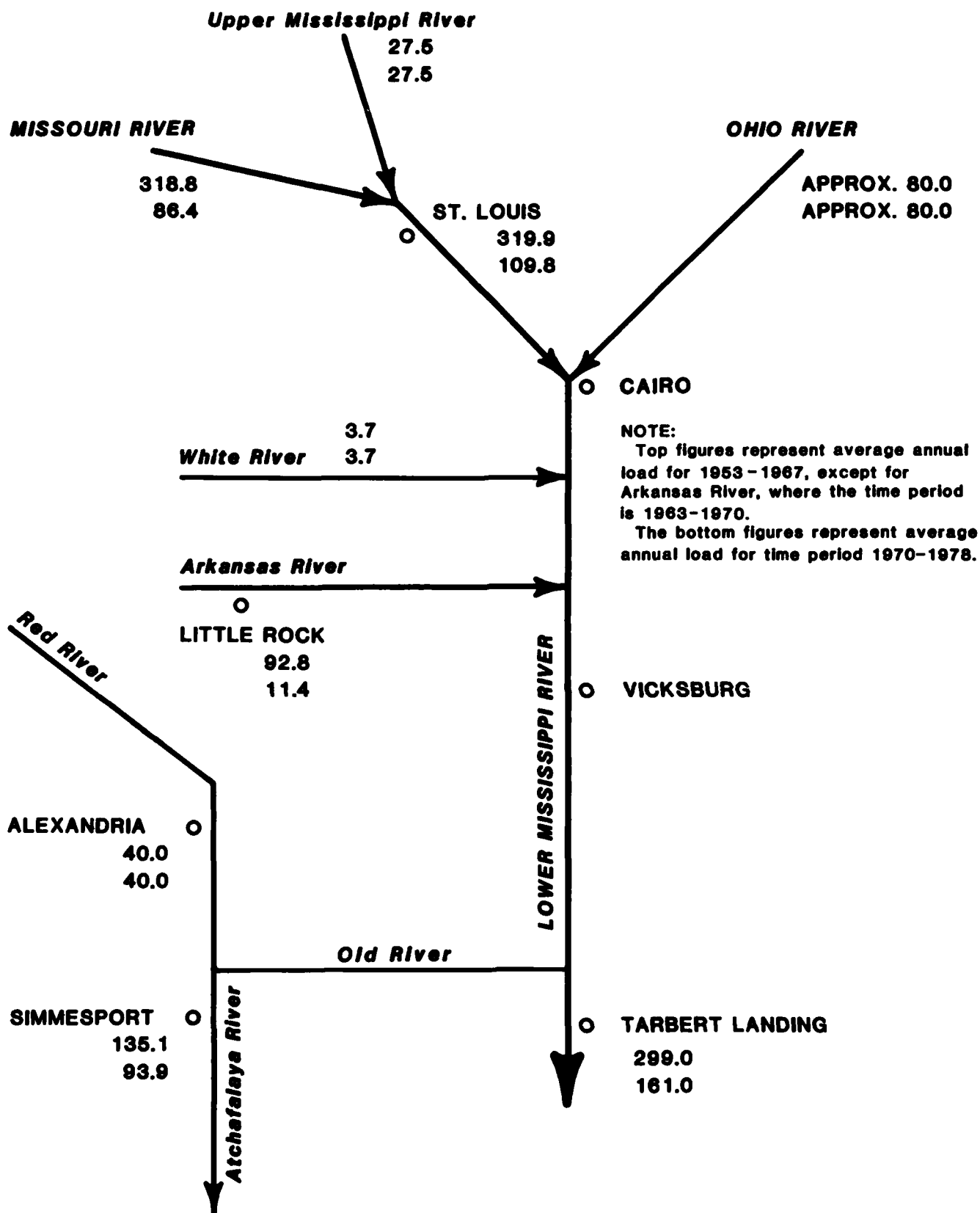
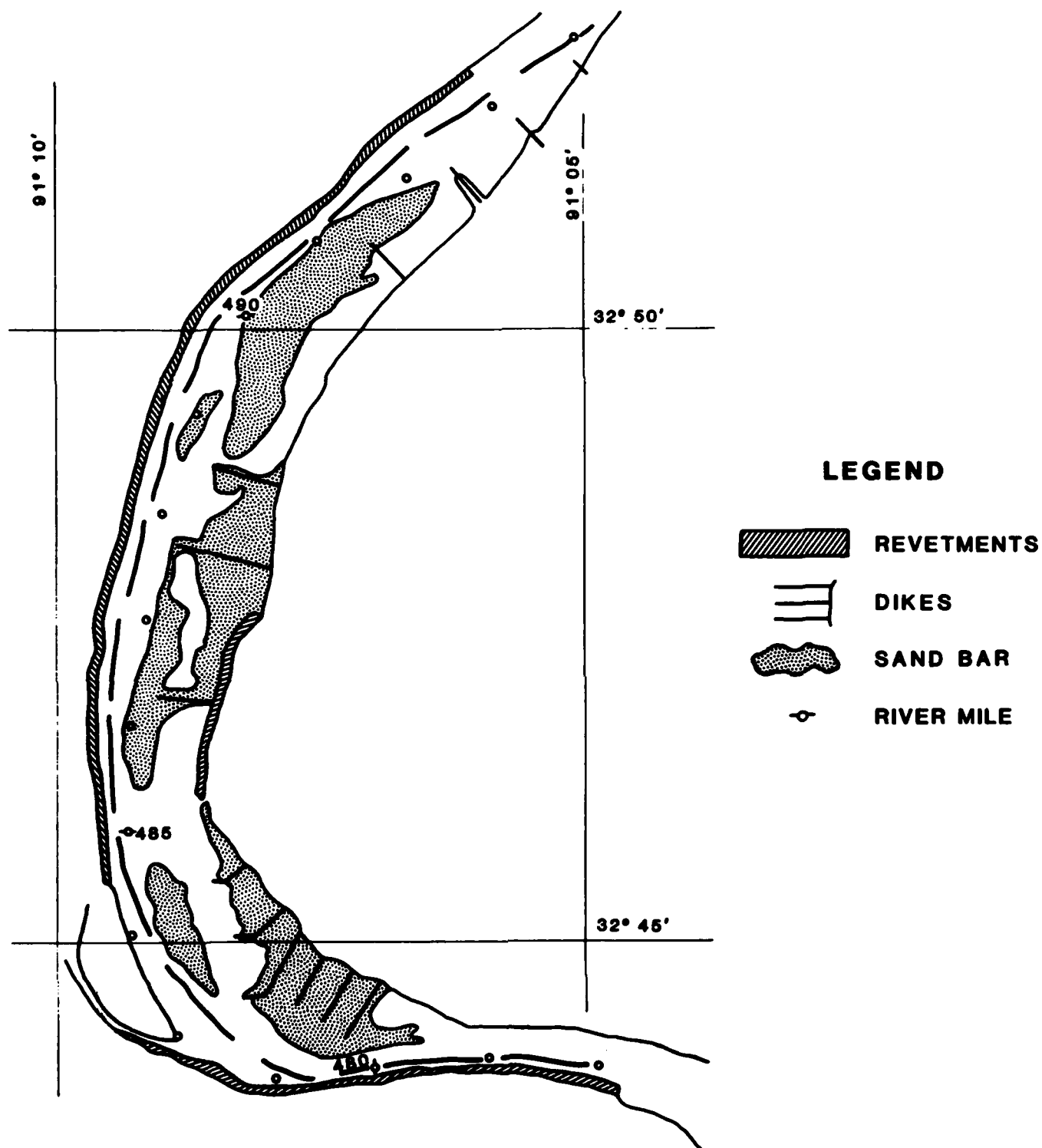


