CONTRACT REPORT Y-75-3

ENVIRONMENTAL INVENTORY AND ASSESSMENT OF NAVIGATION POOLS 24, 25, AND 26, UPPER MISSISSIPPI AND LOWER ILLINOIS RIVERS

A GEOMORPHIC STUDY

by

D. B. Simons, S. A. Schumm, M. A. Stevens,
Y. H. Chen, P. F. Lagasse

Colorado State University
Fort Collins, Colo. 80521

July 1975

Final Report

Approved For Public Release; Distribution Unlimited

Prepared for U. S. Army Engineer District, St. Louis
St. Louis, Missouri 63101

Under Contract No. DACW39-74-C-0148

Monitored by Environmental Effects Laboratory
U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

DEPARTMENT OF THE ARMY
WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
P. O. BOX 631
VICKSBURG, MISSISSIPPI 39180

DIO 3
24/9

Y 75-3

IN REPLY REFER TO: WESYV

15 July 1975

Errata Sheet

ENVIRONMENTAL INVENTORY AND ASSESSMENT
OF NAVIGATION POOLS 24, 25, AND 26,
UPPER MISSISSIPPI AND LOWER ILLINOIS RIVERS

A GEOMORPHIC STUDY

Contract Report Y-75-3
July 1975

This report was printed by Colorado State University and the following corrections should be made:

Page 1, line 13: has instead of have.
line 25: add - Technical Director was Mr. F. R. Brown.

Page 13, line 16: Horberg instead of Horbert.

Page 28, lines 6, 29, and 36: The Secretary of War instead of House Doc. 341.

Page 38, line 18: The Secretary of War instead of House Doc. 341.

Page 39, line 2: The Secretary of War instead of House Doc 341.
line 14: Starrett instead of Starret.

Page 50, lines 2, 8, 21, 26, 29: The Secretary of War instead of House Doc 290.

Page 52, caption: U. S. Army Engineer District, St. Louis, instead of U. S. Army Corps of Engineers.

Page 98, last line: 1975 instead of 1974.

Page B2, line 12: B40 instead of B39.

Page B29, legend: Riverbed instead of Rivebed.

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Contract Report Y-75-3	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ENVIRONMENTAL INVENTORY AND ASSESSMENT OF NAVIGATION POOLS 24, 25, AND 26, UPPER MISSISSIPPI AND LOWER ILLINOIS RIVERS; A GEOMORPHIC STUDY		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) D. B. Simons M. A. Stevens P. F. Lagasse S. A. Schumm Y. H. Chen		8. CONTRACT OR GRANT NUMBER(s) DACW39-74-C-0148
9. PERFORMING ORGANIZATION NAME AND ADDRESS Colorado State University Fort Collins, Colo. 80521		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Engineer District, St. Louis 210 North 12th St. St. Louis, Mo. 63101		12. REPORT DATE July 1975 13. NUMBER OF PAGES 151
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) U. S. Army Engineer Waterways Experiment Station Environmental Effects Laboratory P. O. Box 631, Vicksburg, Miss. 39180		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Channel improvements
Channel stabilization
Geomorphology
Illinois River
Locks and Dams
Mathematical model
Mississippi River
Navigation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report is a study of the past and present geomorphic features of the reach of the Upper Mississippi River which includes Pools 24, 25, and 26 and the lower reach of the Illinois River. In addition, the report presents the anticipated future geomorphic changes that will result from past, present, and planned future developments of these reaches. The study was based primarily on data collected by the Corps of Engineers, aided with a mathematical model of the river system. On the basis of this study of the past geomorphic changes (Continued)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued).

in Pools 24, 25, and 26 and with the mathematical simulation of future river response, it was concluded that 50 years from now the study area will be essentially as it is today. The present day manner of operation does not have any serious detrimental effects on the geomorphology or hydraulics of the river system in the study area.

FOREWORD

The work described in this report was performed under Contract No. DACW39-74-C-0148 and supplemental agreement modification No. DACW39-74-C-0148-P001 titled "A Geomorphic Study of Pools 24, 25, and 26 in the Upper Mississippi and Lower Illinois Rivers," dated June 12, 1974, between the U.S. Army Engineer Waterways Experiment Station (WES) and Colorado State University (CSU). The research was sponsored by the U.S. Army Engineering District, St. Louis, and directed by the Environmental Effects Laboratory, WES.

The report is a study of the past and present geomorphic features of that reach of Upper Mississippi River which includes Pools 24, 25, and 26 and the lower 80-mile reach of the Illinois River. The study identifies the principal processes by which the geomorphology of these reaches has ~~have~~ been changing. With the aid of a numerical mathematical model, future geomorphic changes which will occur from past, present, and possible future developments in these reaches have been assessed.

The report was prepared by Dr. D.B. Simons, Associate Dean, Engineering Research Center, Dr. S.A. Schumm, Professor of Geology, Dr. M.A. Stevens, Associate Professor of Civil Engineering, Dr. Y.H. Chen, Assistant Professor of Civil Engineering, and P.F. Lagasse, Research Associate of Civil Engineering, Colorado State University.

The contract was managed by Mr. R. Charles Solomon, Acting Chief, Environmental Monitoring and Assessment Branch, WES. The study was under the general supervision of Dr. Conrad K. Kirby, Chief, Environmental Resources Division, and Dr. John Harrison, Chief, Environmental Effects Laboratory. Director of WES was COL G.H. Hilt, CE. TECHNICAL Director WAS Mr. F.R. Brown

CONTENTS

	Page
FOREWORD	1
LIST OF TABLES	5
LIST OF FIGURES	7
PART I: INTRODUCTION	8
Background	8
Purpose and Scope	9
Organization of Report	11
PART II: ICE AGE	13
PART III: THE NATURAL RIVER	18
Early Exploration and Surveys (1673-1818)	18
River Position	20
Surface Areas	22
Definitions	22
River	23
Islands	23
Riverbed	23
Width	24
Water Depth	25
Side Channels	25
Water and Sediment Transport	26
Summary	26
PART IV: EARLY DEVELOPMENTS	27
Commercial Navigation and Channel Improvements (1810-1891)	27
River Position	29
Surface Areas	31
River	31
Islands	31
Surface Widths	32
Riverbed Elevations	33
Side Channels	34
Levees	35
Water and Sediment Transport	36
Summary	36
PART V: THE SIX-FOOT CHANNEL PROJECT	38
Channel Improvements (1905-1930)	38
River Position	39
Surface Areas	42
River	42
Islands	42
Riverbed	44

	Page
Surface Widths	44
Riverbed Elevations	44
Side Channels	46
Levees	46
Natural Levees	47
Illinois River	47
Water and Sediment Transport	48
Summary	49
PART VI: THE NINE-FOOT CHANNEL PROJECT	50
Locks and Dams 24, 25, and 26 (1927-Present)	50
Operation of Dams	53
Short-Term Response	54
Surface Areas in 1939	54
Number of Islands in 1939	54
Riverbed Elevations in 1939	54
Long-Term Responses	55
Surface Areas in 1973	56
Island Areas in 1973	58
Riverbed Areas in 1973	61
Surface Widths in 1973	61
Riverbed Elevations in 1971	61
Side Channels	63
Levees	63
Floodplains	64
Tributaries	64
Illinois River	65
Discharges and Stages	67
Gaging Stations	68
Floods at Hannibal	68
Trends in Discharges	70
Trends in Stages	71
Summary	77
Sediment Transport	77
Dredging	77
Summary	79
PART VII: THE FUTURE	81
With Present-Day Operations	82
Riverbed Changes	82
Floodplain Deposits	84
One Foot Above Normal Pool	85
One Foot Below Normal Pool	85
Zero Sediment Inflow	85
Maximum Sediment Inflow	87
Dredging	87
Dikes	90
Effects of Increased Boat Traffic	91

	Page
PART VIII: SUMMARY.	93
In the Past	93
In the Future	95
LITERATURE CITED	98
APPENDIX A: FLOOD RANKS IN THE STUDY REACH.	A1
APPENDIX B: MATHEMATICAL MODEL OF THE PRINCIPAL PHYSICAL PROCESSES OF THE RIVER	B1

LIST OF TABLES

Table		Page
1	Islands in the Natural River	24
2	Surface Areas of the 1891 Mississippi River.	31
3	Changes in Surface Areas of Islands from 1800's to 1891	33
4	Average River Surface Widths and Riverbed Elevation in the 1891 Mississippi River.	34
5	Surface Areas of the Mississippi River in 1929 . . .	42
6	Changes in Surface Areas of Islands from 1891 to 1929	43
7	Average River Surface Widths in the Pool 25 Reach of the Upper Mississippi River in 1929	45
8	Average Riverbed Elevations in the 1929 Mississippi River.	45
9	Number of Islands, 1929 and 1939	55
10	Average Riverbed Elevations in the 1939 Upper Mississippi River.	56
11	Surface Areas of Pool 25 in 1973	58
12	Change in Surface Areas of Islands from 1929 to 1973	59
13	Average River Surface Widths in Pool 25 of the Upper Mississippi River in 1973.	61
14	Average Riverbed Elevations in the Mississippi River in 1971.	62
15	Surface Areas of the Lower Illinois River, 1939-1940 and 1956	66
16	Average River Surface Widths in the Lower Illinois River.	66
17	Locations of Selected Features in the Study Reach. .	69
18	Top Twenty Stages Mississippi River at Hannibal. . .	70
19	Top Ten Flood Discharges Mississippi River at Hannibal	71
20	Trends in Annual Discharges and Stages	77
21	Future Riverbed Elevation Changes in the Upper Mississippi River.	83

Table		Page
22	Future Riverbed Elevation Changes in the Lower Illinois River.	83
23	Future Riverbed Elevation Changes in the Upper Mississippi River Assuming No Sand Transport into Pool 24.	86
24	Future Riverbed Elevation Changes in the Upper Mississippi River Assuming Maximum Sand Transport into Pool 24.	88

LIST OF FIGURES

Figure		Page
1	Index map	10
2	Preglacial map of the river system.	14
3	Pleistocene changes - Mississippi and Illinois Rivers.	15
4	Franquelin's Great Map of 1684.	19
5	Map of the Pool 25 reach of the Mississippi River in the early 1800's	21
6	Map of the Pool 25 reach of the Mississippi River in 1891	30
7	Location of dikes in Pool 25, Mississippi River .	40
8	Map of the Pool 25 reach of the Mississippi River in 1929	41
9	Mosier Island Reach	43
10	The Navigation Stairway	52
11	Map of the Pool 25 reach of the Mississippi River in 1973	57
12	Decrease in size of Crider Island between 1929 and 1973.	60
13	Growth of Clarksville Island between 1929 and 1973.	60
14	Annual discharges at Alton.	72
15	Annual discharges at Keokuk	72
16	Annual discharges at Meredosia.	73
17	Annual stages at Alton.	74
18	Annual stages at Keokuk	74
19	Annual stages at Hannibal	75
20	Annual stages at Grafton.	75
21	Annual stages at Meredosia.	76

PART I: INTRODUCTION

Background

> ". . . the extensive view up and down the river and wide over the wooded expanses of Illinois, is very beautiful--one of the most beautiful on the Mississippi, I think: which is a hazardous remark to make, for the eight hundred miles of river between St. Louis and St. Paul afford an unbroken succession of lovely pictures."
>
> Mark Twain, 1896

> ". . . of all the river scenery that I know, that of the Upper Mississippi is by far the finest . . ."
>
> Anthony Trollope, 1869

The Mississippi River above its junction with the Missouri has long been acclaimed a scenic delight not only by Twain and Trollope who viewed this riverscape in the 19th century but by many people throughout time. In contrast, while traveling by steamboat from Louisville, Kentucky to St. Louis, Missouri Charles Dickens wrote this about the Middle Mississippi River at Cairo, Illinois:

> ". . . A dismal swamp, on which the half-built houses rot away: cleared here and there for the space of a few yards; and teeming, then, with rank, unwholesome vegetation, in whose baleful shade the wretched wanderers who are tempted hither droop, and die, and lay their bones; the hateful Mississippi circling and eddying before it, and turning off upon its southern course, a slimy monster hideous to behold; a hotbed of disease, an ugly sepulchre, a grave uncheered by any gleam of promise: a place without one single quality, in earth or air or water, to commend it: such is this dismal Cairo."
>
> Charles Dickens, 1842

The Upper Mississippi River has been considered beautiful not only because of the attractiveness of its bluff line but also because of the stability of riverbanks which permit vegetation to grow to the waterline. Also there is a lack of scars due to bank failure. This condition is in marked contrast to the river below St. Louis, which was and is relatively less stable (Simons, Schumm, and Stevens, 1974).

The Illinois, a major tributary which joins the Mississippi above St. Louis (Fig. 1), has been accorded much less attention perhaps because of the impressive size of the Mississippi.

In addition to the scenic attractions of this area of middle America, the Upper Mississippi and Illinois Rivers provide natural routes for commerce. The rapid economic development of north central United States was, in part, due to the commercial use of these waterways. As an indication of the increasing significance of the Upper Mississippi as a route of commerce, the tonnages transported increased from about 3.5 million tons in 1940 to 61 million tons in 1972.

Improvement of the Upper Mississippi River for navigation has been underway for almost 150 years. The first improvement was the removal of snags hazardous to navigation. Later on, dikes were constructed to confine the low flows to a narrow channel thus increasing the depth of flow. At the same time, revetment was placed along caving banklines to hold the channel alignment. In the 1930's, the navigation channel depth was increased to 9 ft by constructing a series of locks and dams in the Upper Mississippi River. Since that time, the navigation channel has been maintained by these structures supplemented with dredging.

Purpose and Scope

A cooperative research team has been assembled under the direction of the U.S. Army Engineer Waterways Experiment Station (WES) to study the environmental effects of Corps of Engineers activities in Pools 24, 25, and 26 in the Upper Mississippi River and Lower Illinois River. The team consists of personnel from the U.S. Army Engineer District, St. Louis, Missouri; the WES, Vicksburg, Mississippi; Southern Illinois University; Illinois Natural History Survey; Missouri Botanical Gardens; and Colorado State University.

In its investigations reported herein, the Colorado State University group studied the past and present geomorphic features of that reach of the Upper Mississippi River which includes Pools 24, 25, and 26 and the lower reach (approximately 80 miles) of the Illinois

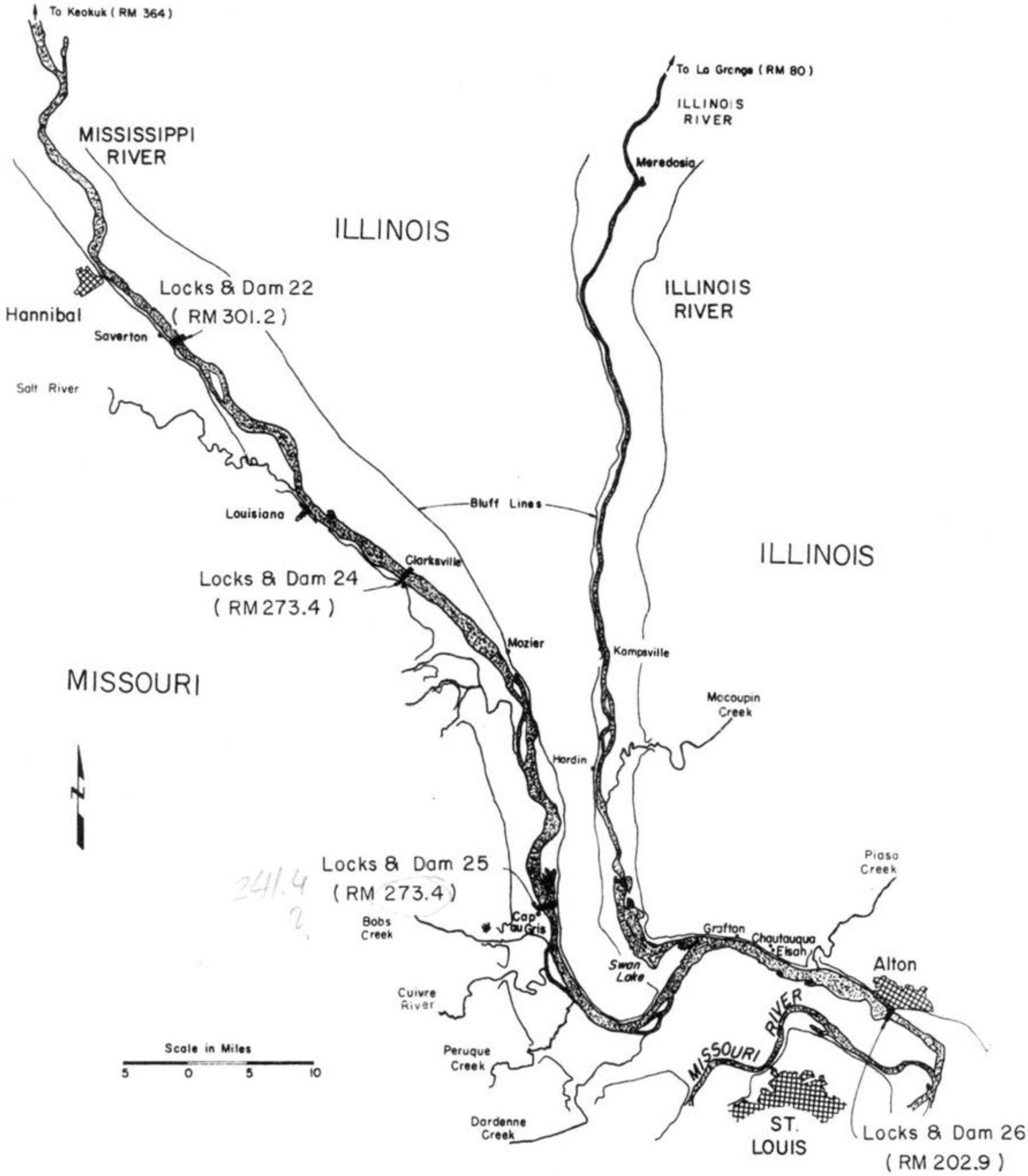


Figure 1. Index Map

River. The principal causes of geomorphic change along the Upper Mississippi River were identified. Also, the influence of Pool 26 on geomorphic changes in the Lower Illinois River was assessed. Trends in discharges and stages were analyzed. These studies were based primarily on data collected by the Corps of Engineers and others. For example, information on the changing character of the river was obtained from maps compiled in 1878, 1880, 1889, 1895, 1930, 1940, and 1970, and from 1927 and 1973 aerial photographs. These maps and photographs provide an excellent source of information for the Mississippi River, but unfortunately significantly less information is available for the Illinois River. Consequently, the discussion of the geomorphology and hydraulics of the Illinois River is less complete.

In addition to studying geomorphic features as they exist today, the Colorado State University group assessed anticipated future geomorphic changes that may result from past, present, and planned future developments in these reaches of Upper Mississippi and Lower Illinois Rivers. The assessments were made on the basis of the information derived from this study of the past geomorphic changes in the same reaches and with the aid of a mathematical model of the river system.

The mathematical model is a numerical representation of the principal physical processes at work in the river. The behavior of this study reach of river is governed mainly by the amount and manner in which water and sediment are delivered to the reach and by man's activities in the channel and on the floodplain. The mathematic representation of these processes is described in Appendix B.

Organization of Report

The preglacial river system in the region of the study area and the drainage system development that took place during the Ice Age are discussed in Part II. The presentation of past and present geomorphic features is organized into historical units based on man's activities in the area. In Part III the natural river during the period of early exploration and surveys from 1673 to 1818 is considered. Part IV concerns the early developments in commercial navigation and channel improvements which took place from 1810 to 1891. The 6-ft channel project and channel improvements during 1905 to 1930 form the third historical unit (Part V). Part VI contains the last time unit, 1927 to the present, and the riverine response to the 9-ft channel project and lock and dam construction is discussed.

The geomorphic features studied include: the river position, river surface area, island surface area, number of islands, riverbed surface area, surface widths, water depth, side channels, and riverbed elevations. In addition, estimates of water and sediment transport are given.

The results of the mathematical model, in Part VII, were used to predict geomorphic changes that might occur in response to various activities including: operating at the present and at different pool levels, sediment inflow changes, dredging, additional wing dams, and increased boat traffic.

A summary of the geomorphic changes that have occurred and those that may occur is given in Part VIII.

PART II: ICE AGE

As the valleys of the Upper Mississippi and Lower Illinois Rivers are features sculptured in the landscapes during the Ice Age, that period is an appropriate place to start the geomorphic study.

The courses followed by the Upper Mississippi and Illinois Rivers today were determined to a large extent by the advances and retreats of the continental ice sheets. The first ice advance in the study area occurred about 1,000,000 years ago and the last retreat was about 10,000 years ago. Prior to glaciation, the Upper Mississippi River system was somewhat different.

As shown in Fig. 2, during preglacial times there were essentially three major drainage systems in the region above the confluence of the Mississippi and Missouri Rivers. On the west side, there was the Iowa River drainage system which rose in southern Minnesota, flowed across northeastern Iowa to Muscatine, then turned south along the present river system to join the eastern drainage at the mouth of the present Illinois River (~~Horbert~~ Horberg, 1956). The northwest region above Hennepin, Illinois was drained by the Upper Mississippi and Rock Rivers. To the east of Hennepin, Illinois the Teays River system drained lands which are now portions of the states of Illinois, Indiana, Ohio, Kentucky, West Virginia, Virginia, and North Carolina. At Hennepin, Illinois the Upper Mississippi and Teays Rivers joined and flowed south through the present-day Illinois valley (Thornbury, 1965, p. 215).