FIGURE 8. AVERAGE ANNUAL MEASURED SUSPENDED SEDIMENT LOADS IN 100,000 TONS AT KEY LOCATIONS, MISSISSIPPI RIVER BASIN



**FIGURE 9. TROUBLESOME STRAIGHT REACH,
BALESHED-BEN LOMOND REACH,
MILE 480 TO MILE 494 AHP (1962)**

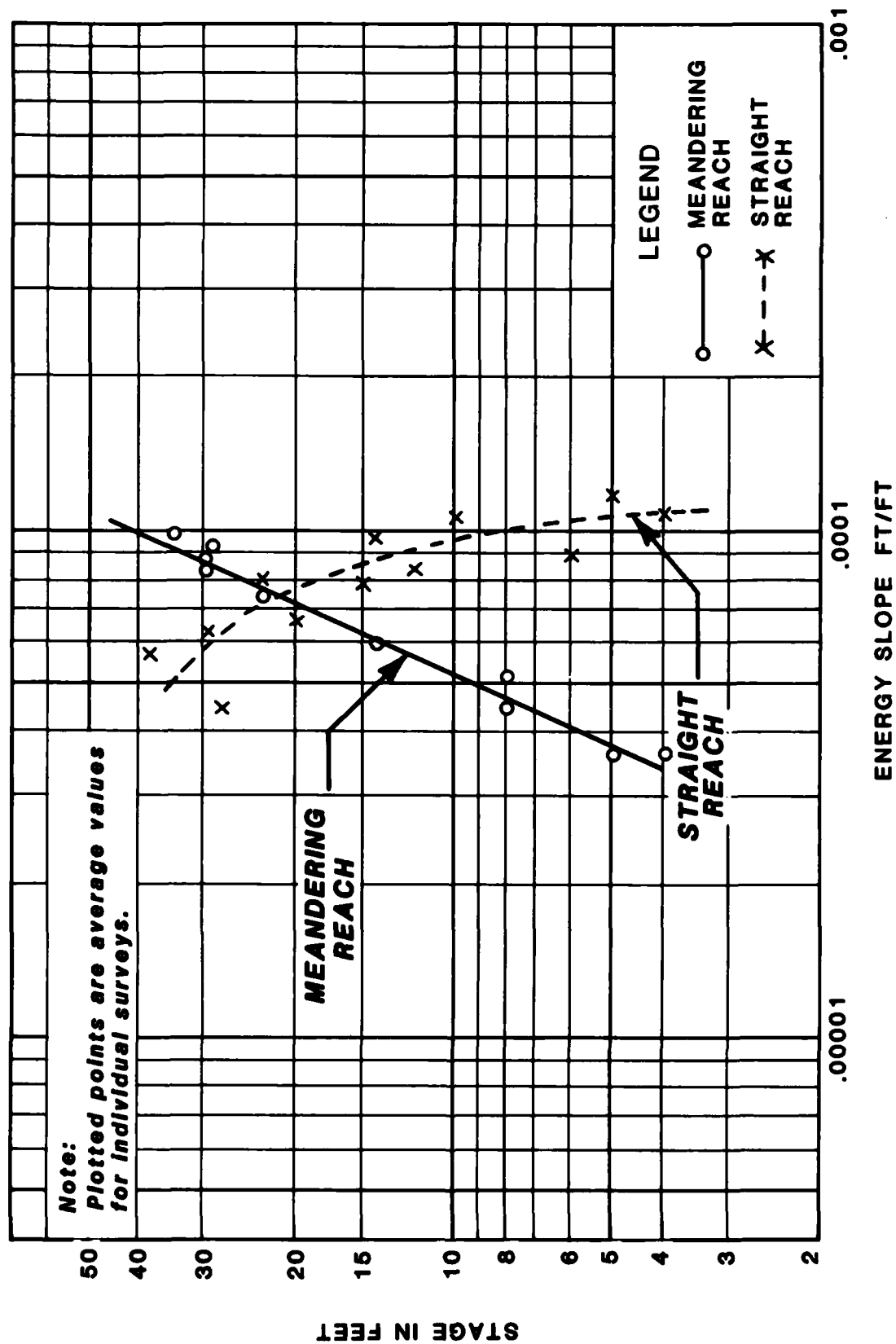


FIGURE 10. COMPARISON OF SLOPES IN TWO REACHES OF THE MISSISSIPPI RIVER

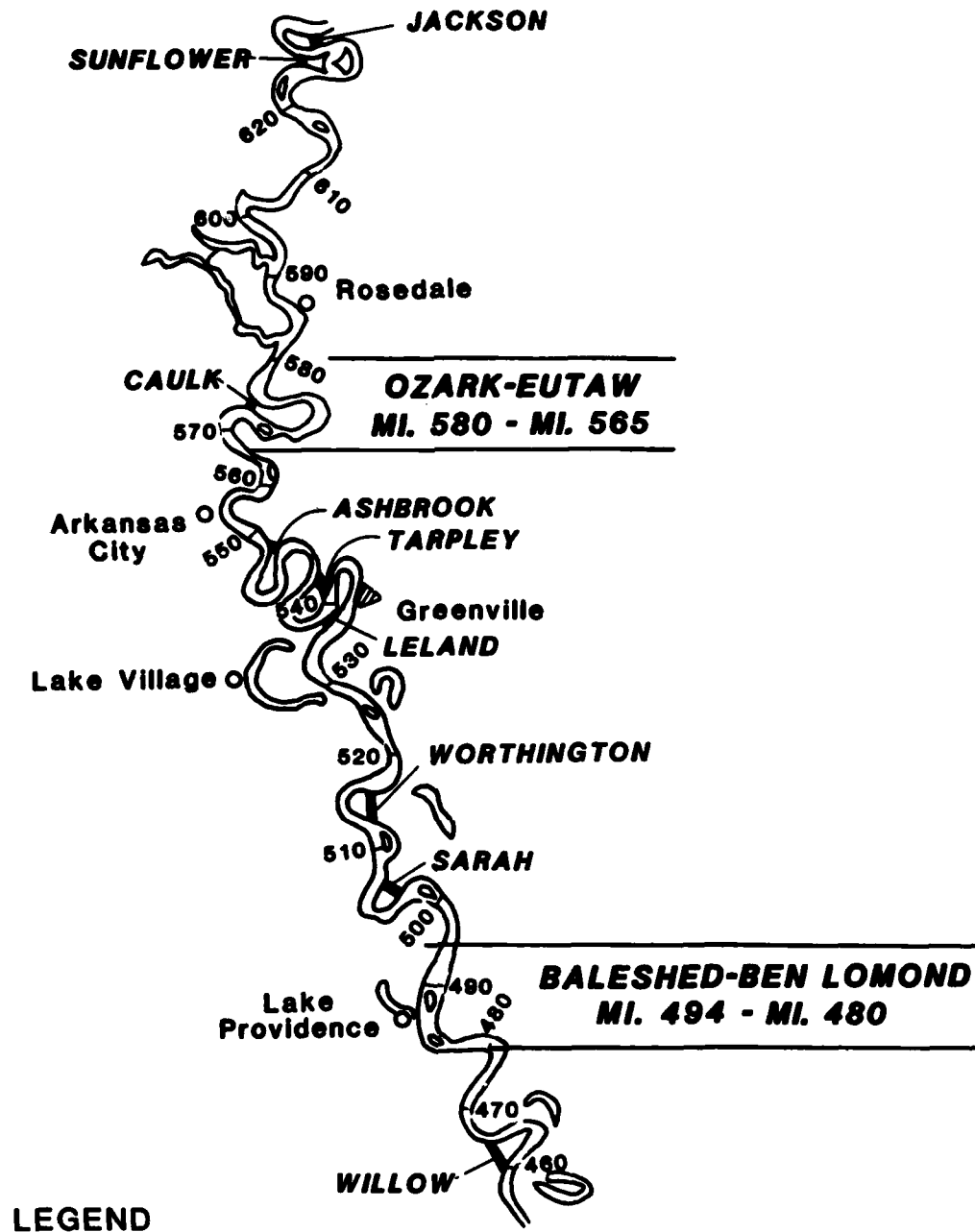
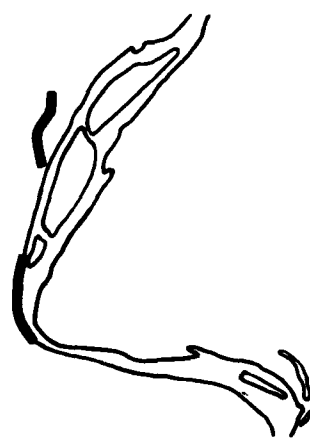
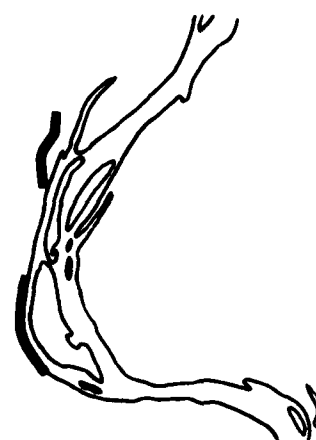


FIGURE 11. REACH LOCATION MAP



BEFORE 1936



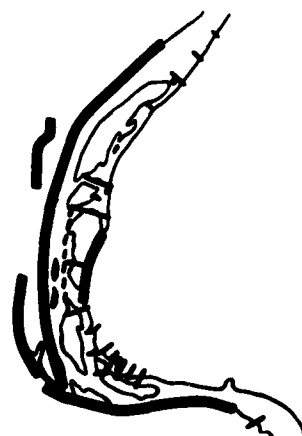
1936 TO 1946



1946 TO 1959



1959 TO 1968



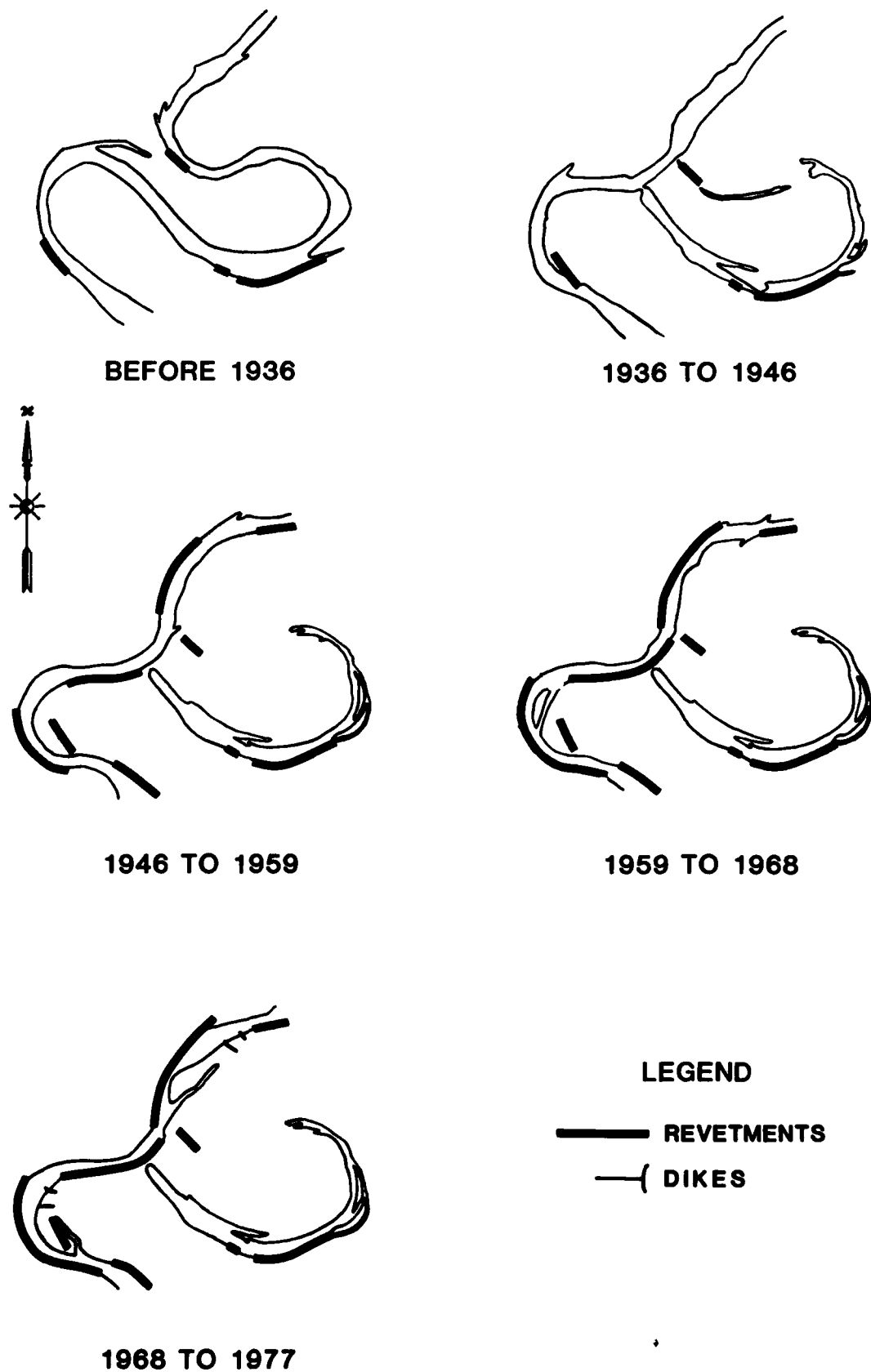
1968 TO 1977

LEGEND

— REVETMENTS

— DIKES