These early preglacial drainage systems shown in Fig. 2 were developed primarily by erosion. The sequential development of the rivers in the Upper Mississippi River Basin in response to Kansan, Illinoian, and Wisconsin glacial advances are illustrated in Fig. 3 (after Frye et al., 1965). The names Kansan, Illinoian, and Wisconsin refer to sequential periods of glaciation.

During Kansan continental glaciation (Fig. 3b), which materially influenced the drainage patterns, the western system was diverted by the ice to the east to join the eastern system at Hennepin, Illinois. This large glacial river cut a deep bedrock valley, now abandoned,

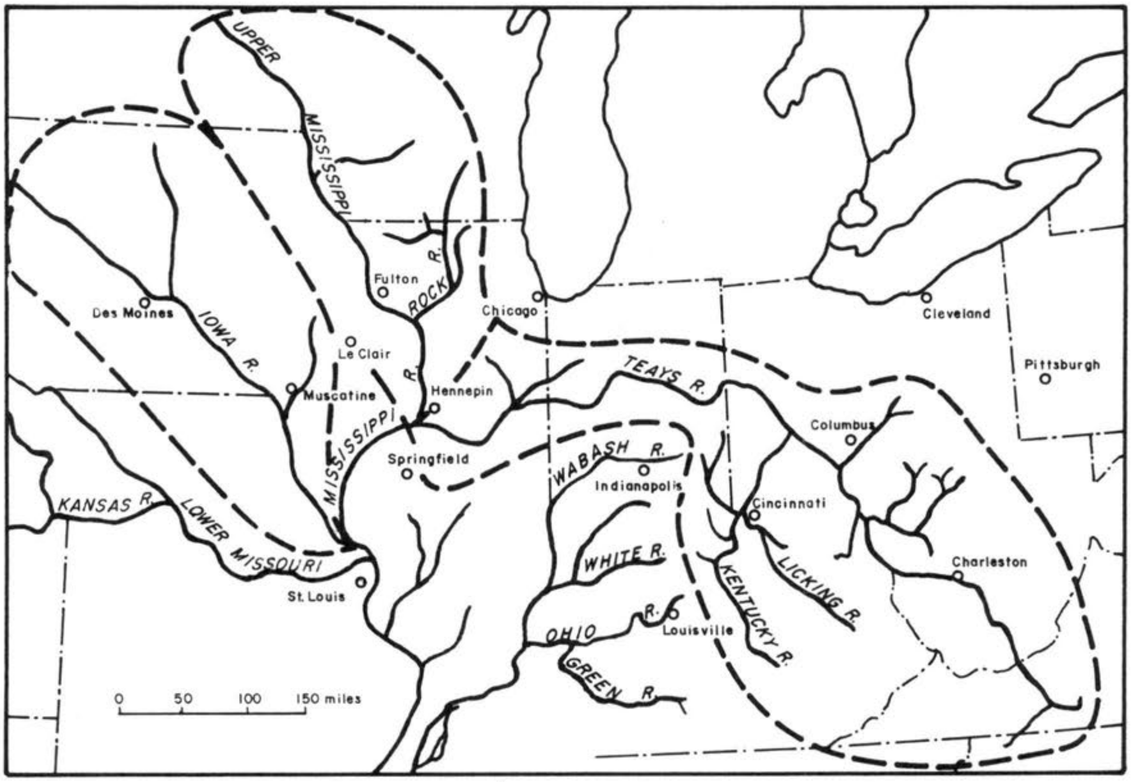


Figure 2. Preglacial map of the river system

between Fulton and Hennepin, Illinois. During the same period, the ancestral Ohio River was forced to the south and the eastern system was greatly reduced in size (Frye et al., 1965). The large size of the Illinois River valley in comparison to its present discharge can be attributed to the large discharges of this period as well as to later flood events.

Following the Kansan glaciation, the drainage reestablished a pattern (Fig. 3c) similar to that of the Aftonian interglacial period (Fig. 3a) with the ancient Mississippi River occupying the Illinois Valley and the ancestral Iowa River occupying the present Mississippi River Valley.

During the Illinoian glaciation (Fig. 3d), the ice sheet advanced from the northeast and forced the ancient Mississippi westward from its

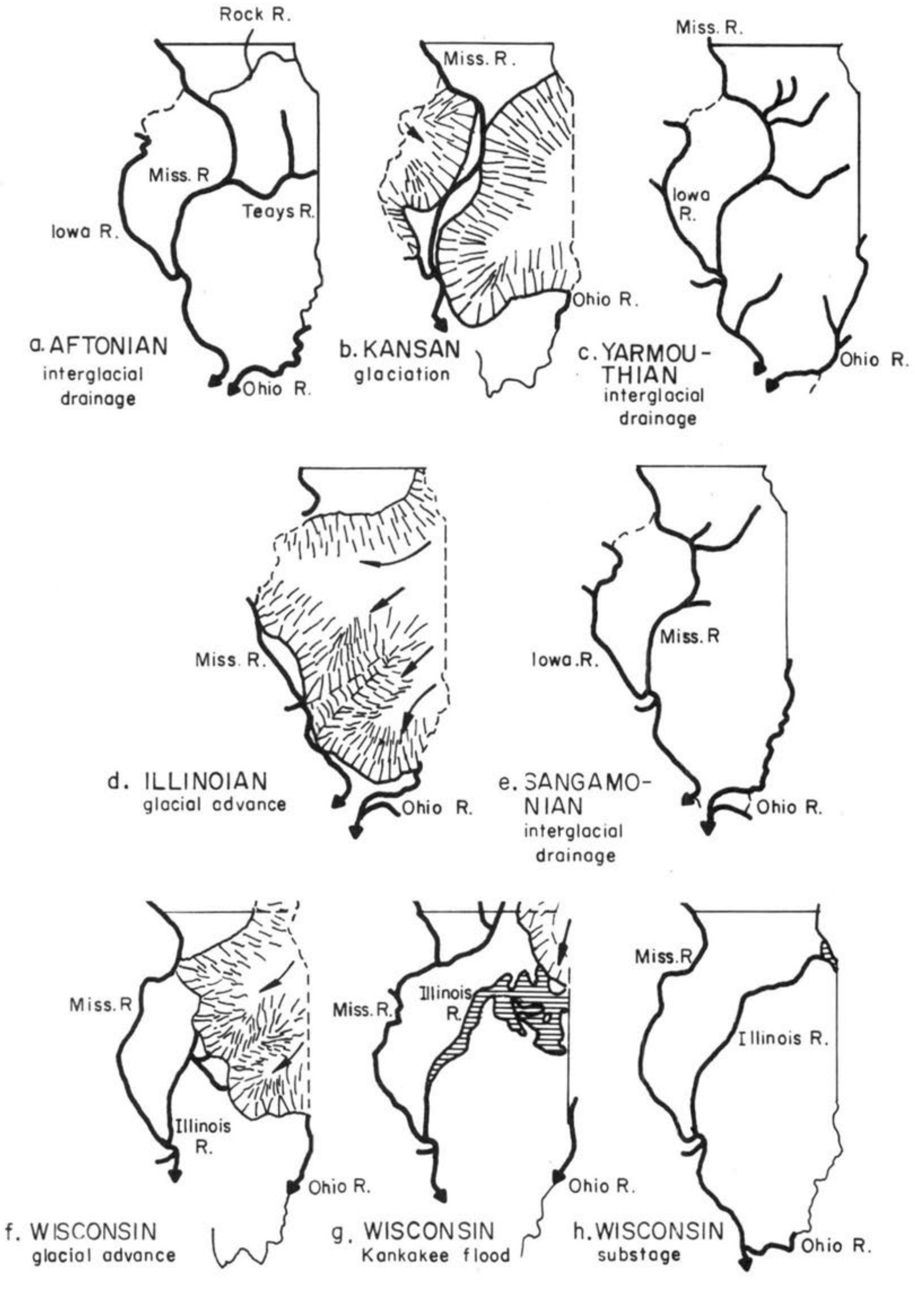


Figure 3. Pleistocene changes - Mississippi and Illinois Rivers
(Reprinted by permission of Princeton University Press)

channel in the Illinois Valley to form a temporary channel crossing eastern Iowa. During this time, a lobe of the ice sheet advanced westward and partly blocked the Mississippi Valley at St. Louis. This caused deposition upstream of St. Louis and the formation of an alluvial deposit in both the Upper Mississippi and Illinois valleys.

Following the retreat of the ice during the Sangamonian interglacial period (Fig. 3e), the Mississippi reoccupied the Illinois Valley, and the Iowa River again passed through the present Mississippi Valley.

The final advance of the Wisconsin ice (Fig. 3f) forced the Mississippi into its present valley. The Illinois River, now draining a much reduced area, occupied the valley formed by the ancient Mississippi. During the retreat of the ice (Fig. 3g), major floods moved through the Illinois Valley as ice dams failed and glacial lakes drained in the Chicago area. By the end of the Wisconsin glaciation (Fig. 3h), the existing drainage patterns of the Upper Mississippi and Illinois Rivers were established.

Even after the retreat of the ice sheet from the study area, the Mississippi River in the study area was strongly influenced by the presence of the ice sheets to the north. Large quantities of glacial debris and melt water moved through the river channel, causing deposition in the valley. When the ice front moved farther north, the reduction in sediment load caused the river to incise to depths of 50 to 75 feet. Subsequent channel widening and terrace and floodplain development occurred in postglacial time.

The remnants of the ice age are the wide valleys formed by melt waters of the receding glaciers and partially filled with glacial outwash sands and gravels. Within the study reach, the average width of the Upper Mississippi River valley floor is 5.6 mi and the slope of the floodplain is approximately 0.5 ft/mi. In the Lower Illinois, the valley floor is 4.1-mi wide and slopes approximately 0.25 ft/mi. The floodplain in the vicinity of the Illinois and Upper Mississippi confluence is higher than it is immediately upstream in either valley.

Possibly the Missouri River is responsible for this local increase in floodplain elevation.

Unlike the New Madrid area in Missouri where a major earthquake occurred as recently as 1811 (Fuller, 1912), there has been no modern tectonic activity in the Upper Mississippi River Basin. A major geologic structure, the Cap au Gris fault zone, crosses both the Mississippi and Illinois Rivers about one mile south of Cap au Gris, Missouri, and Meppen, Illinois (Rubey, 1952, p. 92). South of Cap au Gris, the displacement along the fault is about 1100 ft and the depth to bedrock in the Mississippi Valley is only 25 ft. However, Rubey (1952, p. 146) concluded that there has been no recent movement along this fault zone because the Pleistocene (ice age) terraces are not warped or displaced where they cross the structure.

PART III: THE NATURAL RIVER

Early Exploration and Surveys (1673-1818)

In the intervening period between the ice age and the settlement of the Upper Mississippi Valley by European people, the history of the rivers is contained in the archaeological treasures left by the Indians in the valleys. In 1492, Columbus discovered America. Some 100 years later, the first trappers and traders had worked their way westward to the Mississippi Valley.

For the Upper Mississippi River, the transition from ancient to modern history began in 1673 when the French explorers Marquette and Jolliet advanced from the Great Lakes to the mouth of the Wisconsin River. The two explorers had been commissioned by the governor of Nouvelle France (Canada) to find the outlet of the Mississippi, the leading Big River of the Chippewa Indians. They were the first white men to record for history the discovery of the Upper Mississippi. Marquette and Jolliet continued down the Mississippi River as far as the mouth of the Arkansas and returned to the Great Lakes by way of the Illinois River.

This exploratory mission of 1673 produced the first maps of the river (Tucker, 1942). They are known as the "Joliet Map of 1674" and the "Marquette Map of 1673-1674." The river was called "R. De La Conception," a name which never gained popular acceptance. For the next century, cartographers struggled with the spelling of Mississippi. On the early maps the river has been the Miessisipi, Missicipi, Missisipi, Miffiffipi, Misfisfipi, Mississipi, Missipi, Mifsifsippi, and finally Mississippi.

Immediately after the Marquette and Jolliet expedition, the great French explorer La Salle passed along the Upper River on his way from Canada (Nouvelle France at that time) to the Gulf of Mexico. Having reached the mouth of the Mississippi River and having made alliances with the Indian tribes, La Salle stood with his companions De Tonty and Dautray on the river bank on April 9, 1682 and proclaimed possession of all lands drained by the western tributaries of the Mississippi River in the name of Louis XIV of France. He named this vast territory "Louisiana." At that moment, the western one-half of the Upper Mississippi River channel became French water and by La Salle's omission, the eastern one-half of the channel became English water.

La Salle's companion De Tonty wrote the detailed narrative of this profound acquisition, described the various tributaries of the Mississippi which drained the land of "Louisiana," and prepared a map to accompany his report. Unfortunately nothing is known of this map. On returning to Quebec, La Salle related his discoveries to a young French engineer who then prepared a crude map of Louisiana known as Franquelin's Great Map of 1684 (Hermann, 1900, p. 13). A tracing of this map is given in Fig. 4.

Figure 4. Franquelin's Great Map of 1684

On November 3, 1762, France transferred domain of Louisiana to Spain but regained sovereignty again on October 1, 1800. In the Louisiana Purchase of 1803, the United States Government obtained possession of all of Louisiana. Congress ratified the treaty with the French on October 17, 1803, and on November 25, the Stars and Stripes waved over the great empire west of the Mississippi for the first time (Hermann, 1900, p. 17, 26, 34).

Many of the original maps of the Mississippi River produced between 1674 and 1816 were but "...mere field sketches designed by the explorers to acquaint their superiors with the territory covered..." (Tucker, 1942). When combined with the narratives of the explorers, the sketches provide important historic documents but very little geomorphic information.

In 1816, Topographical Engineer Stephen Long produced the first dimensionally correct map including the study reaches of the Upper Mississippi and Illinois Rivers. The map was made in St. Louis and is dated September 20.

Township surveyors worked their way west to the Illinois River about 1815. With the aid of transits, chains, and stars they began mapping the rivers accurately for the first time. The cost of these first surveys was three dollars a mile.

In the study reach, the first township bordering the Mississippi River to be surveyed was Township 5 north, Range 9 west of the 3rd Meridian. The town of Alton, Illinois, is in this township. By 1818, the survey of the bankline on the Missouri side had been completed.

The surveyor's notes were compiled on maps called township plats. By placing adjoining plats together, a composite map of the river bankline was prepared for portions of the study reach (Fig. 5). From the composite map, the plan view dimensions of the natural river immediately prior to the great influx of settlers were obtained.

River Position

The earliest surveys show the Mississippi River channel on the extreme west side of the valley from Hannibal, Missouri, to Clarksville,

Figure 5. Map of the Pool 25 reach of the Mississippi River in the early 1800's

Missouri, except for a few miles north of the town of Louisiana where the entrance of the Salt River had forced the Mississippi River into mid-valley for a short distance (Fig. 1).

As the neck of land separating the Mississippi and Illinois Rivers narrowed towards the south, the influence of the west bank tributaries, primarily the Missouri River, became increasingly significant and 10 miles south of Louisiana at Clarksville, Missouri, the Mississippi River has shifted across the valley to the eastern bluff, which it reached near Mosier, Illinois. The Upper Mississippi River then followed the eastern bluff to Alton, Illinois.

The early position of the Upper Mississippi River banklines between Clarksville, Missouri (RM 273.4), and Cap au Gris, Missouri (RM 241.4), is shown in Fig. 5. Most of the Missouri bankline was surveyed in 1817 and 1818 but that section adjacent to Slim Island was mapped in 1832. The upper section of the Illinois bankline was surveyed in 1816 and the remainder was compiled from the surveys of 1832, 1847, and 1856.

The early township maps show the Lower Illinois River in the same position in its valley as today.

Surface Areas

Definitions

The following definitions related to surface area were used in this study. The surface area of a river is that area between the river banks including the area of the islands. The banks are defined as the location where the land vegetation ceases.

This definition of the surface area has been selected because it is meaningful in terms of determining the area of the water environment. Moreover, the surface area can be obtained easily from maps or photographs taken at any river stage because the land vegetation is usually visible even at flood stage.

As defined here, the surface area of the river is not the water surface area. The water surface area depends primarily on the river stage. Because the river stage changes greatly throughout a year, the water surface area changes greatly. The surface area of the river changes slowly, however, due to encroachments of the land vegetation and to erosion of its islands and banklines.

Islands are defined as areas with land-type vegetation within the channel banks that are separated from the mainland by the main channel and side channels. Riverbed area is defined as the surface area less the area of the islands. Therefore, riverbed area is composed of the area of the main channel plus the area of the side channels.

River

A large amount of data was collected in the study reach. Due to limited time and funding, Pool 25 was selected for the detailed geomorphic study. A similar study could be made for Pools 24 and 26.

The surface of the Mississippi River in what is now Pool 25 was measured from the map compiled from the early township plats (Fig. 5). In the early 1800's this surface area was 31.41 sq mi.

Islands

There were 26 islands shown in the early township plats in the reach of Mississippi River that is now Pool 25. It is not certain whether all the islands in the reach were surveyed; some smaller islands may have been ignored. The total surface area of the 26 islands on the early township plats was 5.55 sq mi. This represented 18 percent of the surface area of the river.

In Table 1 the surface areas of some of the islands at the time of the first surveys are listed. Throughout the modern history of the river some of these islands have been changing due to natural or man-induced factors. In later chapters in this report, the changes in these islands are discussed.

Riverbed

The riverbed area in the Pool 25 reach of river was approximately 25.86 sq mi in the early 1800's. This area represented 82 percent of the surface area of the river.

Table 1

Islands in the Natural River

Name	Approx. River Mile	Date of Survey	Surface Area sq mi
Pool 26:			
Piasa	209	1832	0.420
Mason	220	~1847	0.290
Sweden	234	1818	0.018
Peruque	234	1818	0.359
Cuivre	236	1818	1.979
Pool 25:			
Turner	245	before 1847	0.088
Mosier	260	1821	0.467
Coon	267	1816	0.165
		~1847	0.006
Carroll	268	1816	0.076
		~1847	0.118
Clarksville	272	~1847	0.176
Pool 24:			
Crider	279	1821	0.025
Unnamed	280	1821	0.050

Width

From the vegetated bankline on the Illinois side to the vegetated bankline on the Missouri side, the width of the Upper Mississippi River in the reach that is now Pool 25 was approximately 5350 ft in the early 1800's (Fig. 5).

There is evidence that the Mississippi River was narrowing in some sections. For example, a portion of the Mississippi River floodplain along the left bank opposite Star City, Illinois (RM 251) was apparently an island, Gilead Island when first settled. By 1856 when a resurvey of that part of the township was undertaken the side channel separating Gilead Island from the Illinois mainland had partially filled. There is evidence that the Mississippi River was widening in other sections.

Large trees that floated down the river during floods or became lodged on sandbars came from caving banklines and islands.

Water Depth

Prior 1879, the only hydrographic surveys on the Upper Mississippi River were of local troublesome reaches. However, there is the impression that during the low flow season, the rivers were not very deep. During the summer months when river flows were very low and the temperatures warm, Sunday excursionists would walk across the river (Tweet, 1974, p. 205).

In addition to the many islands, sandbars formed on the average of one in 3 miles (Chief of Engineers, 1930, p. 1189), resulting in water depths of 3 ft and less over the sandbars.

Side Channels

The side channels in the Pool 25 reach of the Upper Mississippi River in the early 1800's are shown in Fig. 5. Long side channels were adjacent to the Missouri bankline at Sandy, Westport, and Slim Islands.

In 1821, Sandy Chute was approximately 550-ft wide and 3-mi long. Westport Chute was 3.8-mi long; the upstream part was approximately 1100-ft wide but the lower portion adjacent to and below Kickapoo Island was much narrower, only 600-ft wide. Slim Chute averaged 500-ft wide and was slightly more than 3.5-mi long.

Immediately above Clarksville, Missouri, on the Illinois floodplain, there were many side channels and backwater areas. These areas were probably relicts of the river left behind as the river migrated across the floodplain in centuries past.

In the Pool 26 reach, most of the chutes were in the section of river between the Cuivre River and the Illinois River. The chute between Cuivre Island and the Missouri bankline was approximately 800-ft wide and 3-mi long.

Water and Sediment Transport

There are no records of water or sediment transport in the Upper Mississippi Basin in the early 19th century, but the sand transport capacity of the early 19th century Mississippi River in the study reach has been estimated by using Toffaleti's method (1969). The transport of clay and silt in this river system is very difficult to estimate, especially in periods with no recorded measurements.

In the Pool 25 reach, the average riverbed width was 4400 ft. Assuming the bed was composed of 0.27 mm sand, the transport capacity of the river would have been about 2,500,000 tons/yr. The sand transport rate was calculated assuming a yearly hydrograph with a peak flow of 200,000 cfs, a minimum flow of 12,000 cfs and a mean annual discharge of 67,000 cfs. This hydrograph closely matches the flow duration curve for the Keokuk, Iowa gage established from measurements between 1878 and 1964 (Upper Mississippi River Comprehensive Basin Study, Vol. 3, 1972, Fig. D-9).

Summary

In the early 19th century, the Pool 25 reach of the Upper Mississippi River was approximately 5350-ft wide and had 26 islands, three of these being three or more miles long. Approximately 18 percent of the surface area of the river was island area. The sand transport capacity of the reach was approximately 2,500,000 tons/yr.