**FIGURE 12. CHRONOLOGICAL CHANNEL DEVELOPMENT,
BALESHED-BEN LOMOND REACH, MILE 480 - MILE 494**



**FIGURE 13. CHRONOLOGICAL CHANNEL DEVELOPMENT,
OZARK-EUTAW REACH, MILE 565 TO MILE 580**

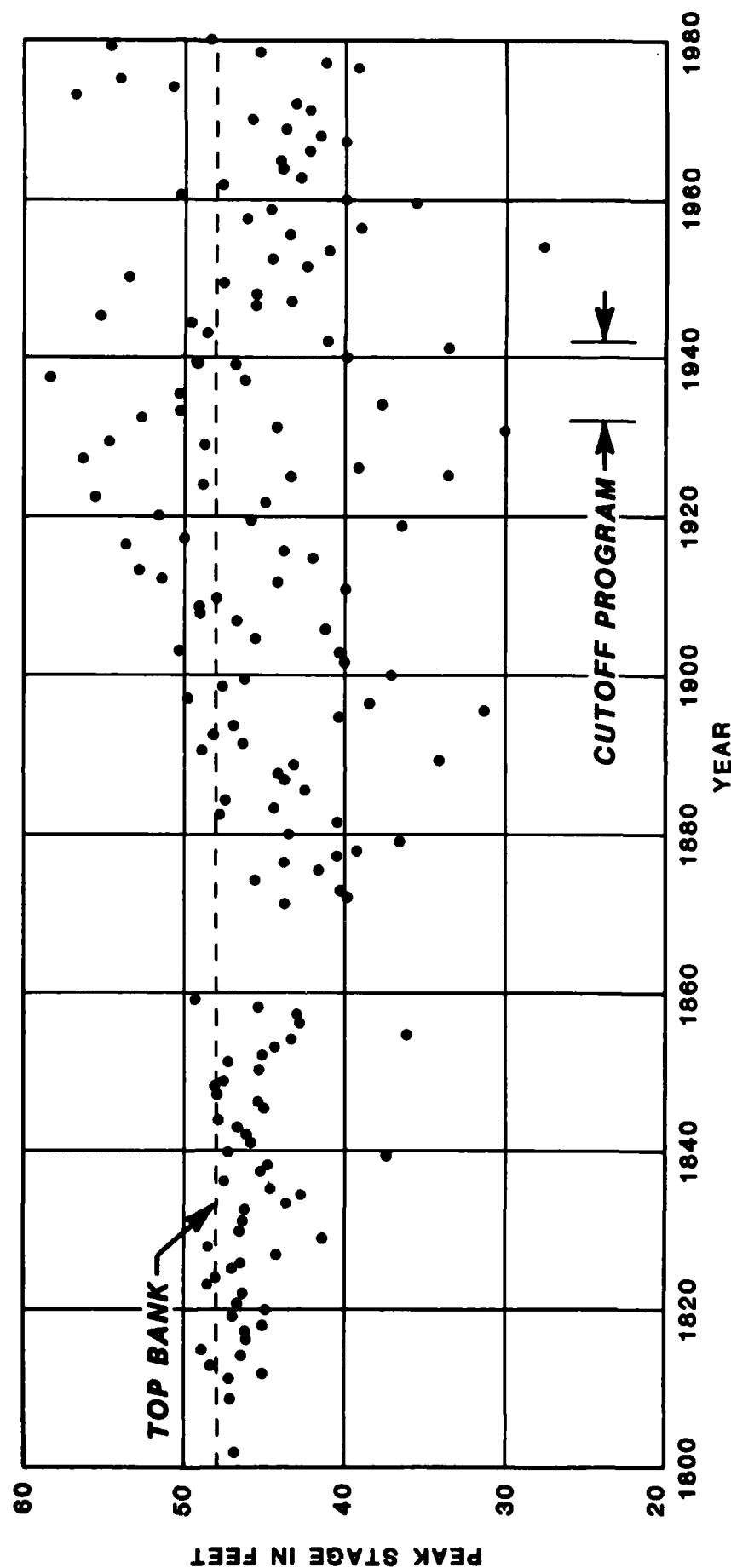
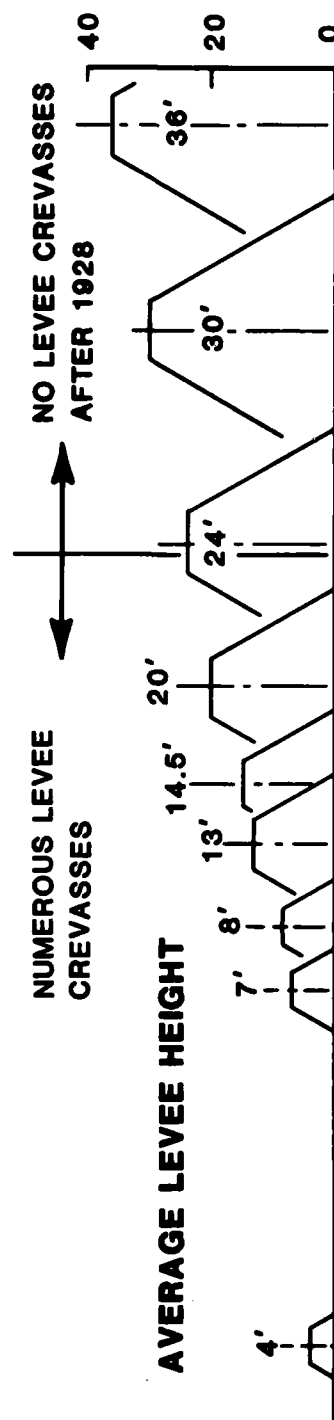