PART IV: EARLY DEVELOPMENTS

Commercial Navigation and Channel Improvements (1810-1891)

In 1810, the famous riverman Henry Shrieve took 70 tons of lead aboard keelboats at the Galena, Illinois mines and floated the cargo down to New Orleans, Louisiana. He made a profit of $11,000 on the trip (Tweet, 1974, p. 20) thus inaugurating big time commercial navigation on the Upper Mississippi. Soon after in 1820, Stephen Long (who had 3 years earlier produced the first topographic map of the study area) constructed and commanded the Western Engineer, the first steamer on the Upper Mississippi River and used it in an exploring expedition up the Missouri River (Tweet, 1974, p. 29).

By the 1830's navigation on the upper river system had increased to the level that the Federal Government began navigation improvements using U.S. Treasury funds. The work was not systematic but consisted of removing obstructions such as snags, wrecks, rocks, and trees. In some years, the entire budget was used to remove snags. On the Illinois River the first survey was made by topographical engineers of the U.S. Army in 1838 and the first snagging operations were authorized in 1852.

Between 1840 and 1860 there was a great influx of settlers into the Upper Mississippi Basin. For example, during this period the population of Illinois increased from 476,000 to 1,710,000. The main cargoes on the rivers were logs, grain, and people. Tourism on the river became fashionable and upper-class families from St. Louis and the East took the grand tour up river to the Falls of St. Anthony (Tweet, 1974, p. 2).

In 1864, the Upper Mississippi River dropped to the lowest level ever experienced and navigation came to a halt. The major obstacles were the Des Moines Rapids and the Rock Island Rapids. Congress responded in 1866 with appropriations to improve the navigation depth in these rapids.

In the same year, a survey of the Illinois River from its mouth to La Salle, Illinois, was undertaken with the intent to improve the channel to enable steamboats to reach the Illinois and Michigan canal. Based on this survey, preliminary recommendations were made for one lock and dam, a snag boat, some experimental dikes, and beacons for the Lower Illinois River.

In 1867, the removal of obstructions such as snags and wrecks became a continuous operation (Secretary of War ~~House Doc. 341~~, 1906) in the Upper Mississippi River, but it was not until 1871 that the first official water level gages were installed at St. Louis and Rock Island.

In 1869, some improvements were made in the Illinois River: the channel was dredged between Henry, Illinois, and Copperas Creek and dikes were built in an attempt to secure a channel at least 150-ft wide and 4-ft deep during low water. A lock and dam was built at Henry by 1871 and another was built at Copperas Creek by 1877. In 1880, Congress approved funds for locks and dams at Kampsville and at La Grange, Illinois (Fig. 1) with the intent of maintaining a slack water depth of 7 ft to the river mouth. The La Grange lock was completed in 1889 and the Kampsville Lock and Dam (presently not in use) was completed in 1893.

Early experiments with dikes were not successful but in 1873, C.W. Durham conceived and built a dike by driving two rows of poles 9 ft apart along the length of the dike and then filled the space between the rows with brush weighted with sacks of sand (Tweet, 1974, p. 105). The finished dike was 600-ft long and 6 to 10-ft high and closed the chute at the head of Pig's Eye Island 5 mi below St. Paul, Minnesota. Within days after the chute closure, the main channel opened and remained open thereafter.

With a proven method of developing a navigation channel through river reaches shoaled with sand, a permanent and systematic improvement of the Upper Mississippi River was inaugurated in 1878 (Secretary of War ~~House Doc. 341~~, 1906, p. 5). The original project consisted of

> "...the closure of chutes, revetment of caving banks, and contraction of the channel by wing dams so as to obtain a channel of a depth of 4-1/2-feet at low water, to be eventually increased to 6 feet."
>
> Secretary of War ~~House Doc. 341~~, 1906

The first continuous river channel survey from St. Paul, Minnesota, to the Illinois River was undertaken in 1878-1879. This survey formed the data base for the project. Actually, no program nor estimate for this entire work

> "...was ever rendered, it being thought best to present projects from year to year, selecting points known to be most troublesome."
>
> Chief of Engineers, 1915

The intention was to provide a channel 4-1/2-ft deep at low water of 1864.

The 1878-1879 continuous survey maps were not available for this study. Instead a set titled "Survey of the Mississippi River" made under the direction of the Mississippi River Commission in 1881 was found. The secondary triangulation and precise levels run in 1881 and the topography and hydrography obtained in 1891 make up what is referred to as the 1891 survey.

Prior to 1891, 41 dikes were constructed in the study reach of the Upper Mississippi River, 15 of them in what is now Pool 25 (Fig. 6). These dikes were low dikes with crests at a level 6 ft above the 1864 low water and were constructed with rock, brush, and sand.

As the amount of effort expended on the 4-1/2-ft channel in the study reach of the Upper Mississippi and Lower Illinois Rivers between 1878 and 1891 was very minimal (the rivers were deeper in the study reach than upstream), the 1891 survey is considered representative of river morphology immediately prior to the 4-1/2-ft channel project. This morphology is described below.

River Position

In general the positions of the Upper Mississippi and Illinois Rivers did not change in the period between the early 1800's and 1891. For example, the 1891 banklines of the Upper Mississippi River in the reach that is now Pool 25 are shown in Fig. 6. By comparing these banklines with those in Fig. 5, it is concluded that the right (Missouri) bankline did not move between 1818 and 1891. Parts of the Illinois bankline moved riverward near Carroll (RM 268) and Coon

Figure 6. Map of the Pool 25 reach of the Mississippi River in 1891

(RM 267) Islands and near Maple Island (RM 249), but otherwise the left bankline remained essentially unchanged.

Surface Areas

River

The surface areas of the study reach of the Upper Mississippi River measured on the 1891 survey map are given in Table 2. Compared to the early 1800's, the surface area of the Pool 25 reach had decreased by 1.3 sq mi or 4.1 percent in 1891.

Table 2

Surface Areas of the 1891 Mississippi River

Location	Surface area, sq mi River	Surface area, sq mi Islands	Surface area, sq mi Riverbed
Pool 26:			
Lower quarter	7.48	0.76	6.72
Middle half	16.53	3.82	12.71
Upper quarter	8.58	2.93	5.65
	32.59	7.51	25.08
Pool 25:			
Lower quarter	7.20	1.70	5.50
Middle half	15.15	3.45	11.70
Upper quarter	7.78	2.52	5.26
	30.13	7.67	22.46
Pool 24:			
Lower quarter	5.60	1.50	4.10
Middle half	11.39	2.12	9.27
Upper quarter	5.94	1.27	4.67
	22.93	4.89	18.04

Islands

The 1891 surface areas of the islands in the study reach of the Mississippi River are given in Table 2. In the period between the time of the township surveys and 1891 the number and size of the islands increased substantially. For example, in the Pool 25 reach, there were

26 islands shown on the township maps (Fig. 5) and 50 islands shown in the 1891 survey map. The total surface area of the 50 islands was 7.67 sq. mi. This represents 26 percent of the surface area of the river.

In Table 3, areas of some of the islands are compared. The five islands in Pool 25 were larger in 1891 than in the early 1800's and in aggregate the island area increased 0.850 sq mi. The reason for the growth in the number and size of the islands has not been determined. Possibly the surveyors did not map all the little islands for the township plats. However, they surveyed Four Acre Island in Pool 25 in 1817 and it was only 4.16 ac (0.006 sq mi) in size. Possibly, the effect of the great influx of settlers in the valley was to denude the landscape of vegetation and thus produce an increase in sediment load without a corresponding increase in water yield. The response of the river would be to deposit some of this sediment. The result would be more islands but usually the river would also widen with the increased sediment supply. Instead, there was a slight narrowing. A small fraction of the island growth could be attributed to the dikes that were built between 1878 and 1891, but many more islands grew without the aid of dikes.

The most plausible explanation for the growth in number and size of the islands would be a period of dry years. With lower water levels and less submergence, the land vegetation could expand out onto the areas that were formerly sandbars. There are no flow records to substantiate this hypothesis.

Surface Widths

The average widths of the Mississippi River in the study reach in 1891 are given in Table 4. The average width was determined by first measuring the surface area of the river reach and then dividing by the length of the reach, measured along the centerline of the river.

The reach of river which is now Pool 24 was very uniform in width and narrower than the other reaches. Pool 25 averaged 5130 ft-wide, nearly 700 ft wider than Pool 24. However, between the early 1800's and 1891 the river had narrowed approximately 200 ft overall in Pool 25.

Table 3

Changes in Surface Areas of Islands from 1800's to 1891

Name	Approx. River Mile	Surface area, sq mi		
		Township[1/]	1891	Change[2/]
Pool 26:				
Piasa	209	0.420	0.383	-0.037
Mason	220	0.290	0.340	+0.050
Sweden	234	0.018	0.056	+0.038
Peruque	234	0.359	0.386	+0.027
Cuivre	236	1.979	2.180	+0.201
Pool 25:				
Turners	245	0.088	0.203	+0.115
Mosier	260	0.467	0.477	+0.010
Coon	267	0.165	0.190	+0.025
Carroll	268	0.076	0.428	+0.352
Clarksville	272	0.176	0.524	+0.348
Pool 24:				
Crider	279	0.025	0.165	+0.140
Unnamed	280	0.050	0.188	+0.138

[1/]The surface area of islands in the natural river and date of survey are listed in Table 1.

[2/]A positive change indicates growth of the island and a negative change denotes a decrease in size.

In 1891, the Mississippi River was much narrower immediately below the confluence with the Illinois River than above. Coincident with this narrowing, there were few islands downstream of the confluence. In general, the 1891 Mississippi River was wider in reaches with many islands and narrower in reaches with fewer islands.

Riverbed Elevations

The 1891 survey included a hydrographic survey of the bed of the Mississippi River in the study reach. The average riverbed elevations for different reaches which are now Pools 24, 25, and 26 are given in Table 4. The average riverbed elevation for a reach was determined by first obtaining the average bed elevation in the deepest

1000 ft of each cross section and then averaging these numbers to get an average value for the reach.

Table 4

Average River Surface Widths and Riverbed Elevation in the 1891 Mississippi River

Location	Surface Width ft	Riverbed Elevation* ft, Amsl
Pool 26:		
Lower quarter	4180	392.0 1/
Middle half	4620	399.8 2/
Upper quarter	4790	403.9
Pool 25:		
Lower quarter	4900	409.7
Middle half	5160	417.0
Upper quarter	5300	422.3
Pool 24:		
Lower quarter	4400	425.5
Middle half	4470	430.7
Upper quarter	4660	435.1

*Average of the riverbed elevations in the deepest 1000-ft width of river channel. During 1891, the stage at Hannibal, Missouri (RM 309) ranged from 448.2 to 461.7 ft, Amsl and the stage at Grafton, Illinois (RM 218) varied from 403.9 to 418.7 ft, Amsl. Trends in discharges and stages are analyzed in Part VI.

1/ Average below confluence with the Illinois

2/ Average in the middle third of Pool 26

Side Channels

There were many more side channels in the study reach of the Upper Mississippi River in 1891 than in the early 1800's because of the proliferation of islands in the river. The side channels in the Pool 25 reach in 1891 are shown in Fig. 6.

The three long chutes in the Pool 25 reach, Slim, Sandy, and Westport did not change much between 1821 and 1891. Slim Chute widened approximately 50 ft to 550 ft but remained the same length (3.5 mi). Because of the elongation of Sandy Island, Sandy Chute became 0.3 mi longer in 1891 than in 1821. Also, this chute narrowed approximately 150 ft to an average width of 400 ft. Westport Chute remained unchanged in the upstream portion but widened from 600 ft to 1100 ft in the downstream portion. Because of the island growth down river of Westport Island, Westport Chute extended to the end of Sterling Island by 1891, which made the chute about 3 mi longer than in the early 1800's.

Between 1821 and 1891, the chute between Cuivre Island and the Missouri mainland in Pool 26 had narrowed from 800 ft to a width of 350 ft while elongating to 4.2 mi because Cuivre Island grew in the upstream direction.

By 1891, the backwater areas on the Illinois floodplain in the Pool 24 had been isolated by the SNY levee. This levee also closed off some of the side channels along the Illinois bank.

Levees

For more than a century, levees have been used in the Upper Mississippi River Basin to protect the people and floodplain property from floods. By 1891, more than 40 mi of levees extended along the Upper Mississippi River bank in the study reach. The longest was the SNY levee along the Illinois side of the Mississippi River from opposite Slim Island (RM 264.5) on upstream past the location of Lock and Dam 22 (RM 301.2). Other levees were not so extensive. On the Missouri floodplain in the Pool 25 reach some individual fields were protected by levees. Otherwise, the Missouri floodplain in the study reach was mostly unprotected.

The effects of levees on a river system are usually twofold. First, sedimentation on the floodplain is arrested because the floodplain is inundated only when the levees fail or are overtopped. Second, the storage capacity of the floodplain is no longer available to help attenuate flood peaks (Simons, et al., 1974).

In the study reach of the Upper Mississippi, sedimentation on the floodplain due to flooding in the early river was not significant in general. Levees affect flood peak attenuation. The ratio of the floodplain storage volume to the volume of water in the peak of the flood hydrograph is the important factor. If this ratio is large, the levees are important and if this ratio is small, the levees are less important. In the study reach, the ratio is small.

In the early stages of development the levees were not adequate to withstand large or long floods. Prior to 1891, at least three sections of the SNY levee in the study reach had been breached. The crevasses were in sections opposite Carroll Island, at River Mile 290 (called the Blackwood Bend Crevasse) and 1.5 mi below the location of Lock and Dam 22.

The effects of levee development and levee improvement on river stage and river behavior are described in later sections.

Water and Sediment Transport

Water discharge records for the study reach begin just 10 years or so prior to 1891. The magnitudes of the water discharges in this period are approximately the same as those recorded in later years.

Although no sediment measurements were made, the transport capacity of the 1891 river channel in the Pool 25 reach has been estimated by using Toffaleti's method (1969). The sand transport rate was approximately 2,800,000 tons/yr for the 1878-1964 flow duration curve. Because of changes in channel geometry, this rate is 13 percent greater than the rate computed for the early 1800's channel. In 1891 the average riverbed width in the Pool 25 reach was 3820 ft.

Summary

In 1891, the study reach of the Upper Mississippi River had many more islands than 70 years previously, resulting in many new side channels. In the Pool 25 reach, there were 50 islands, twice as many as in the early 1800's. Twenty-six percent of the surface area of this river reach was island area in 1891. The river had narrowed 200 ft in the Pool 25 reach, mostly in the upstream half. Some of the old long chutes in the Pool 25 reach changed in width or length and some did not. The sand transport capacity of the reach was approximately 2,800,000 tons/yr. In the Pool 24 reach, the Illinois floodplain had been isolated from the river by the SNY levees cutting off some side channels and backwater areas from obtaining surface flow from the river.

PART V: THE SIX-FOOT CHANNEL PROJECT

Channel Improvements (1905-1930)

As anticipated in 1878, it would soon be desirable to increase the depth of the Upper Mississippi River navigation channel between the Missouri River and St. Paul to a minimum of 6 ft. By 1905, a considerable expenditure in funds had been made in the reach of the Mississippi River between Hannibal and the Missouri River. Apparently though, a 4-1/2-ft channel had been achieved. The total length of the dikes constructed between 1878 and 1905 in the reach was 55.1 mi requiring nearly 1,000,000 cu yd of rock and 1,400,000 cu yd of brush. In addition 238,000 lineal ft of shore protection had been constructed requiring 470,000 and 440,000 cu yd of rock and brush respectively (House Doc. 341, 1906, p. 17).

In the River and Harbor Act of March 3, 1905, Congress authorized the Secretary of War to

> "...cause an estimate to be made of the cost
> of securing a channel 6 feet deep in that portion
> of the river above described."

In a 1906 letter to Congress the Secretary of War outlined the work required to achieve a 6-ft channel (~~House Doc. 341~~ Secretary of War, December 20, 1906).

On March 2, 1907, Congress inaugurated the 6-ft channel project by authorizing an expenditure of 1.5 million dollars to be spent in the next three years. Along with the appropriation for capital works, the Congress set aside $50,000 for each of two years for dredging in harbors and landing places.

In the reach of river between Hannibal, Missouri and the Missouri River confluence, the Mississippi River was to be contracted in width using dikes to obtain the desired depth. The proposed channel widths were 1200 ft from Hannibal to the Illinois River and 1400 ft from the Illinois River to the Missouri. It was estimated that 10 years would be required to complete the work.

The materials required for the 6-ft channel project between Hannibal and the Missouri River were 857,000 cu yd of rock and

4,100,000 cu yd of brush. The estimated cost of obtaining and placing these materials was $2,717,391 (Secretary of WAR ~~House Doc. 341~~, 1906, p. 17).

An example of the extent of dike construction in the study area is illustrated in Fig. 7. In the figure, the locations of the 127 dikes, which have been constructed in Pool 25, are shown. In this 31-mile reach of river, more than 22 lineal miles of dikes were built in the period between 1879 and 1929.

In the Illinois River system, a 7-ft channel project was 95 percent complete from the mouth of the river to the canal at La Salle. In addition to the locks and dams at La Grange (RM 80) near Chicago and Kampsville (RM 31) locks and dams were constructed with state funds to complete the Illinois Waterway. Also, since 1900, water had been diverted into the Illinois River from Lake Michigan through the Chicago drainage canal (Starrett in Oglesby et al., 1972).

In 1930, when the 6-ft channel project in the Upper Mississippi River was 82 percent complete, the 9-ft channel was authorized. In order to prepare estimates of the cost of the 9-ft project, a new hydrographic survey was made in 1929-1930. The maps of this survey, known as the Brown maps, were prepared by W.N. Brown, Inc., Washington, D.C. under contract with U.S. Engineer Office, Rock Island, Illinois. These maps show the geomorphic features of the Upper Mississippi River when the 6-ft channel project was terminated.

River Position

In general the positions of the Upper Mississippi and Illinois Rivers in the study reach did not change in the period between 1891 and 1929. For example, the 1929 banklines of the Upper Mississippi River in the reach that is now Pool 25 are shown in Fig. 8. By comparing this map with the 1891 map shown in Fig. 6, two changes in the Illinois bankline are noted. Immediately upstream of Mosier Island, a small island (Island No. 474 on the 1891 map) became attached to the Illinois floodplain. Opposite Stag Island, the large island called Maple Island in 1891 also became joined to the Illinois floodplain by 1929.