FIGURE 14. PEAK STAGE BY YEAR, NATCHEZ, MISS.

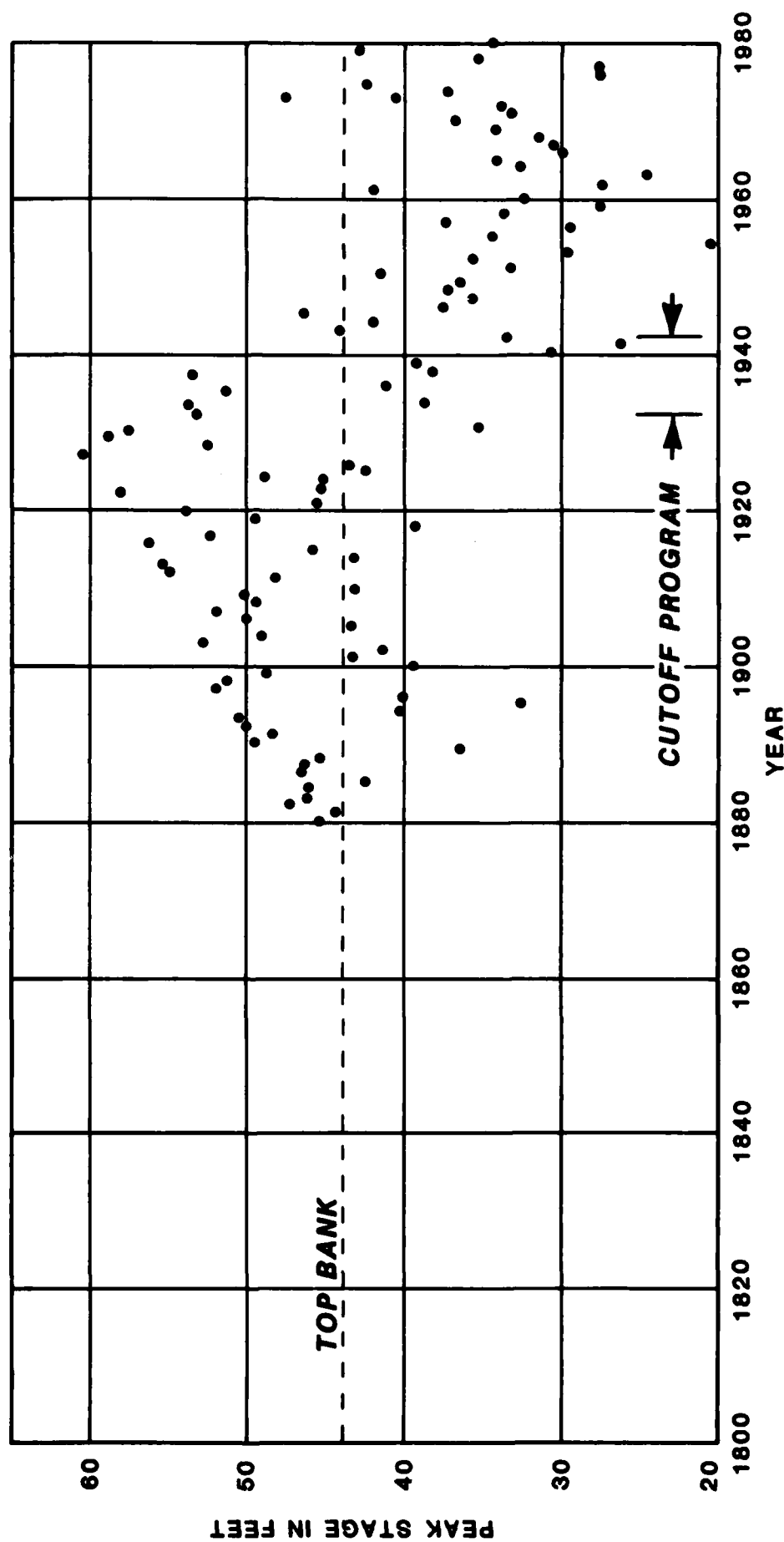
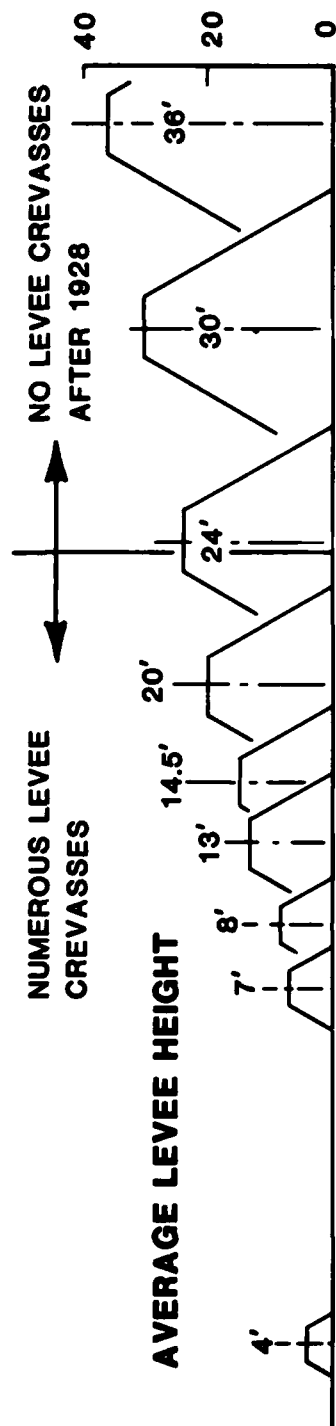