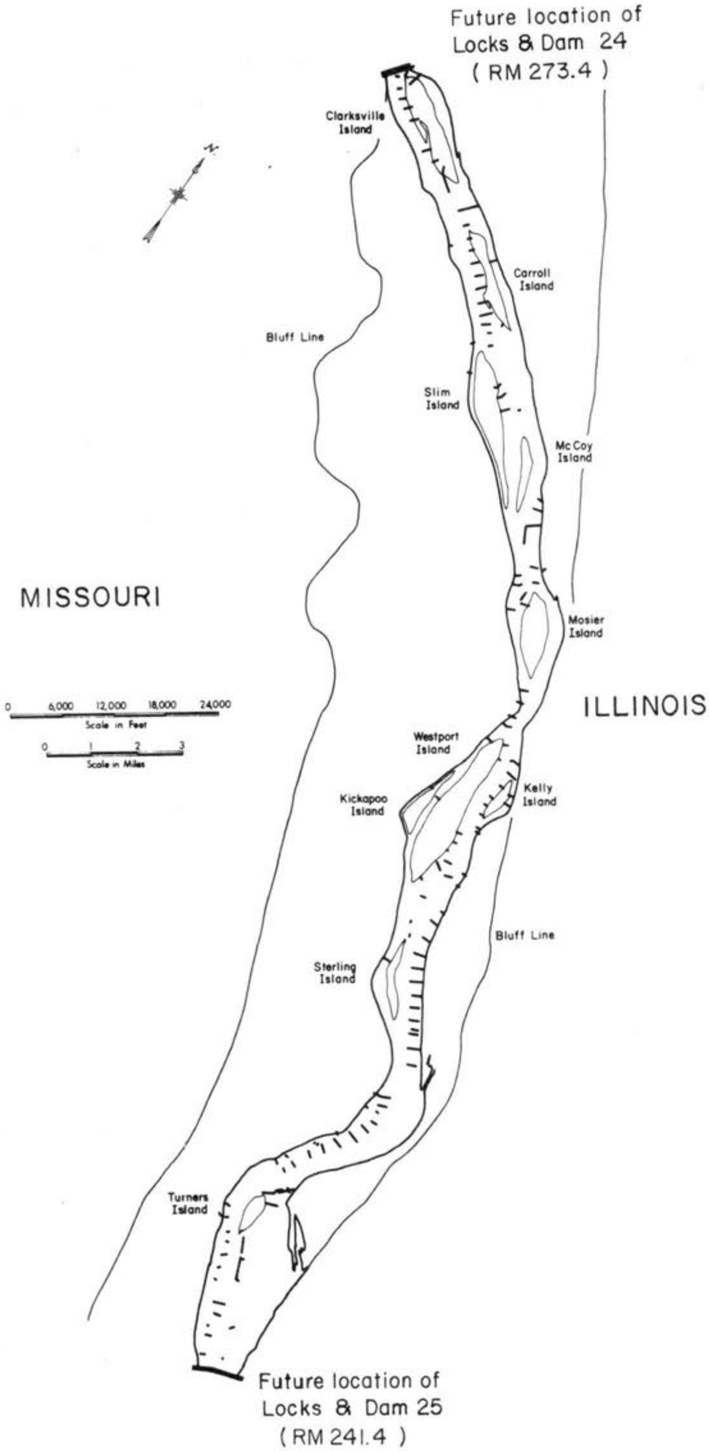


Figure 7. Location of dikes in Pool 25, Mississippi River

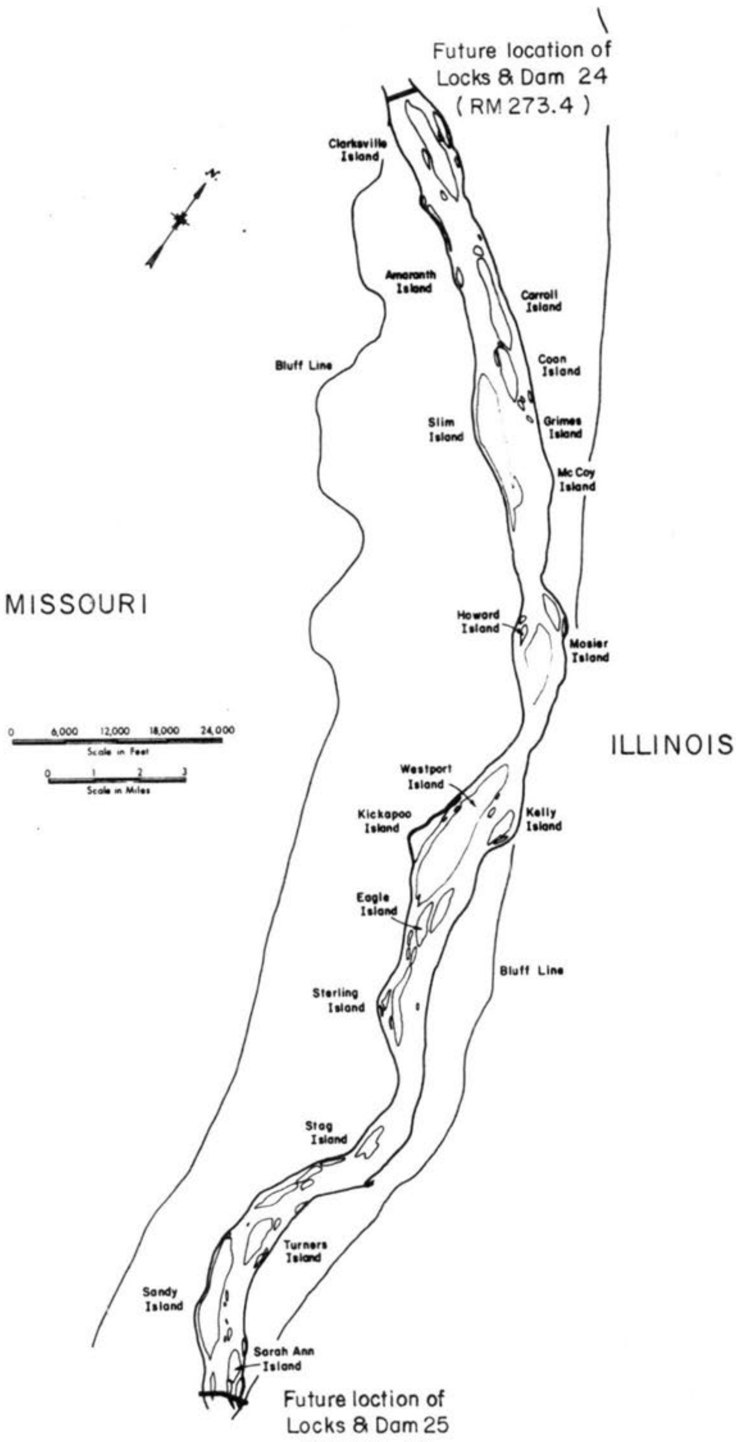


Figure 8. Map of the Pool 25 reach of the Mississippi River in 1929

Surface Areas

River

The surface areas of the Pool 25 reach of the Upper Mississippi River in 1929, measured on the 1929 topographic map, are given in Table 5. Compared to the 1891 river (Table 2) the surface area of the Pool 25 reach had decreased by 0.58 sq mi or 1.9 percent. The decrease was due mainly to the attachment of Island No. 474 (Fig. 9) and Maple Island to the Illinois floodplain.

Islands

The surface areas of the islands in the Pool 25 reach of the Upper Mississippi River in 1929 are given in Table 5. In the period between 1891 and 1929, the number of islands in Pool 25 increased from 50 to 65 and the surface area of the islands increased by 2.30 sq mi, an increase of 30 percent.

Table 5

Surface Areas of the Mississippi River in 1929

Location	Surface area, sq mi		
	River	Islands	Riverbed
Pool 25:			
Lower quarter	6.83	2.14	4.69
Middle half	14.97	4.74	10.23
Upper quarter	7.74	3.09	4.65
	29.54	9.97	19.57

As shown in Table 6, the five islands listed for the Pool 25 reach all grew in size. However, in other reaches some islands decreased in area. The growth of Mosier Island is shown in Fig. 9. Significant deposition occurred on the downstream end and slight erosion occurred at the nose of the island.

Table 6

Changes in Surface Areas of Islands from 1891 to 1929

Name	Approx. River Mile	Surface area, sq mi	
		1929	Change since 1891
Pool 26:			
Piasa	209	-	-
Mason	220	0.454	+0.114
Sweden	234	0.051	-0.005
Peruque	234	0.490	+0.104
Cuivre	236	2.160	-0.020
Pool 25:			
Turners	245	0.370	+0.167
Mosier	260	0.654	+0.177
Coon	267	0.253	+0.063
Carroll	268	0.439	+0.011
Clarksville	272	0.899	+0.375
Pool 24:			
Crider	279	0.144	-0.021
Unnamed	280	0.104	-0.084

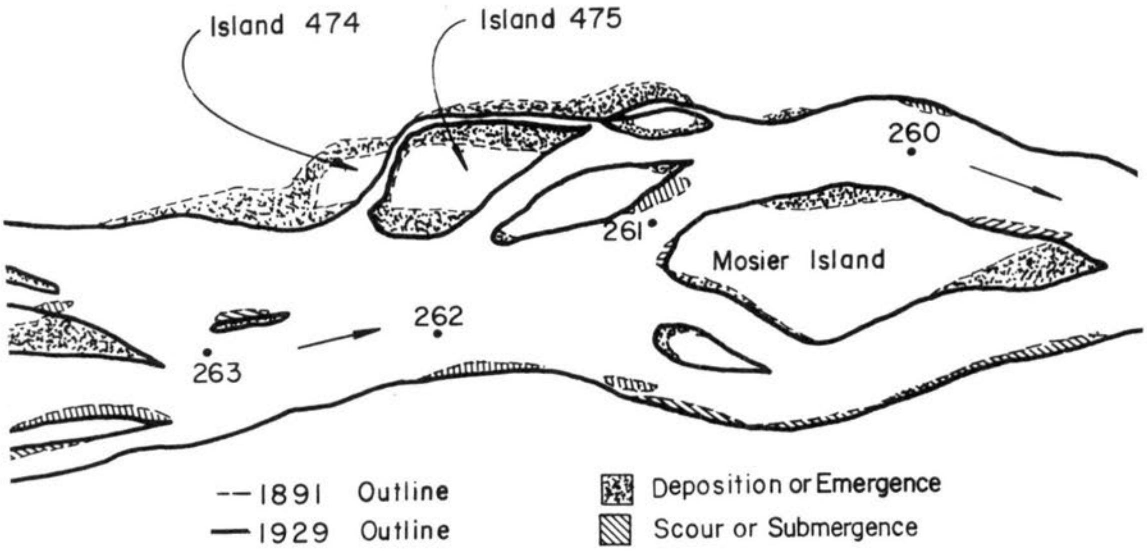


Figure 9. Mosier Island Reach

The increase in the number of islands was the result of building dikes. The river moves sand into the dike fields and creates sandbars. When these bars grow to a sufficient height, land vegetation takes root and the sandbars become islands. For example, the dike field constructed along the east side of Sandy Island between 1891 and 1929 produced five new small islands.

When dikes are used to close chutes, islands may form in the chute; this occurred in Westport Chute where two very small islands formed between 1891 and 1929. Dikes anchored landward to islands usually result in new sand deposits around and at the downstream ends of the islands. In time these deposits build to a height such that the land vegetation encroaches on the bars. Thus the islands grow in size. During the period between 1891 and 1929 many islands in the Pool 25 reach grew this way.

Riverbed

As a consequence of islands growing and small decreases in river widths between 1891 and 1929, the riverbed area in the Pool 25 reach of the Upper Mississippi River (Table 5) decreased by nearly 2.9 sq mi. This was a 13 percent decrease in the flow carrying portion of the river.

Surface Widths

The average surface widths of the Pool 25 reach in the Upper Mississippi River in 1929 are given in Table 7. The average surface width of the Mississippi River in the entire Pool 25 reach was 5030 ft, a decrease of 100 ft since 1891. Most of the narrowing of the river between 1891 and 1929 was due to the attachment of Island 474 (Fig. 9) and Maple Island to the Illinois floodplain.

Riverbed Elevations

The 1929-1930 Brown survey maps included data from the hydrographic survey of the Mississippi River in the study reach. The average riverbed elevations for the reaches that are now Pools 24, 25, and 26 are given in Table 8. The averages are for the deepest 1000-ft wide cross section of river.

Table 7

Average River Surface Widths in the Pool 25 Reach of the Upper Mississippi River in 1929

Location	Surface Width ft
Pool 25:	
Lower quarter	4660
Middle half	5100
Upper quarter	5280

Table 8

Average Riverbed Elevations in the 1929 Mississippi River

Location	Riverbed Elevation,* ft Amsl 1929	Change since 1891
Pool 26		
Below Illinois River	-	-
Middle third	401.5	+1.7
Upper quarter	405.2	+1.3
Pool 25:		
Lower quarter	410.1	+0.4
Middle half	417.1	+0.1
Upper quarter	423.5	+1.2
Pool 24:		
Lower quarter	426.8	+1.3
Middle half	430.5	-0.2
Upper quarter	436.6	+1.5

*Average of the riverbed elevations in the deepest 1000-ft width of river channel. During 1929, the stage at Hannibal, Missouri (RM 309) ranged from 449.5 to 471.5 ft, Amsl (compared to from 448.2 to 461.7 ft in 1891) and the stage at Grafton, Illinois (RM 218) varied from 406.9 to 430.0 ft, Amsl (compared to from 403.9 to 418.7 ft in 1891). Trends in discharges and stages are analyzed in Part V1.

In all reaches except the middle half of Pool 24, the riverbed elevation was higher in 1929 than in 1891. That is, over this period of 38 years the net effect was a slight aggradation (0.8 ft on the average) in the deepest part of the channel. In contrast, dike construction in the Middle Mississippi River between St. Louis, Missouri, and Cairo, Illinois, resulted in riverbed degradation (Simons et al., 1974, p. 19).

Side Channels

The 1929 chutes in the Pool 25 reach are shown in Fig. 8 and the 1891 chutes in Fig. 6. With the creation of new islands, there were more side channels (chutes) in the study reach of the Upper Mississippi River in 1929 than in 1891. Each new island creates at least one more side channel. However, some chutes were filled up during the same period. For example, as shown in Fig. 9, the chute between Island 474 and the Illinois mainland was closed.

Two of the three long chutes in the Pool 25 reach changed little between 1891 and 1929. Sandy Chute remained 400-ft wide and 3-mi long. Slim Chute remained the same length (3.5 mi) but narrowed slightly from an average width of 530 ft to 480 ft. Westport Chute decreased in width to 830 ft (from 1100 ft) due to the lateral growth of Kickapoo and Westport Islands. Westport Chute lengthened because Westport Island grew 0.2 mi in the upstream direction.

Levees

By 1929, improvements had been made to the SNY levees protecting the Illinois floodplain from the Mississippi River in the Pools 24 and 25 reaches.

On the Missouri side, levees were built along the bankline from Bobs Creek (RM 239) up along the Pool 25 reach of river to the bluff line near Clarksville, Missouri and also along a small section of the Missouri floodplain immediately upstream of the Salt River confluence (Fig. 1). In the Pool 26 reach and away from the river a few miles of levees were constructed near Dardenne Creek and the Cuivre River.

One consequence of building levees was to channelize the many creeks on the floodplain. Bobs Creek below Lock and Dam 25 and Kiser Creek in the SNY levee district are examples.

Natural Levees

Rubey noted in 1929 that both the Mississippi and Illinois Rivers flowed between natural levees and that the levees of the Illinois were higher than that of the Mississippi. According to Rubey (1952, p. 123), it is probable that the height of the natural levees is a function of the permanence of the river channels. That is, along the Illinois River the natural levees have grown high by repeated additions of sediment; whereas those along Mississippi River are less high because the river has been more active. Through geologic time, the Upper Mississippi has shifted laterally, thereby destroying the natural levees on one side of the channel and abandoning them on the other.

Illinois River

Major differences between the Upper Mississippi and Lower Illinois Rivers were observed in 1929 by Rubey (1952, pp. 99, 101, 125). At that time he noted that the Illinois River was not actively eroding its banks. He also found that very few changes occurred in Illinois River islands between 1842 and 1929. This was in contrast to the Mississippi which shifted its channel "somewhat at each flood" with new bars forming and old ones being eroded.

The great difference in the type and amount of sediment load transported by the two rivers, as reflected by their gradients, provides an explanation of the disparity in morphology and behavior. The Illinois River has a gradient of 0.1 ft per mile between Kampsville, Illinois and its mouth; whereas the Mississippi River has an average natural gradient of 0.6 ft per mile between Quincy, Illinois and the mouth of the Missouri River.

In addition, the width-depth ratio of the Illinois River channel is about a third that of the Upper Mississippi (Rubey, 1952, p. 128). Both the low gradient and the small width-depth ratio of Illinois River indicate that it is not transporting large quantities of sand. The suspended fine load transported through the gentle, narrow, deep channel at low velocities has not caused significant modification of the Illinois channel through time.

The low gradient of the Illinois River can also be related to Pleistocene events in the Mississippi and Illinois valleys, when large discharges and sediment loads of the Mississippi caused backwater effects and deposition in the Illinois Valley. The evidence for ponding, described by Rubey (1952, p. 96), explains the flat gradient of the Illinois Valley and, in turn, the low sinuosity (approximately 1.1) and relative stability of the Illinois River.

Water and Sediment Transport

By 1929, nearly 50 years of record had been gathered at the discharge gaging stations at Keokuk, Iowa, and Alton, Illinois. No discharge measuring stations had yet been established on the Lower Illinois River.

Of the top ten flood peaks recorded in the Upper Mississippi River at the Keokuk, Iowa station, six occurred prior to 1929. Ranking these in order from one as the highest to ten as the lowest, these six peaks were 1, 4, 5, 6, 8, and 9. At the Alton, Illinois station, six of the ten largest flood peaks of record also occurred before 1929. Those ranked 1, 2, 4, 6, 7, and 8. In the lower Illinois River at Meredosia, Illinois, the fourth and sixth highest stages of record were obtained in 1926 and 1927. Other high ranking discharges and stages at these stations are listed in Appendix A.

In conjunction with the topographic and hydrographic surveys, 1929-1930, borings were made into the alluvium on the bed of the Upper Mississippi River at the proposed locations of the locks and dams. At the proposed site of Lock and Dam 24 (RM 255.3), the alluvium under the bed of the main channel was almost entirely sand with a few lenses of clay and sand or mud and sand; however, no sediment discharge measurements were made.

Based on the geometry of the 1929 Mississippi River channel in the Pool 25 reach, the sand transport of the channel has been estimated at 3,100,000 tons/yr for the long-term flow duration curve. This rate is 11 percent greater than the estimated rate for 1891. In 1929 the average riverbed width in the Pool 25 reach was 3330 ft.

Summary

The development of the 6-ft navigation channel using the method of contraction with low dikes did not affect the river morphology greatly. In the Pool 25 reach of the Upper Mississippi River, 15 new islands were created and a slight narrowing of the river occurred. In 1929, the average surface width of the river in this reach was 5030 ft, 100 ft less than in 1891. The size of the islands in this reach increased by 30 percent between 1891 and 1929 while most of the large chutes remained unchanged.

The average riverbed elevations in the study reach of the Upper Mississippi River were slightly higher (0.8 ft on the average) than in 1891 indicating that the deepest part of the river aggraded slightly during the period of dike construction from 1891 to 1929. This is opposite to the situation in the Middle Mississippi River where the construction of high dikes produced degradation of the riverbed (Simons et al., 1974). The sand transport capacity of the Pool 25 reach was approximately 3,100,000 tons/yr.

By 1929, both the Missouri and Illinois floodplains in the Pools 24 and 25 reaches had been protected by levees along the riverbanks. A portion of the Missouri floodplain in the Pool 26 reach was protected with levees in a few areas back from the river.

PART VI: THE NINE-FOOT CHANNEL PROJECT

Locks and Dams 24, 25, and 26 (1927-Present)

The River and Harbor Act of January 21, 1927 authorized the Secretary of War to conduct (~~House Doc. No. 290~~ Secretary of War, 1930, p. 1)

> "...a partial survey of the Mississippi River between Missouri River and Minneapolis, with a view to securing a channel depth of 9 feet at low water, with suitable widths."

In their feasibility study of the 9-ft project, the Office of the Division Engineers argued that (~~House Doc. No. 290~~ Secretary of War, 1930, p. 1)

> "The present 6-foot project and the methods of prosecuting it were designed to aid types of river trade which have become obsolete, the project is certainly inadequate for present needs."

The principal benefits to be derived from the 9-ft channel project would be the savings in the cost of shipping grain and grain products from the Upper Mississippi Valley by water instead of by land.

The River and Harbor Act of July 3, 1930 authorized the 9-ft channel project in the Upper Mississippi River. The estimated capital cost was $98,423,000 and the annual maintenance was estimated at $1,950,000 (~~House Doc. No. 290~~ Secretary of War, 1930, p. 2).

Initially it was recommended that the lower reach of the Upper Mississippi River (Quincy, Illinois, to the mouth of the Illinois River) be improved by means of open-river regulation. The cost of this work was estimated at $8,100,000 with annual maintenance charges of $450,000 (~~House Doc. No. 290~~ Secretary of War, 1930, p. 45). Although it was not recommended in the preliminary studies the estimated cost of improving the Mississippi River in the study reach by building Locks and Dams Nos. 24, 25 and 26 was $12,490,000 (~~House Doc. No. 290~~ Secretary of War, 1930, p. 46). When the preliminary studies were upgraded, it was recommended that Locks and Dams Nos. 24, 25 and 26 be constructed but not in the same locations considered in the first studies. The locations of these locks and dams are shown in Fig. 1.

Viewed in longitudinal profile, the locks and dams on the Upper Mississippi River 9-ft channel project form a series of steps in a river stairway (Fig. 10). River traffic ascends this stairway when moving upstream toward Minneapolis-St. Paul and descends when moving downstream toward St. Louis. The locks and dams regulate river flows to maintain the minimum 9-ft depth required for navigation. In Fig. 10, the lower irregular line depicts the riverbed and the intermediate, stepped line indicates minimum pool water surface levels maintained by the locks and dams. The upper line depicts the water surface as it would appear under conditions of higher flow; that is, when the gates of the dams are raised out of the water and the river is flowing as an open river.

Work began officially in the study reach on January 13, 1934 at Lock and Dam No. 26. First full pool was obtained in Pool 26 on August 8, 1938, in Pool 25 on July 11, 1939, and in Pool 24 on May 14, 1940. The 9-ft channel project in the study reach was placed completely in operation on March 12, 1940.

The dams in the Upper Mississippi River are the movable type. That is, they are not massive structures blocking the river valley but are a series of piers across the river with movable gates between the piers. The dam is formed when the gates are lowered into the water and cause the water level upstream of the dam to rise. This increase in water level creates a slack-water pool with the required depth for low-flow navigation. During periods of high flow, it is not necessary to create a pool because flow depths are naturally sufficient for navigation. At these times the gates are raised above the water and the river flows freely as an open river.

The locks in the Upper Mississippi are the same size as those built in the Ohio River navigation system (which was developed earlier than the Upper Mississippi system). The majority of the lock chambers in the 9-ft channel project are 110-ft wide and 600-ft long. In addition to the lock and gated section, most of the locks and dams have an earth embankment section of various lengths.

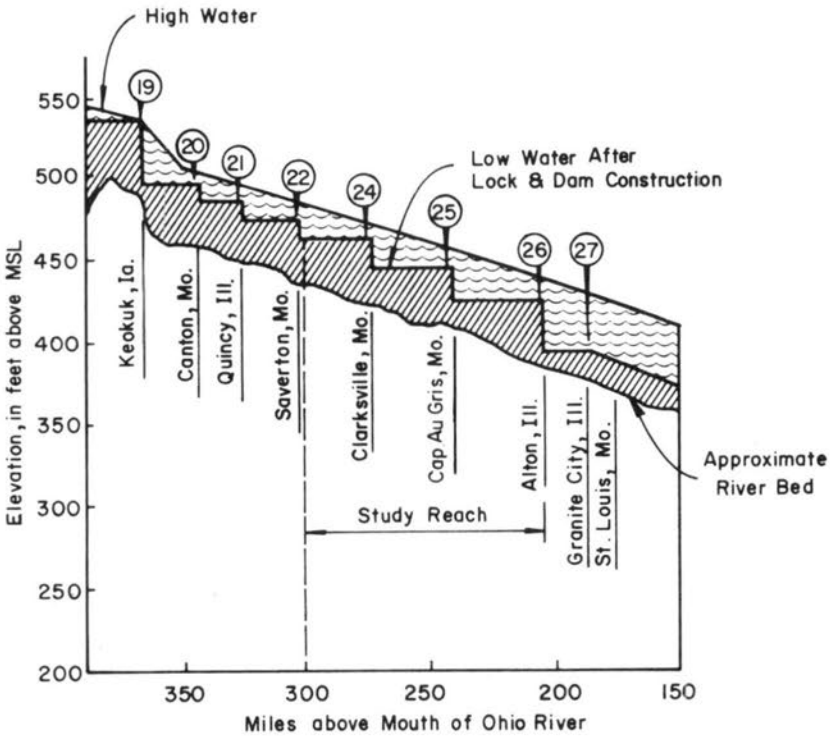


Figure 10. The Navigation Stairway (U.S. Army ~~Corps of Engineers~~ Engineer District, St. Louis, 1968)

Dams 24, 25, and 26 are low structures which preclude economical water-power development or any flood control benefits.

Locks and Dam 26 at Alton, Illinois, is representative of the locks and dams in the study reach. Built between 1934 and 1938, it consists of two locks located adjacent to the Illinois bank and a gated dam extending from the locks to the Missouri bank. The twin locks, opened to traffic in 1938, include a main lock 110 ft by 600 ft and an auxiliary lock 110 ft by 360 ft. The gated spillway, approximately 1,725 ft in length, consists of 30 tainter gates, 40-ft wide and 30-ft high, and three roller gates, each 80-ft wide and 25-ft high.

The locks and dams have changed the character of the river. The permanent change in low-flow water levels submerged the dikes constructed during the 4-1/2-ft and 6-ft channel projects, and no longer can Sunday excursionists walk across the river at low water. In addition, the creation of the pools and a stable low-water level has been a boon to wildlife (Gabrielson, 1937).

Operation of Dams

Gate operation to control the water level in the pool upstream is a complex undertaking involving river flow forecasting and maintenance of navigable water levels. Each pool has a control point about halfway upstream to the next lock and dam. At this control point section, the water level must be maintained above a minimum elevation for navigation and below a maximum elevation to prevent flood damage other than normal flooding due to runoff.

When river flows are very small, the gates at the dam are closed or nearly closed to maintain the minimum level at the control point. At this time, the water in the pool is nearly level. As the flow of water into a pool is increased at the beginning of a flood, the water level in the upper end of the pool rises. Simultaneously, the gates at the dam are opened to pass the increased discharge and to hold the water level at the control point below the maximum. This way, the flooding of lands along the river is controlled within limits. With larger inflows to the pool, the water level in the pool rises even as the gates are opened. When the gates are completely out of the flow, the river is an open river.

The locks and dams are not used for flood control because the pools do not have enough storage capacity to attenuate the flood peaks in the Upper Mississippi River. The storage available in the pools is such a small fraction of the amount of water in a flood that the locks and dams could not be operated to effectively control flooding in downstream areas.

However, the locks and dams were designed so that the structures would not aggravate the flood damages in the river system; the dams pass the flood flows with only a slight increase in water level upstream. This increase, called backwater or swellhead, is caused by the piers, sills, and abutments at the dam. For example, the drop in water level across Locks and Dam No. 24 at the peak flood stage in

1973 was 0.52 ft (U.S. Army Engineer District, St. Louis, 1974, p. 20). A part, 0.19 ft, of this fall was normal river gradient (0.63 ft/mi at peak stage) and the remainder, 0.33 ft, was backwater caused by Locks and Dam No. 24.

Short-Term Response

In the fall of 1939, the first continuous hydrographic survey of the study reach of the Mississippi River subsequent to construction of the three dams was made. This survey provides a picture of the immediate response of the river to construction of the locks and dams. The 9-ft channel project in the study reach was placed completely in operation on March 12, 1940.

Surface Areas in 1939

In 1939, the surface area of the river had not yet changed in response to the closure of Dams 24, 25, and 26. More time was required to convert land-type vegetation submerged by the closures into water and water-type vegetation. During the first two winters after dam closure timber was logged in the areas flooded by the pools.

Number of Islands in 1939

In 1939, the closures of Dams 25 and 26 had not yet affected the size and number of islands but, for the record, the number of islands in the study is given in Table 9. The great increase in the number of islands in Pool 24 was due probably to the degradation in Pool 24 that in turn resulted from the sequence of construction (discussed in the following section). Also, as the 1930's were dry, the low water levels caused by droughts and degradation allowed land vegetation to become established on exposed sandbars.

Riverbed Elevations in 1939

The 1939 average riverbed elevations in the deepest 1000-ft width of the Mississippi River channel in the study reach are given in Table 10. For comparison, the change in riverbed elevations between 1929 and 1939 is also presented. The immediate response of the river

Table 9

Number of Islands, 1929 and 1939

Location	Number of Islands 1929	1939	Change
Pool 26:			
Below Illinois confluence	-	11	-
Middle third	23	21	+ 2
Upper quarter	11	11	0
Pool 25:			
Lower quarter	13	17	+ 4
Middle half	28	32	+ 4
Upper quarter	24	16	- 8
Pool 24:			
Lower quarter	13	19	+ 6
Middle half	29	57	+28
Upper quarter	9	20	+11

channel bed in the study reach to the construction of locks and dams in and upstream of the study reach was, in general, to degrade. For the study reach as a whole, the riverbed in the deep part of the channel decreased in elevation approximately 2.0 ft between 1929 and 1939. Only the upper quarter of Pool 26 and the lower quarter of Pool 25 had aggradation.

General degradation occurred because the normal movement of sediments in the pools upstream of Pools 24, 25, and 26 was stopped. The variation in degradation throughout the study reach was probably due in part to the sequence in which the locks and dams were constructed. That Locks and Dam 22 were completed two years before Locks and Dam 24 and one year before Locks and Dam 25 might explain that greater degradation in the Pool 24 reach.

Long-Term Responses

During the record floods of 1973, the U.S. Army Corps of Engineers obtained color-infrared aerial photographs of the study reach of the

Upper Mississippi River. These photographs and the 1973 hydrographic survey data were used to assess the long-term response of the river to Locks and Dams 24, 25, and 26. The geomorphic features shown in the photographs developed over a 33-year period of lock and dam operations.

Table 10

Average Riverbed Elevations in the 1939 Upper Mississippi River

Location	Average Riverbed Elevation,* ft Amsl† 1939	Change since 1929
Pool 26:		
Below Illinois River	390.2	-
Middle third	400.7	-0.8
Upper quarter	405.7	+0.5
Pool 25:		
Lower quarter	410.9	+0.8
Middle half	414.5	-2.6
Upper quarter	421.5	-2.0
Pool 24:		
Lower quarter	424.7	-2.1
Middle half	427.2	-3.3
Upper quarter	430.8	-5.8

*Average of the riverbed elevations in the deepest 1000-ft width of river channel. During the year of 1939, stage at Hannibal, Missouri (RM 309) ranged from 449.9 to 467.4 ft, Amsl (compared to 449.5 to 471.5 ft in 1929) and stage at Grafton, Illinois (RM 218) varied from 410.5 to 425.8 ft, Amsl (compared to from 406.9 to 430.0 ft in 1929). Trends in discharge and stage are analyzed in a later section.

†Amsl = Above 1929 adjusted mean sea level.

Surface Areas in 1973

An uncontrolled mosaic of Pool 25 was prepared from 9 in. by 9 in. color prints of the 1973 aerial photographs. The surface areas of Pool 25 were measured from a copy of this mosaic (Fig. 11), and are given Table 11.

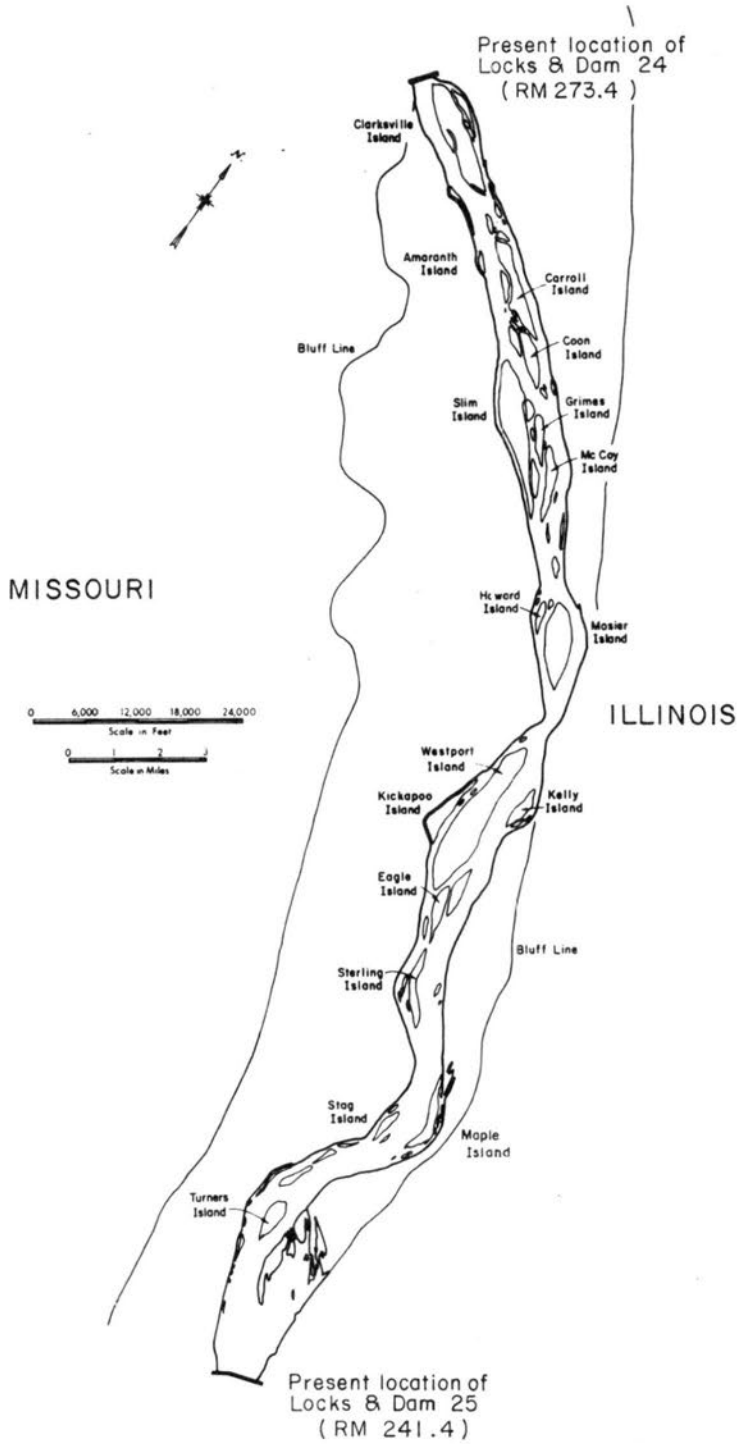


Figure 11. Map of the Pool 25 reach of the Mississippi River in 1973

Table 11

Surface Areas of Pool 25 in 1973

Location	Surface area, sq. mi		
	River	Islands	Riverbed
Pool 25:			
Lower quarter	10.20	1.70	8.50
Middle half	14.97	4.82	10.16
Upper quarter	7.75	3.84	3.91
	32.92	10.36	22.57

Between 1929 and 1973 the surface area of the river in the Pool 25 reach increased 3.38 sq mi or 11 percent. The increase was due primarily to the submergence of floodplain areas immediately upstream of Locks and Dam 25. There were no appreciable changes in the surface areas of the middle half and upper quarter of Pool 25.

Island Areas in 1973

The surface areas of the islands in Pool 25 are given in Table 11. In 1973 there were 92 islands in Pool 25 having a total area of 10.36 sq mi. This is an increase of 27 islands and an area increase of 3.9 percent since 1929. Most of the new islands were in the lower quarter of the pool. These islands were created by submerging low areas on the floodplain and on larger islands to form new chutes. For example Maple Island (RM 249) came back into existence due to the submergence of the former side channel resulting from the operation of Locks and Dam 25. This island had become joined to the Illinois mainland between 1891 and 1929.

Many of the former islands in the lower quarter of Pool 25 were lost by the construction of Locks and Dam 25. Sandy Island (Fig. 8) became attached to the Missouri floodplain during the construction period. Sarah Ann Island and its three neighbors became submerged. Agricultural lands on some islands were abandoned between 1927 and 1973.

As water levels rose behind the locks and dams, the fields on the islands were submerged.

As shown in Table 12, the islands in the lower part of the pools decreased in size and the islands in the upper parts grew in the period between 1929 and 1973. The two situations are illustrated in Figs. 12 and 13. In Fig. 12, the outlines of Crider Island and the unnamed island immediately upstream are shown for 1929 and 1973. These islands, in the lower quarter of Pool 24 and immediately upstream of Locks and Dam 24, are good examples of the decrease of island area and the formation of a "crab-claw" outline of some islands. The Clarksville Island reach immediately below Locks and Dam 24 is shown in Fig. 13. Between 1929 and 1973 there was a significant enlargement of Clarksville Island, new islands were formed and some chutes were abandoned.

Table 12

Changes in Surface Areas of Islands from 1929 to 1973

Name	Approx. River Mile	Surface area, sq mi	
		1973	Change since 1929
Pool 26:			
Piasa	209	0.236	-
Mason	220	0.442	-0.012
Sweden	234	0.113	+0.062
Peruque	234	0.525	+0.035
Cuivre	236	2.305	+0.145
Pool 25:			
Turners	245	0.230	-0.140
Mosier	260	0.722	+0.068
Coon	267	0.296	+0.043
Carroll	268	0.568	+0.129
Clarksville	272	1.051	+0.152
Pool 24:			
Crider	279	0.093	-0.051
Unnamed	280	0.097	-0.034

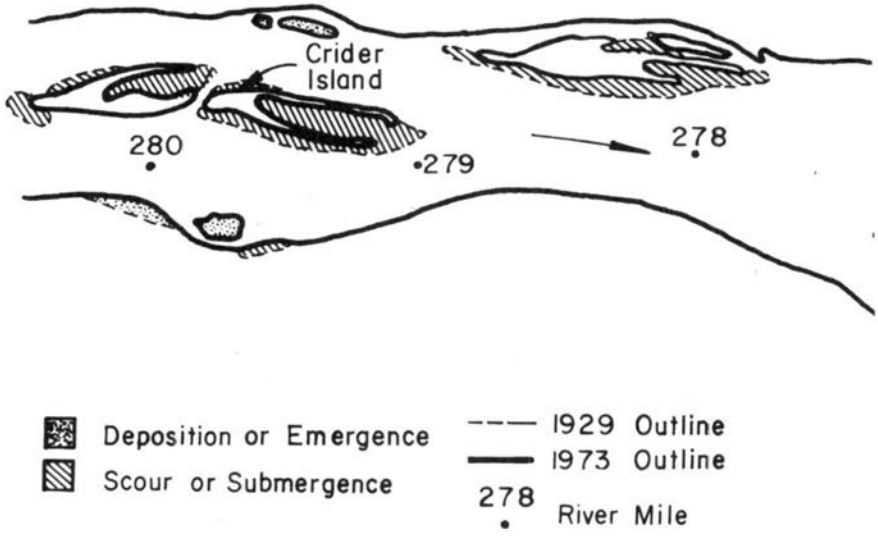


Figure 12. Decrease in size of Crider Island between 1929 and 1973

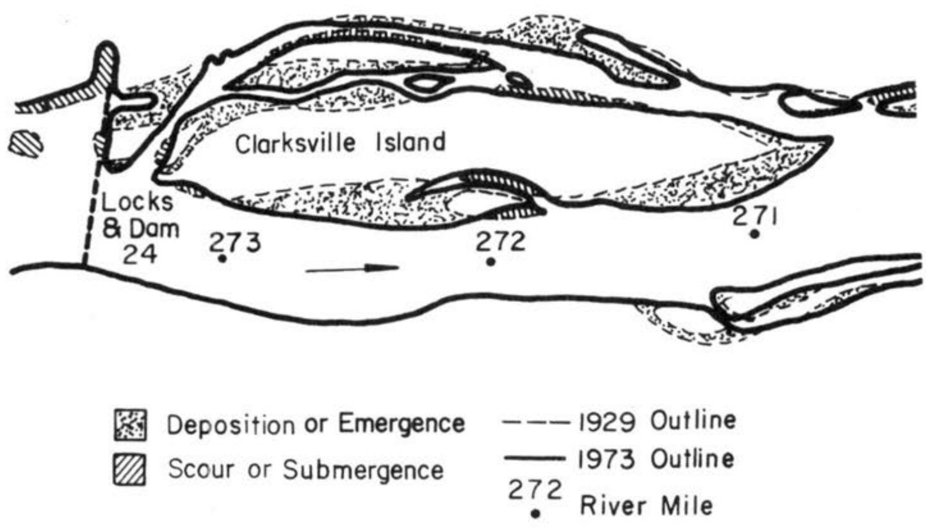


Figure 13. Growth of Clarksville Island between 1929 and 1973

Riverbed Areas in 1973

The riverbed areas in Pool 25, measured on the 1973 mosaic, are given in Table 11. The growth in number and size of the islands in Pool 25 between 1929 and 1973 was more than offset by the submergence of parts of the floodplain. Because of this, the riverbed area in Pool 25 increased only slightly due to the operation of Locks and Dam 25.

Surface Widths in 1973

The average surface widths in Pool 25 in 1973, measured on Fig. 11, are given in Table 13. The average surface width of the Mississippi River in Pool 25 was 5610 ft, an increase of 580 ft since 1929. Almost all of the river widening between 1929 and 1973 was due to the submergence of the Illinois floodplain in the lower quarter of Pool 25 immediately above Locks and Dam 25.

Table 13

Average River Surface Widths in Pool 25 of the Upper Mississippi River in 1973

Location	Surface Width ft
Pool 25:	
Lower quarter	6950
Middle half	5100
Upper quarter	5280

Riverbed Elevations in 1971

The 1971 average riverbed elevations in the deepest 1000 ft of the Mississippi River channel in the study reach are given in Table 14. The long-term response (from 1930 to 1973) of the riverbed in Pools 24, 25, and 26 to the construction and operation of the locks and dams in the Upper Mississippi River has been degradation in the deep part of the river channel. The amount of degradation is determined by comparing the 1929 riverbed elevations (before locks and dams) to the 1971 elevations. These values are given in Table 14.

Table 14

Average Riverbed Elevations in the Mississippi River in 1971

Location	Average Riverbed Elevation,* ft Amsl		
	1971	Change since 1939	Change since 1929
Pool 26:			
Below Illinois River	389.0	-0.4	-
Middle third	400.8	+0.1	-0.7
Upper quarter	402.4	-3.3	-2.8
Pool 25:			
Lower quarter	408.2	-2.7	-1.9
Middle half	415.4	+0.9	-1.7
Upper quarter	419.0	-2.5	-4.5
Pool 24:			
Lower quarter	427.4	+2.7	+0.8
Middle half	429.2	+2.0	-1.3
Upper quarter	432.7	+1.9	-3.9

*Average of the riverbed elevations in the deepest 1000-ft width of river channel. During the year of 1971 stage at Hannibal, Missouri (RM 309) ranged from 458.8 to 466.9, Amsl (compared to from 449.9 to 467.4 ft in 1939 and from 449.5 to 471.5 ft in 1929) and stage at Grafton, Illinois (RM 218) varied from 418.4 to 422.2 ft, Amsl (compared to from 410.5 to 425.8 ft in 1939 and from 406.9 to 430.0 ft in 1929). Trends in discharge and stage are analyzed in a later section.

Between 1939 and 1971, the riverbed in the deep part of the channel in Pool 24 aggraded approximately 2.0 ft but the two downstream pools degraded on the average. After the initial bed lowering between 1929 and 1939, Pool 24 has been filling slowly. Pools 25 and 26 may still be degrading slightly.

Side Channels

With the creation of many new islands resulting from the construction and operation of Locks and Dams 24, 25, and 26, many new side channels were formed between 1929 and 1973. The 1973 chutes in Pool 25 are shown in Fig. 11. However, during the same period some chutes were filled. For example, Sandy Chute had been in existence for more than a century but was lost due to the construction of Locks and Dam 25. The other two long chutes in Pool 25 have survived. In 1973, Westport Chute remained approximately 830-ft wide and 3.9-mi long (the same as in 1929). Slim Chute lengthened slightly between 1929 and 1973 but remained the same width.

The closure of side channels in the study reach of the Mississippi River is apparently a slow process and is almost negligible on the Illinois River. From the data available for this study it was apparent that the dikes have accelerated the closure of some side channels but have not affected others.

Levees

The levee system shown in the 1972 Upper Mississippi River Navigation Charts is essentially the same as the 1929 system. The Illinois and Missouri floodplains are protected adjacent to Pools 24 and 25 and the Illinois River floodplain is also protected. However, the Missouri floodplain between the Upper Mississippi and Missouri Rivers is not protected. In fact, overbank flows from the Missouri River cross the floodplain into Pool 26 and are measured as Upper Mississippi River flows at the Alton gage.