FIGURE 15. PEAK STAGE BY YEAR, ARKANSAS CITY, ARK.

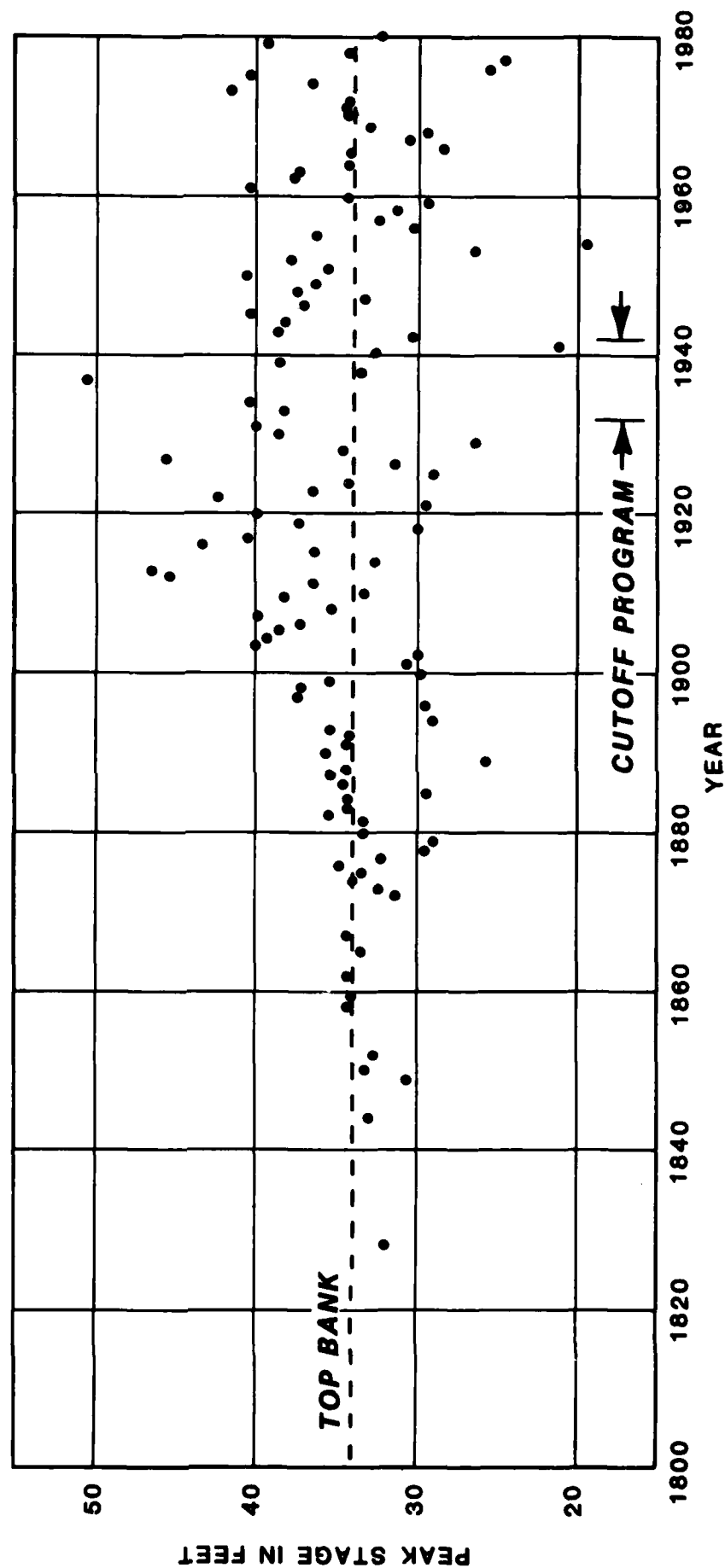
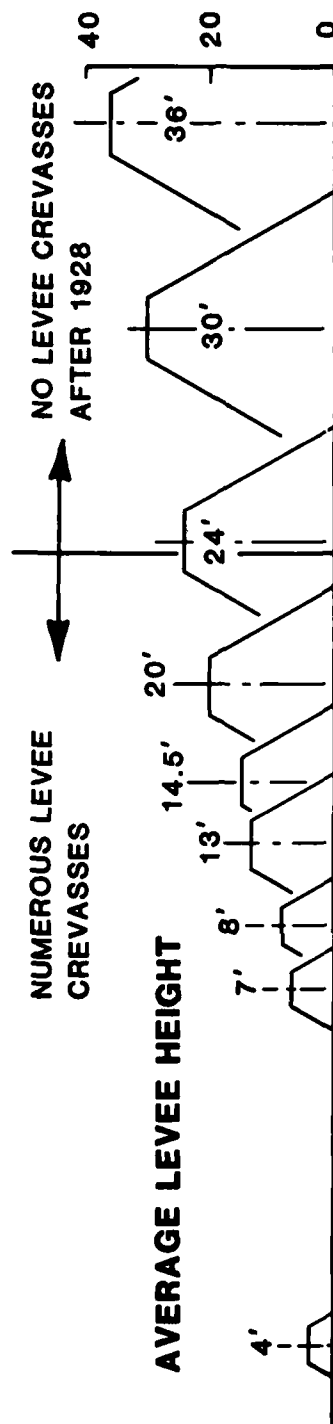


FIGURE 16. PEAK STAGE BY YEAR, MEMPHIS, TENN.