The effect of the levees in the study reach of the Upper Mississippi River on flood peaks of a typical yearly hydrograph has been calculated. For a peak inflow of 227,000 cfs into the reach and a 40-day long flood, the flood stage level would be approximately 0.1 ft lower without the levees. The effect of the levees is less for longer peaks. It is concluded that the levees have no appreciable influence on the flood peaks in the study reach.

Floodplains

Except in the floodplain region between the Upper Mississippi and Missouri Rivers, the floodplains in the study reach are protected from flooding by levees.

During the last 100 years, agricultural development on the floodplains of both the Mississippi and Illinois Rivers has been extensive. Tributary streams have been channelized between the bluff line and the major rivers. To a large extent the normal floodplain morphology has been obliterated by leveling and cultivation. In short, the floodplains have been extensively developed and modified, while the river control effort was underway.

These two very different development schemes undoubtedly influence one another. Channelization of tributaries and upland agricultural activities deliver more sediment to the major rivers, which, because of their development, may or may not be competent to move the sediment out of the area. For example, sediment delivered to a backwater area is probably deposited permanently.

There is, of course, a natural rate of deposition adjacent to the main channel. Although no field information on this topic is available for the study area, a recent study carried out in the state of Louisiana after the 1973 flood showed that average sediment deposits were 21 in. along the natural levees and 0.4 in. in backswamp areas (Kesel et al., 1974). Based on the difference in sediment transport rate and the type of sediment in the Upper Mississippi and the Lower Mississippi River, the sediment deposition rate in the Upper Mississippi River is estimated to be approximately half of the lower Mississippi rate.

Tributaries

The increased depth of water behind the dams causes deposition in tributary channels, especially at very high water. It is not possible to separate the effect of the higher water levels on the Mississippi and that of upland agriculture activities; nevertheless, according to measurements made at bridges over Piasa, Elsah, and

Chautauqua Creeks in Illinois, there has been a net deposition in the tributary channels since the bridges were constructed. The channel bed level in Piasa Creek about 1500 ft from the Mississippi channel was 2.5 ft higher in 1974 than in 1956. In Elsah Creek about 100 feet from the Mississippi, the bed was 2 to 4 ft higher in 1974 than in 1961 (T. J. Bach, Research Assistant, Southern Illinois University, Environmental Section, U.S. Army District, St. Louis, personal communication, 1974). In addition, the state highway departments frequently clear sediment from the channels tributary to both the Mississippi and Illinois Rivers.

The town of Grafton, Illinois located at the junction of the Illinois and Mississippi Rivers and about 15 miles upstream from Locks and Dam 26, has been troubled in recent years by deposition in five small tributary streams. Sediment was cleared from these streams in 1970, but it was necessary to clean them again in 1974 when about 5000 cu ft of sediment was removed from 680 linear ft of channel. This corresponds to approximately 12 cu ft of sediment per linear ft of channel.

The tributaries show evidence of aggradation not all of which can be attributed to the higher water levels created by the locks and dams. Channelization and increased agricultural and urban activity can also be major factors.

Illinois River

The surface areas of the Lower Illinois River in 1939-1940 and in 1956 are given in Table 15. In general these values show a negligible change in island and river surface areas between these dates. In the Lower Illinois River upstream of Swan Lake, the channel has undergone only minor changes in area. The major islands have not changed and no new islands have appeared.

The width of the Lower Illinois River has remained remarkably stable except near its junction with the Mississippi River as shown in Table 16. The width in this area was approximately 1100 ft in 1878 but increased greatly when the major inundation of the flood plain in the Swan Lake area occurred following closure of Locks and Dam 26. For about nine miles above the junction, the backwater from Locks and Dam 26 has increased the width of the Illinois River from approximately 1000 ft to a maximum of 6000 ft. Farther upstream the width is nearly constant.

Table 15

Surface Areas of the Lower Illinois River, 1939-1940 and 1956

Location	River Miles	Year	Surface Area, sq mi		
			Riverbed	Island	Total Surface
Swan Lake	3 to 9	1940	3.6	1.1	4.7
		1956	4.4	0.9	5.3
Apple Creek	30 to 36	1940	1.1	0.06	1.2
		1956	1.2	0.05	1.3
Little Sandy Creek	43 to 51	1939	1.1	0.1	1.2
		1956	1.0	0.2	1.2
McGee Creek	67 to 72	1939	0.78	0.09	0.87
		1956	0.72	0.08	0.80

Table 16

Average River Surface Widths in the Lower Illinois River

Location	Average Width, ft		
	1939	1956	1973
River Mile 0 to 8	2480	2970	2100
River Mile 9 to 73	1230	1230	1200

Discharges and Stages

Locks and Dams 24, 25, and 26 have had an effect on how water and sediment move through the study reach. Moreover, upstream dams have decreased the amount of sediment coming into the study reach.

At low and intermediate flows, the dams raise pool levels above the natural level. This increases the depth of flow, decreases the flow velocity, and decreases the sediment movement. Thus, flow velocities and sediment transport at low and intermediate flows are less in the pools than in the natural river.

At low and intermediate flows, the velocity in the upper end of a pool is generally greater than in the lower end. As the sediment transport rate is largely dependent on the flow velocity, the sediment transport rate at the upper end of the pool is greater than at the lower end and is also greater than the supply rate from the pool immediately upstream. The result is that erosion occurs in the upper reach of the pool and deposition occurs in the lower reach.

At high flows, the gates are opened above the water level and flow conditions approach the natural river state. During floods, the portion of the river that was eroded at low flow (the upper end of the pool) carries less sediment than that supplied from upstream. This results in deposition. In contrast, erosion occurs in the portion of the river that was aggraded at low flow (the lower end of the pool). This erosion and deposition occurs because of the locks and dams and is repeated on a yearly cycle.

The river crossing areas in a pool accumulates a slightly larger amount of sediment during the deposition part of the cycle than during the erosion part. Conversely, the deep areas in the river tend to deepen. Thus, over a long period of time, the shallow areas undergo a net aggradation and the deep areas in the river channel deepen slightly.

The effects of the Locks and Dams on the geomorphology of the rivers are reflected in the river gage records in the study reach.

Gaging Stations

The study area is bracketed by three gaging stations with relatively long-term discharge and stage records. The Alton, Illinois, station on the Mississippi River immediately below Locks and Dam 26 has reported discharges and stages intermittently from 1844 to 1896 and then continuously to the present. Immediately below Locks and Dam 19 at Keokuk, Iowa, on the Mississippi River (65 river miles above the study area), the discharge record is discontinuous from 1851 to 1880 and continuous thereafter; while maximum and minimum stages have been reported intermittently from 1851 to 1870 and then continuously to the present. The Meredosia Illinois station (published as "at Beardstown" prior to 1939) has continuous discharge data since 1921, as well as intermittent stage data from 1844 to 1879 and continuous stage data thereafter. In addition, the Corps of Engineers has compiled stage records at Hannibal, Missouri, nine river miles above Locks and Dam 22; and at Grafton, Illinois, at the confluence of the Mississippi and Illinois Rivers. The River Mile locations of the gages and other important features are given in Table 17.

Floods at Hannibal

The Alton stage gage, located downstream of Locks and Dam 26, is influenced by backwater from the Missouri River. Similarly, the Keokuk gage, located immediately below Locks and Dam 19, is influenced by backwater from the Des Moines River. To provide a long-term stage and discharge comparison not affected by backwater from a major tributary, discharges from Keosauqua on the Des Moines River and Keokuk on the Mississippi River were combined downstream at Hannibal, where Corps of Engineers stage data are available. The Hannibal gage is in Pool 22. The discharge at Hannibal on any given day was estimated by combining the discharge reading at Keosauqua two days earlier with the discharge reading at Keokuk one day earlier.

The highest twenty stages at Hannibal are shown in Table 18. The largest ten synthesized discharges with corresponding stages are listed in Table 19. Analysis of the information in Tables 18 and 19 indicates that the flood-stage-versus-discharge relation at Hannibal has not changed appreciably during the period of record. That is, floods produce approximately the same stages passing Hannibal today as they did before locks and dams.

Table 17

Locations of Selected Features in the Study Reach

Feature	River Mile	Remarks
	Locks and Dams	
Locks and Dam 26	202.9	At Alton, Illinois
Locks and Dam 25	241.4	At Cap Au Gris
Locks and Dam 24	273.4	At Clarksville, Missouri
Locks and Dam 22	301.2	Above study reach
	Cities and Towns	
St. Louis, Missouri	179	
Alton, Illinois	203	
Grafton, Illinois	218	
Clarksville, Missouri	273	
Louisiana, Missouri	283	
Hannibal, Missouri	309	
	Gages	
Alton, Illinois	202.7	Immediately downstream of Locks and Dam 26
Grafton, Illinois	218.0	Approximately 15 mi upstream of Locks and Dam 26
Meredosia, Illinois	70.8*	Approximately 85 mi upstream of Locks and Dam 26
Hannibal, Missouri	309.0	Approximately 8 mi upstream of Locks and Dam 22
Keokuk, Iowa	364.2	Immediately downstream of Locks and Dam 19
	Confluences	
Mouth of Illinois River	218.0	In Pool 26
Mouth of Dardenne Creek	227.0	In Pool 26
Mouth of Cuivre River	236.5	In Pool 26
Mouth of Salt River	284.2	In Pool 24

*Illinois River Mile measured from the confluence of the Illinois and Mississippi Rivers.

Table 18

Top Twenty Stages
Mississippi River at Hannibal

Rank	Stage ft	Year
1	28.59	1973
2	24.59	1965
3	24.1	1947
4	23.4	1960
5	22.6	1951
6	22.53	1944
7	22.5	1903
8	22.5	1969
9	22.1	1929
10	21.8	1888
11	21.67	1952
12	21.6	1948
13	21.6	1851
14	20.9	1962
15	20.8	1897
16	20.8	1892
17	20.6	1881
18	20.1	1919
19	19.8	1945
20	19.7	1967

Period of record: 1851 to 1973

Trends in Discharges

The annual maximum, mean, and minimum discharges for the discharge gaging stations at Alton, Keokuk, and Meredosia are given in Figs. 14, 15, and 16, respectively, On the Upper Mississippi River, the annual flood discharges gaged at Alton and Keokuk have remained on the average unchanged in the last 110 years. The mean annual flow at Alton has been increasing slightly whereas it has been decreasing slightly at Keokuk. The annual minimum discharge has been increasing at both gages. The changes are small and the causes have not been identified. The history of maximum, minimum, and mean annual discharges on the Illinois River at Meredosia does not show any trends.

Table 19

Top Ten Flood Discharges
Mississippi River at Hannibal

Rank	Discharge cfs	Year	Rank of corresponding stage
1	381,000	1973	1
2	342,000	1960	4
3	340,000	1965	2
4	335,000	1903	7
5	323,000	1947	3
6	323,000	1944	6
7	300,000	1951	5
8	275,000	1952	10
9	273,000	1962	14
10	273,000	1948	12

Period of record: 1903 to 1906, 1912 to 1973

Locks and Dams 24, 25, and 26 have no appreciable effect on the amount of water moving through the study reach. Further the yield of runoff from the Upper Mississippi Basin has not changed appreciably in the period of record.

Trend in Stages

The annual maximum and minimum stages at Alton, Keokuk, Hannibal, Grafton, and Meredosia are shown in Figs. 17, 18, 19, 20, and 21 respectively. At the Alton stage, gage immediately below Locks and Dam 26, there is no trend in the annual maximum stage in the 100 years of record (Fig. 17). The annual minimum stage record shows a sharp decrease in minimum stage after the mid 1930's followed by a sharp increase in minimum stage in 1960. The decrease was probably the result of some degradation below Locks and Dam 26, which was completed in 1938. The increase in 1960 corresponds to the completion of the low-water rock fill Dam 27 downstream.

The records at the Keokuk gage, immediately below Locks and Dam 19, also show a decrease in minimum annual stage in the period between 1920 and 1940. This decrease could be attributable to degradation

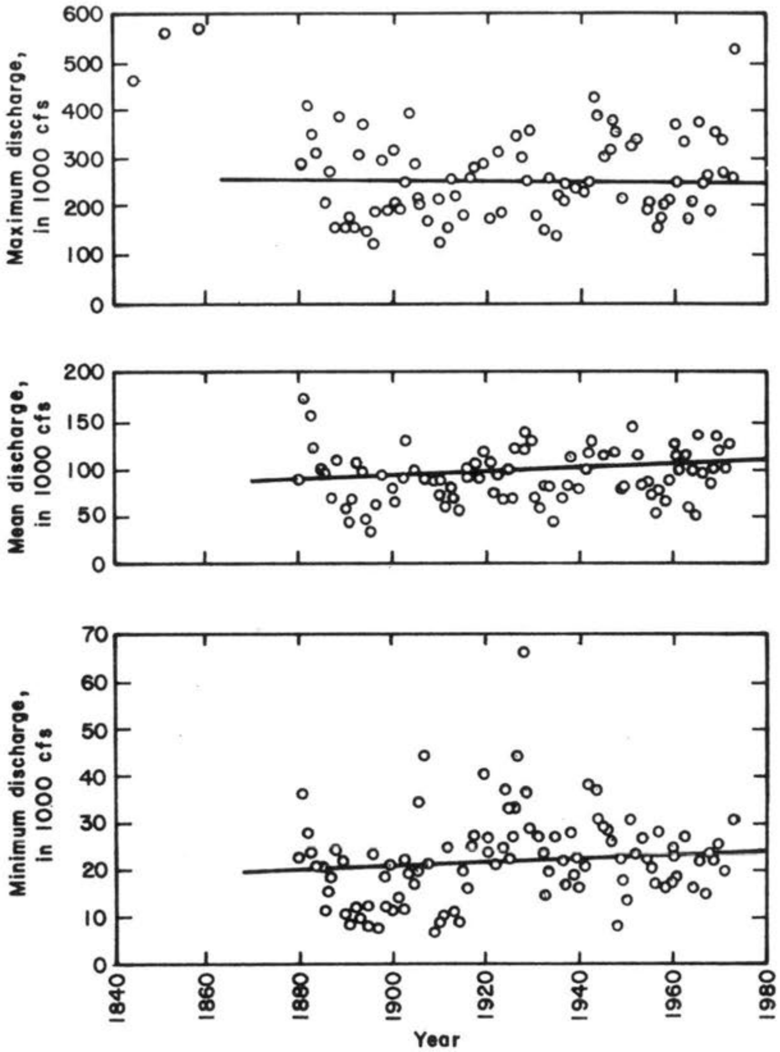


Figure 14. Annual discharges at Alton

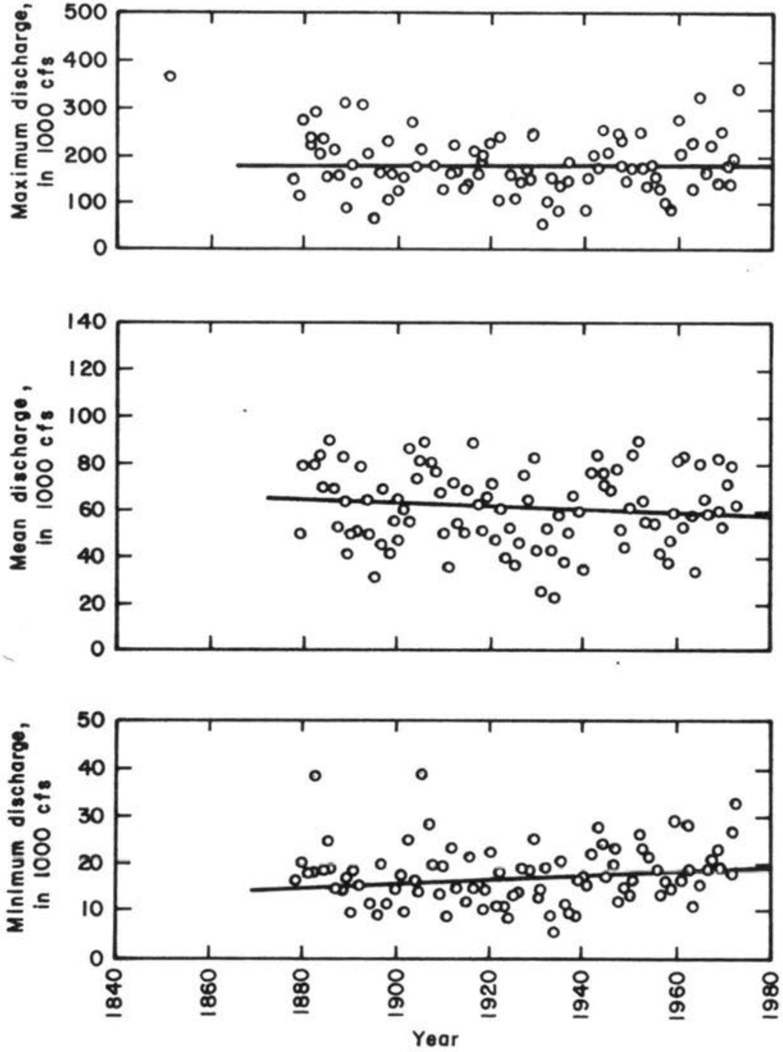


Figure 15. Annual discharges at Keokuk

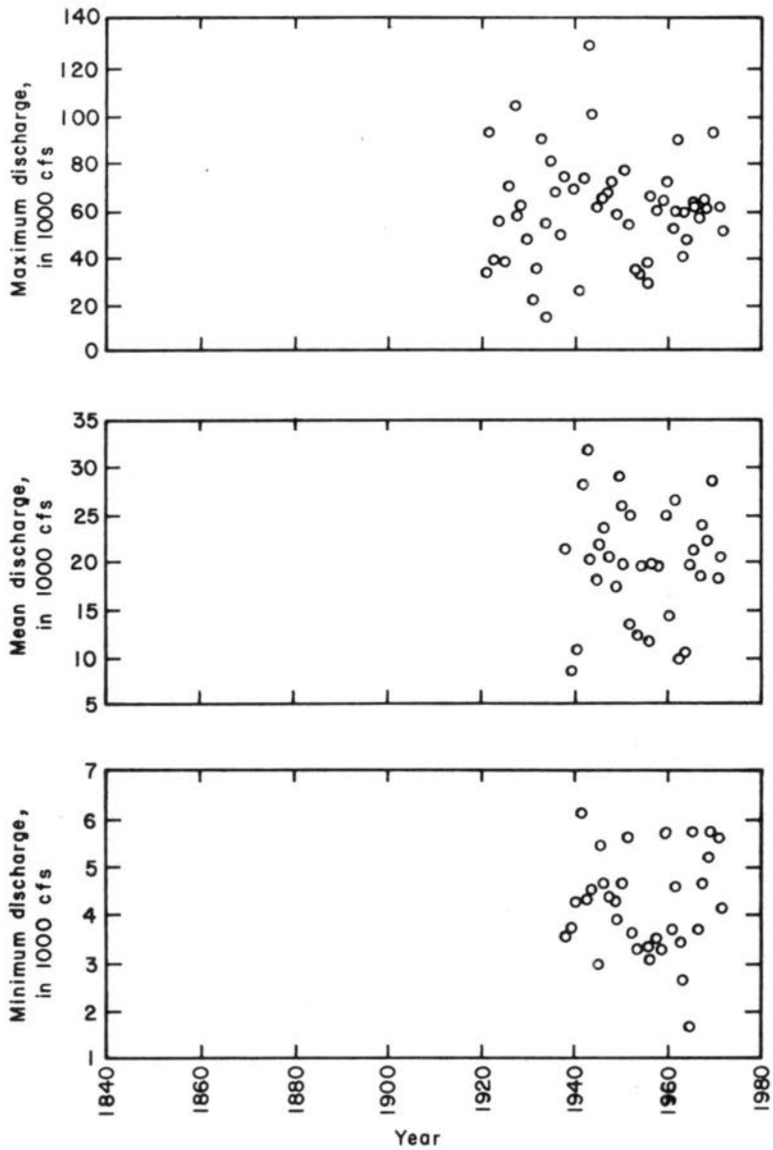


Figure 16. Annual discharges at Meredosia

below Locks and Dam 19 but riverbed elevations immediately below Locks and Dam 19 were not studied because this reach is outside the study reach.