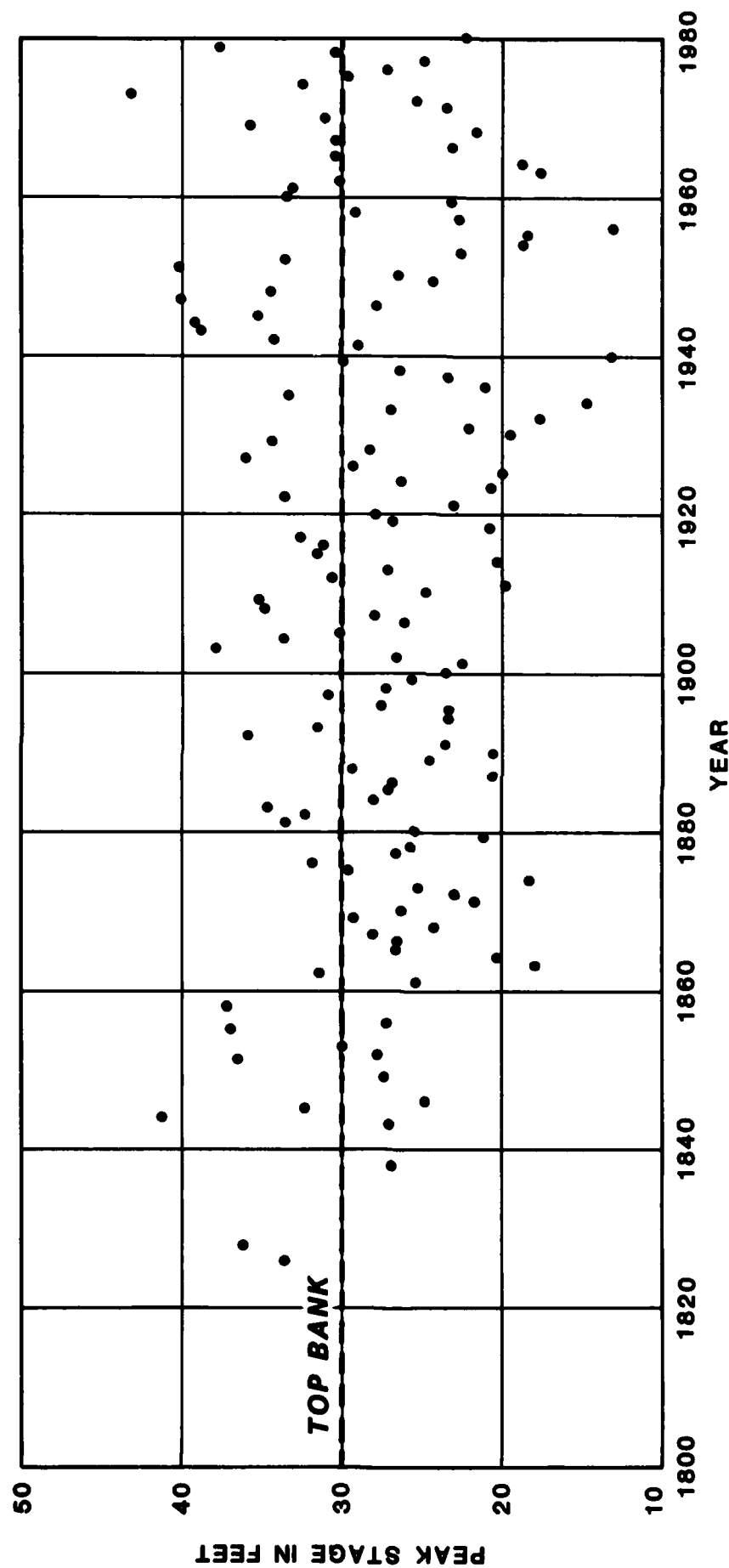


FIGURE 17. PEAK STAGE BY YEAR, ST. LOUIS, MO.

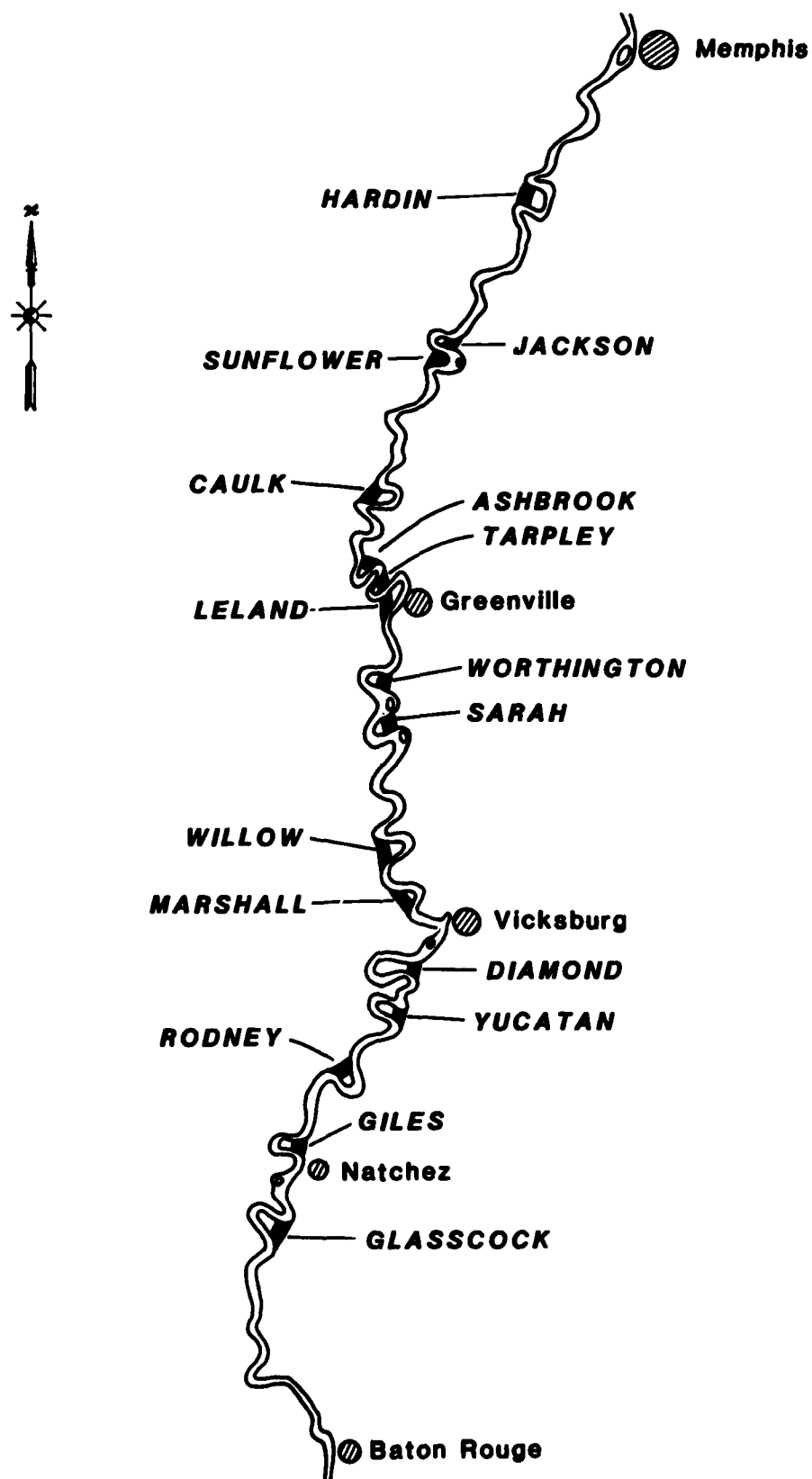


FIGURE 18. MISSISSIPPI RIVER CUTOFFS

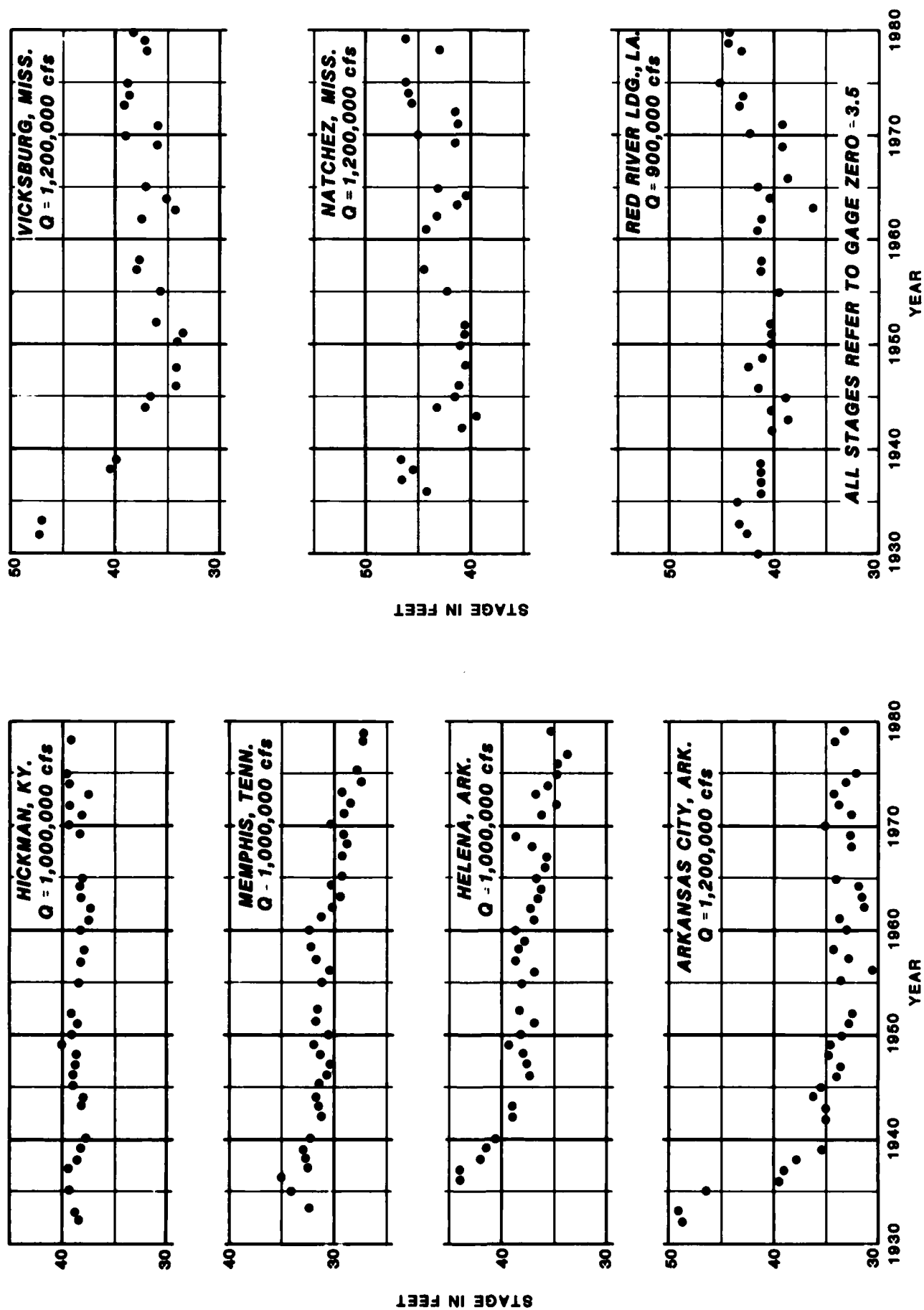


FIGURE 19. TIME SERIES OF AVERAGE STAGE FOR A SPECIFIC DISCHARGE

END