The locks and dams have affected minimum stages immediately upstream of locks and dams as shown in miminum stage records at Hannibal and Grafton. Records of both the Hannibal gage in Pool 22

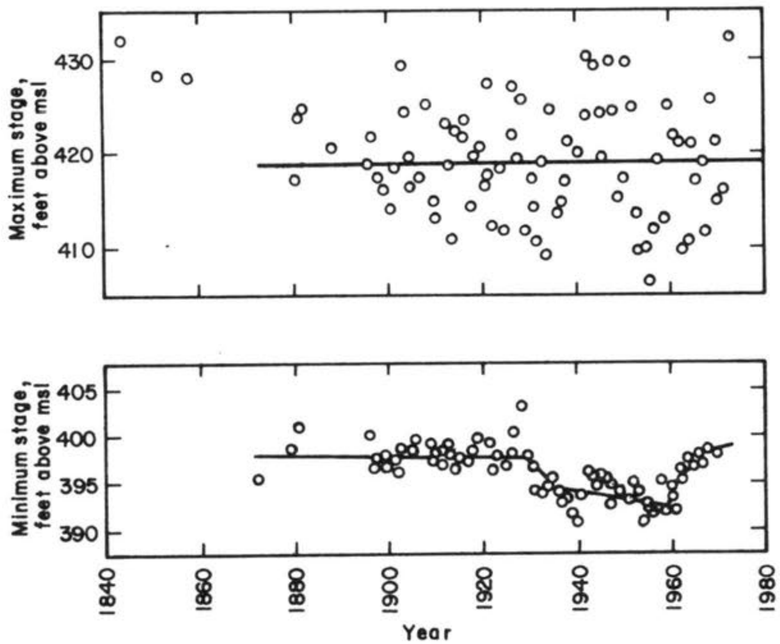


Figure 17. Annual stages at Alton

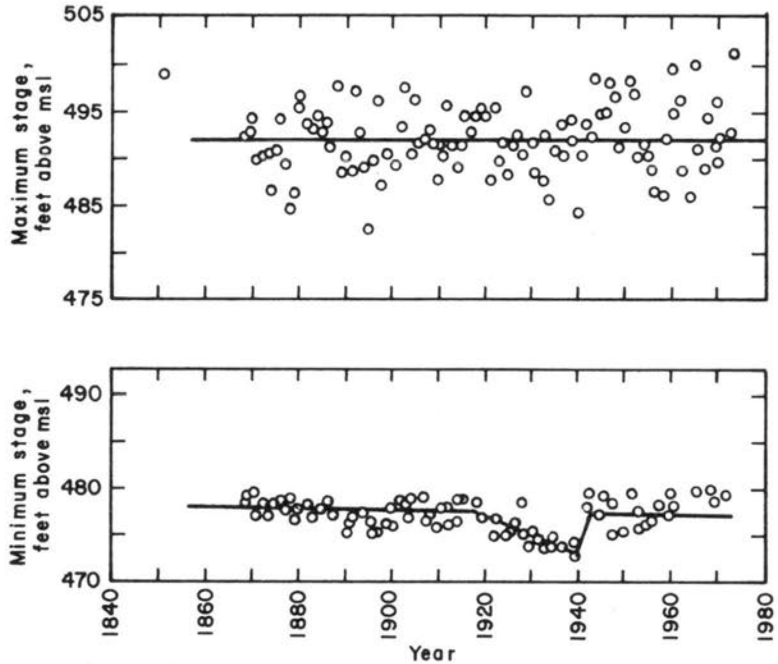
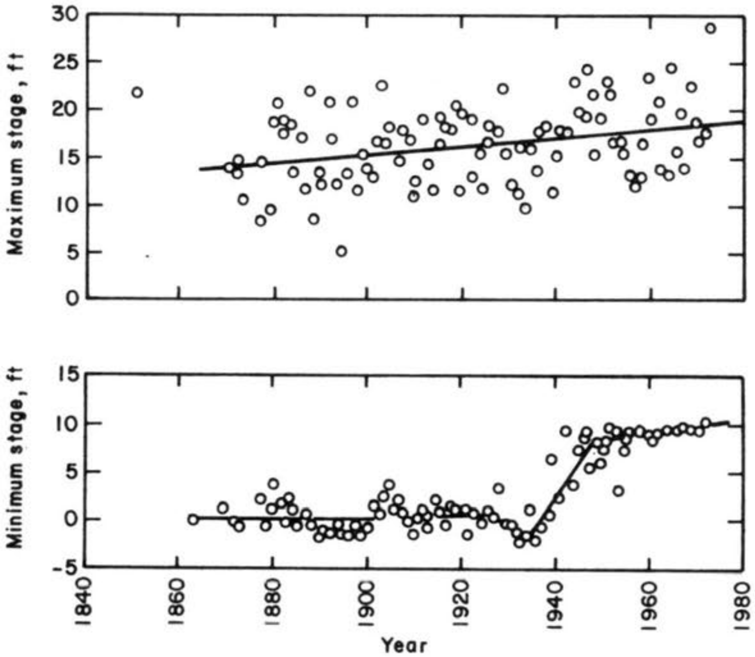
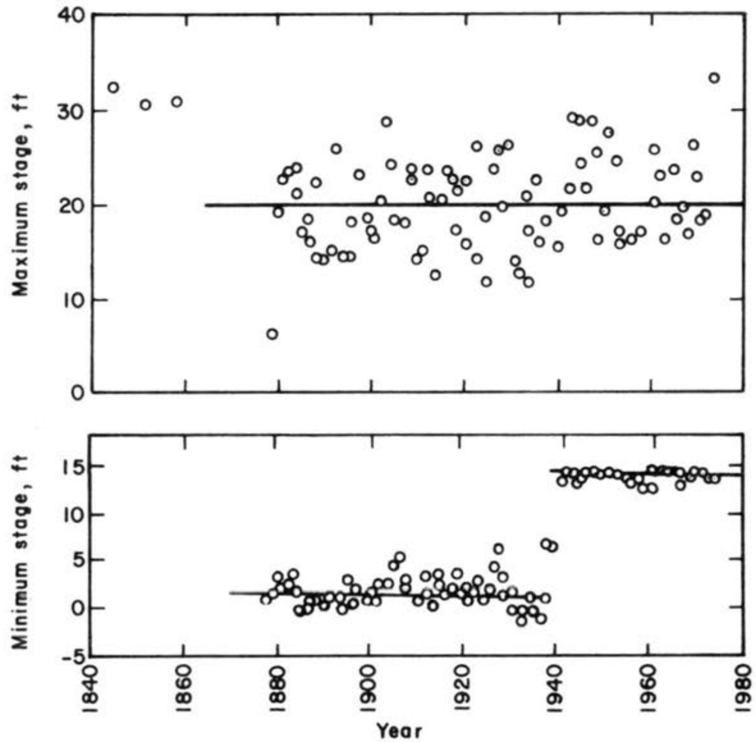


Figure 18. Annual stages at Keokuk



Note: Zero on the Hannibal gage is at 449.07 ft above msl.



Note: Zero on the Grafton gage is 403.79 ft above msl.

Figure 19. Annual stages at Hannibal

Figure 20. Annual stages at Grafton

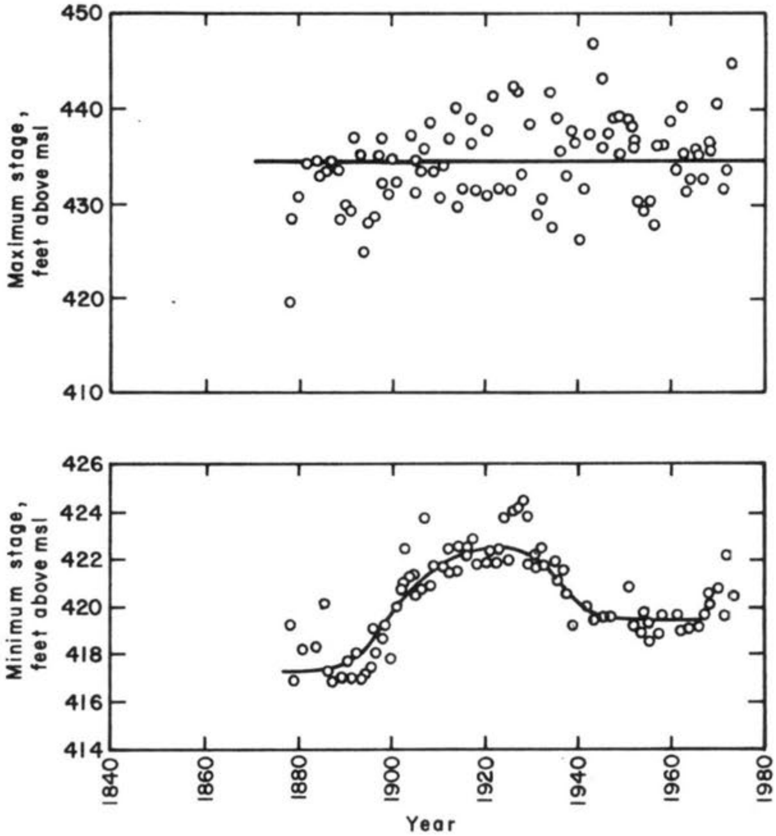


Figure 21. Annual stages at Meredosia

(Fig. 19) and the Grafton gage in Pool 26 (Fig. 20) show a large increase in annual minimum stage after 1940. This increase is a result of operating the dams to raise the minimum pool elevation during low flow.

The unusual form of the low stage curve at Meredosia on the Illinois River (Fig. 21) also reflects the influence of man. The upward trend initiated in the 1890's corresponds with water diversion into the Illinois River through the Illinois and Michigan Canal. According to Starrett (1972),

> "Between 1900 and 1938 the average amount of Lake Michigan water diverted into the Illinois River system through the Chicago Sanitary and Ship Canal was 7,222 c.f.s. The diversion during this period ranged from 2,990 c.f.s. in 1900 to 10,010 c.f.s. in 1928. A decree of the United States Supreme Court limited the amount of diversion after 1938 to 1,500 c.f.s. in additon [sic] to the domestic pumpage of Chicago."

Increasing minimum stages since 1940 reflect the influence of Pool 26 on the Lower Illinois River.

Summary

The trends in the historical record of discharges and stages in the study reaches of the Upper Mississippi and Lower Illinois River are summarized in Table 20.

Table 20

Trends in Annual Discharges and Stages

Location	Discharges			Stages	
	Maximum	Mean	Minimum	Maximum	Minimum
Mississippi River:					
Alton	None	Up	Up	None	--
Keokuk	None	Down	Up	None	--
Hannibal	--	--	--	Up	Up
Grafton	--	--	--	None	Up
Illinois River:					
Meredosia	None	None	None	None	Up

Sediment Transport

The sand carrying capacity of the upper three-quarters of Pool 25 in 1973 has been estimated. Assuming that the gates at the dams are open all year, the estimated rate is 3,200,000 tons/yr, an increase of 3 percent over the capacity estimated for the same reach in 1929. Under normal pool regulation, the sediment transport rate is about 70 percent of this estimated value. The average riverbed width in the upper three-quarters of Pool 25 in 1973 was 3200 ft.

Dredging

The importance of dredging to the program for extension and improvement of a navigable waterway in the Upper Mississippi River was clearly recognized in the authorizing legislation for the 9-ft channel project. The River and Harbor Act of 1930 provided for a navigation channel 9 ft deep and of adequate width from the mouth of the Missouri River to Minneapolis, to be established by construction of a series of locks and dams, and maintained by channel dredging. For example, the initial estimate of the dredging requirements for Pool 25 was 735,000 cu yd per year.

Subsequent of the construction of locks and dams, no dredging was performed in Pools 24, 25, and 26 until 1949 (Degenhart, 1973; Lagasse, 1975). The amounts dredged between 1949 and 1973 were:

	Accumulated	Average Annual
Pool 26	9,120,000 cu yd	364,800 cu yd
Pool 25	10,000,000 cu yd	400,000 cu yd
Pool 24	2,090,000 cu yd	83,600 cu yd

A comparison of geomorphic data with records of dredging quantities required to obtain and maintain the 9-foot channel on the Upper Mississippi provides a basis for determining those factors that influence dredging requirements in the Pool 24, 25, and 26 study area. Such non-engineering factors as project funding and dredge plant availability can influence the records of dredged volumes and limit, to a degree, the establishing of a direct cause and effect relation between dredged quantities and hydraulic or geomorphic change. Nevertheless, increasing dredged volumes on the Upper Mississippi appear closely related to such factors as:

1. Initial dredging requirements to make the transition from the 6-foot channel to the 9-foot channel.
2. Extended periods of abnormally low-flow where lack of water in the system becomes a controlling factor.
3. Extended periods of unusually high flow.
4. Operational policies such as the practice of overdepth and overwidth dredging.
5. Effectiveness and efficiency of dredging operations.

In studying the relation between dredging frequency and volume by location in Pools 24, 25, and 26, Lagasse (1975) found that the most troublesome reaches were straight reaches located upstream of the pool primary control point and divided by alluvial islands. The most troublesome crossings were between River Miles 227 and 237 in Pool 26 and between River Miles 260 and 270 in Pool 25. In the ten-mile reach in Pool 26, sections at Miles 235 and 237 were dredged nine times in 25 years. In the ten-mile reach in Pool 25, River Mile 266 was dredged 15 times in 25 years and the total volume of dredged material removed from this crossing was 1,600,000 cu yds.

The dredged material, primarily silt and sand, is moved by hydraulic pipeline dredge. The most common disposal technique is into open-water. The material is placed along the bankline of the river channel, in dike fields, or on islands and may be moved again by subsequent floods.

Summary

The pronounced degradation and a large increase in the number of islands in Pool 24 were the most noticeable immediate responses of the Upper Mississippi River to the construction of Locks and Dams 24, 25, and 26 and other dams upstream.

After 32 years of operation, the riverbed in Pool 24 had aggraded slightly but was not yet to its level prior to the construction of Locks and Dams 22 and 24. In Pools 25 and 26, the average riverbed levels in 1971 were lower than in 1929.

In Pool 25, submergence of part of the Illinois floodplain, caused by the closure of Locks and Dam 25, resulted in an 11 percent increase in surface area of the river. Overall, the surface width of this reach widened approximately 580 ft. Also, the number and surface area of islands in Pool 25 increased. Those in the lower end of the pool decreased in size and those in the upper end enlarged. The computed sand transport capacity of the 1973 river in Pool 25, assuming that the gates at the dams were open all year, was approximately 3,200,000 tons/yr, a slight increase since 1929. Under normal pool regulation the sediment transport rate is about 70 percent of this estimated value.

There are more side channels in the study reach of the Upper Mississippi River after 34 years of lock and dam operation than there were prior to dam construction. The long chutes in Pool 25 have hardly changed in this 34-year period.

The levees in the study reach have had no appreciable effect on the flood peaks in the reach. However, many of the tributaries on the floodplain have aggraded due to the higher low-flow stages in the pools.

Annual flood discharges at Alton, Illinois, and Keokuk, Iowa have remained unchanged in the last 110 years. The mean annual and annual minimum flows at Alton have been increasing slightly. Flood stages at Alton are approximately the same in the present-day river as in the river before locks and dams.

Generally, annual minimum stage decreased appreciably immediately below locks and dams and increased appreciably immediately above.

PART VII: THE FUTURE

What will Pools 24, 25, and 26 in the Upper Mississippi and Lower Illinois Rivers look like 50 years from now? Will the side channels fill with sediment? Will the riverbed aggrade, making the maintenance of the 9-ft channel project more expensive? Are there any viable alternatives to the present-day operations that would enhance the environmental aspects of the pools and at the same time maintain the navigation channel?

Future geomorphic changes in Pools 24, 25, and 26 have been assessed on the basis of the information derived from the study of the past geomorphic changes and with the aid of a mathematical model of the river system. A detailed description of the mathematical model is given in Appendix B. The mathematical model, calibrated using data obtained from the study reaches, reproduces faithfully the 1965 and 1967 flow conditions and the geomorphic changes of the study reach from 1939 to 1970.

Basically, the response of a reach of river depends on the amounts of water and sediment delivered to the reach, the time sequence in which these amounts are delivered, and man's activities within the reach.

In the absence of major modifications to the climate, the amount of water entering the study reach is dependent mainly on land-use practices in the Upper Basin. From the study of the historical records of river flows, it is concluded that the peak discharges and flow volume frequency curves for the period 1932 to 1973 are adequate to represent future river flows in the next 50 years.

The amount of silt and clay sediment entering the study reach depends mainly on the land-use practices. It has been assumed that the yields of silt and clay will remain low in the next 50 years. The amount of sand entering the study area depends primarily on the operation of the upstream locks and dams. Three situations were considered. First, the sand transport into Pool 24 would be equal to the sand transport capacity of the Pool 22 reach. Second, there would be no sand transport into Pool 24. Third, the sand transport into Pool 24 would be the maximum obtained by removing (hypothetically that is) Locks and Dam 22.

Various man-induced activities in the study reach were considered in the study of the future river. Operating the pools at higher and lower pool control levels, dredging, and adding more dikes were the major activities modeled.

With Present-Day Operations

The mathematical model of the present river system was operated to assess future geomorphic changes that would result if the present scheme of operations to maintain the 9-ft channel were continued for 50 years. The hydrographs used in the model were synthesized from the 1932 to 1973 peak discharge and flow volume frequency curves. The sediment supply rate employed were those obtained in the calibration of the model.

Riverbed Changes

The anticipated river bed elevation changes in the study reaches in the next 50 years are given in Tables 21 and 22.

In the upper half of Pool 24, the riverbed degrades until Year 2000 and remains essentially unchanged thereafter. The maximum bed degradation is 2.5 ft below 1975 riverbed level. In the earlier years the flow in the upper reach has capability to carry more sediment than is released from Pool 22. Channel erosion results enlarging the river cross section, which in turn reduced the flow velocity and the sand transport capability of the upper reach. After years of degradation, the channel conditions of the upper reach approach equilibrium. In the meantime, bed degradation begins slowly in the lower half of Pool 24 after 1995 and causes its aggraded bed to degrade.

In Pool 25, 3 ft of degradation occurs below Dam 24 in 50 years. Downstream of this degraded reach there is a reach of braided channel where the sediment transport capability is small. In this braided reach 3 ft of bed aggradation is anticipated in the next 50 years.

Table 21

Future Riverbed Elevation Changes in the Upper Mississippi River

Location	Riverbed Elevation Change after 1975,* ft				
	1985	1995	2005	2015	2025
Pool 26:					
Below Illinois River	1.1	0.4	0.2	0.6	0.6
Middle third	0.2	0.5	0.3	0.4	0.2
Next eighth	3.5	2.8	2.2	1.8	1.2
Upper eighth	-1.9	-3.7	-4.9	-6.0	-6.7
Pool 25:					
Lower quarter	-0.9	-0.7	-1.1	-1.1	-1.0
Lower middle quarter	0.1	-0.9	-0.3	-0.3	-0.2
Upper middle quarter	0.0	1.0	1.5	1.8	1.9
Next eighth	1.9	1.9	2.3	3.0	3.2
Upper eighth	-2.0	-2.7	-1.3	-2.6	-3.0
Pool 24:					
Lower quarter	0.1	1.1	0.7	0.7	0.3
Lower middle quarter	1.1	0.7	-0.5	-1.1	-1.2
Upper middle quarter	-0.2	-1.8	-2.8	-2.7	-2.7
Upper quarter	-1.5	-0.7	-1.1	-2.1	-2.4

*Positive changes signify aggradation and negative changes degradation of the riverbed.

Table 22

Future Riverbed Elevation Changes in the Lower Illinois River

Location	Riverbed Elevation Change after 1975,* ft				
	1985	1995	2005	2015	2025
Lower third	0.1	0.2	0.3	0.3	0.4
Middle third	0.1	0.1	0.2	0.3	0.3
Upper third	-0.2	-0.6	-1.0	-1.3	-1.5

*Positive and negative changes signify aggradation and degradation respectively.

It should be pointed out that the riverbed generally fluctuates with time as the sandbars move downstream. Sediment may deposit on the riverbed during low or medium flow, but the deposited sediment may be eroded away during the high flow or vice versa. In general, however, the crossing areas accumulate sediment easier than the other portions of the river reach. Therefore, at crossings the bed elevation fluctuates with a trend toward aggradation. The opposite occurs in the deep part of the channel bends.

In the lower half of Pool 25 the riverbed degrades until Year 2000 because large amounts of sediment are being trapped in the upper reach. After Year 2000, the upper reach approaches the equilibrium state and passes more sediment load, which stops the degrading of the lower reach.

In Pool 26, the riverbed immediately downstream of Locks and Dam 25 degrades for the entire 50 years. The lower end of the pool aggrades 3.5 ft within 10 years, then aggrades more slowly for a while, and finally begins to degrade.

In the Illinois River, the sediment transport rates are small because the river gradient is very small. As shown in Table 22, 1.5 ft degradation and 0.4 ft aggradation are expected in Year 2025 in the upper third and the lower two-thirds reaches, respectively.

Floodplain Deposits

The natural levees along the Upper Mississippi and Lower Illinois River banklines and islands continue to grow in the 50 years simulated. It is estimated that the natural levees along the Mississippi increase 2.5 ft in height in 50 years and those along the Illinois increase 1.8 ft.

Away from the natural levees, the deposition of sediments (mainly silts and clays) on the floodplain is not large. In the Pool 24 reach, approximately 1 in. of silt and clay is deposited in 50 years. On the Illinois River floodplain, the deposits are only 0.1 in. in 50 years.

One Foot Above Normal Pool

The geomorphic changes in the study reach caused by holding the pool level 1 ft above the normal pool level for 50 years are not significantly different from operation at normal pool level. The geomorphic changes of these two systems are similar. However, increasing the pool level reduces the sediment transport capability of the river reach. The reach aggrades more and degrades less when the pool is held 1 ft higher than normal pool. The maximum difference is on the order of 1.0 ft in the degrading reach immediately below Locks and Dam 24.

There is a 10 percent increase in floodplain deposits of silts and clay resulting from holding the normal pool level 1 ft higher, but as these floodplain deposits are very small, the increase is of no significance. The natural levee heights are not increased significantly either.

One Foot Below Normal Pool

The effects of holding the pool level 1 ft below the normal pool level on the geomorphic changes are not much different than for 50 years of operation at normal pool. The trends of the changes are similar but decreasing the pool level increases the transport capacity so that there is less aggradation and more degradation with the lower pool. The maximum difference in riverbed levels is 0.7 ft in the degrading reach immediately below Locks and Dam 24.

The effect of operation at lower than normal pool for 50 years is that floodplain and natural levee deposits are less, but this not an important factor.

It is then clear that by changing the operation scheme for the locks and dams to raise or lower the normal pool level by 1 ft has limited effects on the morphology of the river and adjacent lands.

Zero Sediment Inflow

Suppose it were possible to completely arrest the transport of sediment into Pool 24; then the river system in Pools 24, 25, and 26 would degrade the maximum amount possible. These amounts of degradation have been calculated assuming present-day operations for the next 50 years and are given in Table 23.

Table 23

Future Riverbed Elevation Changes
in the Upper Mississippi River
Assuming No Sand Transport into Pool 24

Location	Riverbed Elevation Change after 1975,* ft				
	1985	1995	2005	2015	2025
Pool 26:					
Below Illinois River	1.1	0.4	0.1	0.5	0.5
Middle third	0.2	0.5	0.2	0.4	0.1
Next eighth	3.5	2.9	2.2	1.8	1.2
Upper eighth	-1.9	-3.7	-5.0	-6.0	-6.7
Pool 25:					
Lower quarter	-0.8	-0.8	-1.1	-1.0	-1.1
Lower middle quarter	0.1	-0.8	-0.3	-0.3	-0.2
Upper middle quarter	0.0	1.0	1.6	1.8	2.1
Next eighth	1.9	1.9	2.2	2.9	3.2
Upper eighth	-2.1	-2.9	-1.6	-3.0	-4.0
Pool 24:					
Lower quarter	0.1	1.1	0.6	0.5	-0.1
Lower middle quarter	1.0	0.6	-1.1	-2.0	-3.0
Upper middle quarter	-0.3	-2.6	-5.1	-5.9	--
Upper quarter	-4.3	--	--	--	--

*Positive and negative changes signify aggradation and degradation respectively.

The maximum degradation occurs in the upper reaches of Pool 24 and is calculated until the riverbed has degraded 6 ft. The bed could degrade more, but since no information was available on the sand sizes this far below the bed surface, the calculations were terminated. Usually the bed material becomes coarser as the bed lowers, and degradation is arrested because the velocity cannot move as many coarse particles.

The effects of the upper reach degradation do not reach the lower end of Pool 24 until Year 2015. Thus, completely stopping the flow of sediment into the study reach for the next 50 years affects Pool 24, but has very little effect on riverbed elevations in Pools 25 and 26.

Maximum Sediment Inflow

If the control gates of Locks and Dam 22 were raised out of water at all times or if Pool 22 were to become filled with sediment, the rate of sand transport into Pool 24 would be the maximum. In this case, the riverbed in Pool 24 aggrades 3 ft in next 50 years as shown in Table 24. However, the effects of discharging the maximum sand load into Pool 24 do not go beyond Locks and Dam 24. The geomorphic changes in Pools 25 and 26 in next 50 years are quite similar to that obtained with normal sand loads and there are no changes in the Lower Illinois River.

It is then clear that any change in the delivery of sediment and water from upstream of Locks and Dam 22 to the study reach does not significantly affect the morphology of the river and adjacent lands below Locks and Dam 24, at least in a period of 50 years.

Dredging

Dredging is important in the maintenance, extension, and improvement of the navigable waterway in the Upper Mississippi River. The problem of dredging, dredged material disposal, and sedimentation in the channel and on the adjacent floodplain has been studied by employing the mathematical model of the river system. The effects of dredging on the hydraulics of the study reach have been estimated and some dredging guidelines have been developed.

In Pool 25 a crossing that has required extensive dredging and the pool immediately downstream were identified and modeled. In the model a simulated dredge cut 3-ft deep and 950-ft long (from River Mile 268.91 to 268.72) was made in the crossing area over the channel width. The dredged material was disposed in three different ways: on the adjacent floodplain; in the downstream pool area (River Mile 268.46 to 268.28); and half on the floodplain and half in the downstream pool area. The cut was made at the beginning of the low-water season and the riverbed

Table 24

Future Riverbed Elevation Changes
in the Upper Mississippi River
Assuming Maximum Sand Transport into Pool 24

Location	Riverbed Elevation Change after 1975,* ft				
	1985	1995	2005	2015	2025
Pool 26:					
Below Illinois River	1.2	0.5	0.2	0.6	0.6
Middle third	0.2	0.6	0.3	0.4	0.1
Next eighth	3.6	3.0	2.2	1.9	1.3
Upper eighth	-1.9	-3.7	-5.0	-5.8	-6.7
Pool 25:					
Lower quarter	-0.9	-0.8	-1.0	-1.3	-1.4
Lower middle quarter	0.1	-0.8	-0.3	-0.3	-0.1
Upper middle quarter	0.0	1.1	1.6	1.9	2.3
Next eighth	1.9	2.0	2.3	3.2	3.5
Upper eighth	-1.9	-2.8	-1.2	-2.2	-3.0
Pool 24:					
Lower quarter	0.1	1.1	1.3	1.5	1.8
Lower middle quarter	1.1	1.2	1.2	1.4	2.2
Upper middle quarter	0.0	0.0	0.1	1.2	1.5
Upper quarter	1.7	2.5	2.7	2.9	2.5

*Positive and negative changes signify aggradation and degradation respectively.

level changes in the modeled reach were computed during the next year for the 2-yr annual hydrograph. These riverbed levels were compared with those that would occur during the same year if no dredge cut were made. The results are very interesting.

Without dredging, the crossing aggrades and the pool area degrades. With dredging from the crossing and disposing the dredged material in the pool area, the dredge cut is filled in and the disposal bar is eroded away within a year. That is, after one year both crossing and pool return to the natural state. This result is supported by field observation and explains why many river reaches require repeated dredging. If all the dredged material is placed on the floodplain, then the downstream pool deepens much more than when no dredging is done. This eroded sediment may be deposited in part on the downstream crossings.

In general, the river is not affected by disposal of dredged material except in the reach close to the disposal site. A dredge cut in a crossing could cause a larger amount of erosion in the immediate downstream pool than would occur without dredging. The reason is that dredging a crossing enlarges its cross-sectional area, traps the sediment load in the reach, and reduces sediment supply to downstream reaches.

If the dredged material is deposited in the downstream pool area, the bar of dredged material is generally eroded away within a year unless the next hydrograph following the dredging is uncommonly small. There is a risk that if the annual hydrograph which follows dredging and thalweg disposal is small, the material disposed in the pool area will be scoured and will deposit on the next crossing downstream. The result could be inadequate navigation depths and consequent dredging requirements on that crossing. This is particularly true if the crossing below the disposal pool is already experiencing dredging problems, and could also be true if a divided reach or unstable straight reach is located below the disposal pool.

The model was also subjected to an annual hydrograph with a larger flow volume and a higher peak than the 2-year hydrograph to evaluate the impact of large floods on the thalweg disposal process. The 1973 flood hydrograph was used. Neither the dredged cut on the crossing nor the disposal bar in the pool persisted for long under the high sediment transport conditions of a flood of this magnitude. After 100 days into the hydrograph the bed elevation changes closely approximated those expected under natural river conditions with no dredging.

The mathematical modeling of a particularly troublesome reach of Pool 25 on the Upper Mississippi indicates that dredging from a crossing and disposing the dredged material in a downstream pool does constitute a feasible dredge disposal method. The process involves a degree of risk to the navigation channel downstream from the pool, particularly if dredging is followed by a small discharge hydrograph. However, at many locations the risks incurred by thalweg disposal would be outweighed by the potential environmental benefits of avoiding bankline disposal. In addition, any serious ecological problems associated with open water disposal on marshlands and near chute channels, sloughs, and backwater areas are avoided by disposing dredged materials in the thalweg. Although conditions downstream of a proposed disposal site may preclude thalweg disposal at certain locations, in many cases disposing only a portion of the dredged material along the thalweg would still result in reduced environmental impacts. Consequently, the concept of thalweg disposal offers a viable alternative to both long-term and emergency disposal requirements.

The results of this limited study are sufficiently promising to warrant additional investigation of the concept of thalweg disposal of dredged material.

Dikes

The response of the Upper Mississippi River to development for navigation using dikes has been different than that of the Middle Mississippi River. The principal difference is that flood stages are not appreciably affected by low dikes (low in comparison to the bank-full stage) the high dikes (about bank-full level) in the Middle Mississippi have increased the flood stages in that river (Simons et al., 1974). Also, during the period of dike construction in the study reach of the Upper Mississippi River, the reach of river aggraded overall. In the Middle Mississippi the riverbed degraded appreciably.

There are two main reasons for the different response to dikes in the Upper and in the Middle Mississippi Rivers. First, the dikes in the Upper Mississippi were low in comparison to the bank-full stage. The high dikes are more effective in concentrating all flows in the navigation channel. Second, because of the amount of sediment brought in by the Missouri River, the amount of sediment transported in the

Middle Mississippi is much greater than that transported in the Upper Mississippi.

The combination of large sediment loads and high dikes in the Middle Mississippi River transformed a part of the former river channel section into floodplain, thus decreasing the channel capacity at large flows (Simons, et al., 1974). The channel capacity did not change appreciably in the Upper Mississippi because the dikes were low and there is not much sediment.

Based on hydraulic computations and model studies, lengthening low dikes may not be very effective in increasing the depth in the navigation channel. Increasing the height of a low dike field can be very effective in producing degradation if the dikes are not too short in relation to the river width. The most effective dikes are high long dikes placed in a channel that transports a lot of sediment. Adding more dikes confines the low-water level and could reduce dredging requirements if properly designed and installed.

Effects of Increased Boat Traffic

The effects of waterborne traffic on the Lower Illinois and Upper Mississippi Rivers with regard to the resuspension of bed sediment caused by boat passage and the problem of wave generation by loaded and unloaded towboats and pleasure crafts have been studied qualitatively by Karaki and vanHoften (1975).

Karaki and vanHoften concluded the following:

1. The resuspension of riverbed sediments due to the passage of a boat is dependent on the boat size, speed, draft, depth of channel, and bed-material size. Large towboats in a shallow water channel with a fine-material bed cause the greatest resuspension of bed materials. Thus, the Lower Illinois River is more susceptible to the effects of boat traffic than is the Upper Mississippi River because the Illinois has finer bed material and generally shallower depths.

2. During low-flow periods increasing river traffic will result in an increase in resuspension and thus turbidity at a rate proportional to the frequency of towboat passage. The resuspended sediments would be confined generally to the main channel during low flows and should not contribute appreciably to side channel sedimentation during floods.

3. Boat-generated wave heights are primarily dependent on boat speed. Thus small fast-moving pleasure crafts generate higher waves than large slow-moving towboats. The effect of waves on the riverbanks from increased boat traffic would be to cause some resuspension of fine material along the shoreline and to accelerate erosion on unstable banks.

PART VIII: SUMMARY

From the foregoing analyses of the geomorphic changes in Pools 24, 25, and 26 on the Upper Mississippi and Lower Illinois Rivers, the following conclusions have been reached concerning the rivers' response to developments in the last century and anticipated responses to future activities.

In the Past

1. The positions of the rivers in the valleys have been governed by activities during glaciation and have remained essentially fixed in the last 150 years.
2. In the period immediately prior to development for navigation the Upper Mississippi River was narrowing and many new islands were forming. This change in width and in number of islands could have been due to a series of dry years or to changing land uses resulting from large influxes of settlers.
3. The use of low dikes to create a 4-1/2 and then a 6-ft deep navigation channel in the Upper Mississippi River resulted in a slightly narrower river in 1929 than in 1891. During the intervening period, the riverbed aggraded slightly in most of the study area. Some new islands and side channels formed as a result of sedimentation in dike fields. Many old islands increased in size but old chutes were not affected.
4. The levees protecting the floodplain adjacent to Pools 24 and 25 in the Upper Mississippi River and along the Illinois River above Pool 26 have not affected flood peaks significantly in the upper river system.
5. The construction of Locks and Dams 24, 25, and 26 during the late 1930's resulted in an immediate widening of the river caused by inundating a portion of the floodplain.
6. The long-term effect of the locks and dams has been to increase the river width immediately upstream and to narrow the river slightly immediately downstream of a lock and dam. In the period between 1930 and 1973, the riverbed degraded in most of the study area, mainly because much of the sediment that would have normally been delivered to the study reach was being trapped in upstream pools.
7. Locks and Dam 26 caused widening of the Illinois River immediately above its confluence with the Mississippi but the remainder of the Lower Illinois River retained its original width of 1200 ft.

8. As a result of high water levels in the main rivers and/or changing agricultural practices in the headwaters, portions of the tributary rivers and creeks in the Mississippi and Illinois River floodplains have been aggrading.

9. The number of islands, the total surface area of islands, and the number of side channels have increased greatly in the river system since the construction of Locks and Dams 24, 25, and 26.

10. Some old chutes were closed due to the construction of Locks and Dams 24, 25, and 26 but many other side channels have remained essentially unchanged for more than 150 years.

11. In the study reach, the annual minimum discharge has been increasing in the last 100 years and the annual peak flood has remained unchanged. At Alton, Illinois the average annual flow has been increasing slightly.

12. Annual minimum stages are lower now than in the past at locations immediately below locks and dams and are higher at locations immediately above locks and dams.

13. The locks and dams create a slight backwater effect during floods but this effect in Pools 24, 25, and 26 is not significant.

14. Dredging to maintain the 9-ft channel is required in all three pools. The amount dredged in Pool 24 is much less than in the other pools because the river is much narrower in Pool 24. The total amount of dredging has been much less than was originally estimated at the time of authorization.

15. The most frequently dredged reaches are crossings in heavily braided sections upstream of the control points in the pools. Dredging could be reduced in these sections by realigning and narrowing the sections with wing dams.

Within the study reach, natural and man-made activities in the last 150 years have produced subtle changes in the river geomorphology. Comparison of 1820 and 1891 maps indicates that the Upper Mississippi River in the study reach was narrowing during this period. This is in contrast to the Middle Mississippi River to the south, which apparently widened approximately 50 percent between 1821 and 1888. In the Upper Mississippi River, the low dike fields narrowed the river slightly, created new islands and chutes, and enlarged old islands, but did not cause a lowering of the riverbed. Locks and Dams 24, 25, and 26 have widened the river and increased the number of islands in the pools.

Very little sedimentation in the river channel has resulted from the effects of these locks and dams. Since 1939, the riverbed in Pool 24 has aggraded approximately 2 ft. In constrast, degradation has occurred in Pools 25 and 26.

In the Future

Future geomorphic changes that may occur in Pools 24, 25, and 26 in the Upper Mississippi and Illinois Rivers due to present and anticipated future developments have been assessed. The responses expected are as follows.

1. If the pools are operated in the present-day manner for the next 50 years and if the sediment load to the study reach remains essentially unchanged, the riverbed in Pool 24 will have degraded approximately 1.5 ft overall. Pool 25 will have degraded 3.0 ft immediately upstream of the control point and remain unchanged in the lower portion. Pool 26 will have degraded between 6 and 7 ft immediately downstream of Locks and Dam 25 and will have aggraded approximately 2.5 ft in the middle and near Locks and Dam 26.
2. Under the present-day manner of operation and with normal sediment loads, the upper third of Pool 26 in the Illinois River will have degraded approximately 1.5 ft in 50 years whereas the lower two-thirds will have aggraded approximately 0.4 ft.
3. Under the present-day manner of operation, the natural levees along the riverbanks and on the islands would grow on the average approximately 2.5 ft in height in the Upper Mississippi and approximately 1.8 ft in height in the Lower Illinois in the next 50 years.
4. Under the present-day manner of operation, on the average approximately one inch of silts and clays would be deposited on the unprotected floodplains along the study reaches of the Upper Mississippi and 0.1 inch on that of the Lower Illinois River.
5. The geomorphic changes caused by operating with the pool one ft above normal pool for 50 years are not significantly different from operation at normal pool level. Increasing the pool level causes aggrading reaches to aggrade more and degrading reaches to degrade less.
6. Holding the pool one ft above normal for 50 years causes increased deposits on the natural levees and on the floodplains but these increases are not significant.

7. The effects of holding the pool level one ft below the normal pool level for 50 years are not much different than for operation at normal pool level. Decreasing the pool level results in less aggradation and more degradation.

8. Holding the pool one ft lower than normal for 50 years results in less deposition on the floodplain and natural levees but this is not an important factor.

9. If no sediment is supplied to Pool 24, the river would degrade severely in Pool 24 but there would be very little effect on riverbed elevations in Pools 25 and 26.

10. With the maximum sand transport rate passing Locks and Dam 22 into Pool 24, the riverbed in Pool 24 would aggrade 3 ft in the next 50 years. However, the effect would not go beyond Locks and Dam 24, at least for 50 years.

11. The effects of dredging a crossing are extended both upstream and downstream at that crossing and can adversely affect the downstream crossings. The effects do not extend in time for more than a few annual hydrographs unless there are unusual conditions.

12. Disposing dredged material in downstream pools appears to be a good alternative to reduce environmental impacts of disposal and should be studied in more detail.

13. Increasing the height, length, and number of dikes in certain reaches of the rivers would decrease the amount and frequency of dredging.

14. Increased river traffic results in more boat-generated waves on the rivers, and during low-flow periods, increases the resuspension of bed-material sediments. Resuspension would be greater in the Lower Illinois River than in the Upper Mississippi River.

15. Large deep-draft slow-moving towboats cause most of the resuspension and fast-moving pleasure craft generate the highest waves.

On the basis of this study of past geomorphic changes in Pools 24, 25, and 26 and with the mathematical simulation of future river response, it was concluded that 50 years from now the river scene in the study reach will be essentially as it is today. The present-day manner of operation does not have any serious detrimental effects on the geomorphology or hydraulics of the river system in the study reach. Holding the normal pool level one ft higher or lower would not create any sedimentation problems.

There are two promising approaches to reducing the dredging problem in Pools 24, 25, and 26. One is to realign and narrow the troublesome reaches with dikes to decrease the amount of dredging required and the other is to investigate more fully the possibility of placing dredged materials in downstream pools.

LITERATURE CITED

Chen, Y.H., "Mathematical Modeling of Water and Sediment Routing in Natural Channels," dissertation presented to Colorado State University, at Fort Collins, Colorado, in 1973, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Chief of Engineers, "Report of the Chief of Engineers," U.S. Army, U.S. Government Printing Office, Washington, D.C., 1915.

Chief of Engineers, "Annual Report of the Chief of Engineers," Part 1,: U.S. Army, U.S. Government Printing Office, Washingtion, D.C., 1930.

Colby, B.R., "Discharge of Sands and Mean Velocity Relationships in Sand-Bed Streams," USGS Prof. Paper 462-A, 1964.

59th Congress, United States Statutes at Large, Vol. 34, Part 1, Public Laws, 1905-1907.

Degenhardt, E.A., "Channel Stabilization of the Middle Mississippi River," thesis presented to Colorado State University, at Fort Collins, Colorado, in August 1973, in partial fulfillment of the requirements for the degree of Master of Science.

Dickens, C., American Notes, Premiere Americana, Fawcett Publications, Inc., Greenwich, Connecticut, 1961.

Frye, J.C., Willman, H.B., and Black, R.F., "Outline of Glacial Geology of Illinois and Wisconsin," Wright, H.E., Jr., and Frye, D.G. eds., The Quarternary of the United States, Princeton University Press, Princeton, New Jersey, 1965, pp. 43-61.

Fuller, M.L., "New Madrid Earthquake," Bulletin 494, U.S. Geological Survey, 1912.

Gabrielson, I., "Floods and Wildlife," Scientific American, Vol. 156, 1937, pp. 100-102.

Hermann, B., "The Louisiana Purchase and Our Title West of the Rocky Mountains, with A Review of Annexation by the United States," Document No. 708, House of Representatives, Government Printing Office, Washington, D.C., 1900.

Horberg, L., Pleistocene Deposits along the Mississippi Valley in Central-Western Illinois, Illinois Geological Survey Dept. Invest. 192, 1956.

Jordan, P.R., "Summary and Analysis of Sediment Records in Relation to St. Louis Harbor Sedimentation Problem," USGS Open-file report, 1968.

Karaki, S. and vanHoften, J., Resuspension of Bed Material and Wave Effects on the Illinois and Upper Mississippi Rivers Caused by Boat Traffic, CER74-75SK-JV9, Colorado State University, Ft. Collins, Colorado, November, ~~1974~~. 1975

Kesel, R.H., et al., "Erosion and Overbank Deposition on the Mississippi River in Louisiana Caused by 1973 Flooding," Geology. Vol. 2, 1974, pp. 461-464.

Lagasse, P.F., "Interaction of River Hydraulics and Morphology with Riverine Dredging Operations," dissertation presented to Colorado State University, at Fort Collins, Colorado, in 1975, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Rubey, W.W., "Geology and Mineral Resources of the Hardin and Brussels Quadrangles," USGS Prof. Paper 218, 1952.

The Secretary of War, "Mississippi River Between Missouri River and St. Paul, Minn.," Document No. 341, House of Representatives, 1906-1907.

The Secretary of War, "Mississippi River, Between Mouth of Missouri River and Minneapolis, Minn.," Document No. 290, House of Representatives, 1929-1930.

Simons, D.B., Schumm, S.A., and Stevens, M.A., Geomorphology of the Middle Mississippi River, CER73-74DBS-SAS-MAS9, Colorado State University, Fort Collins, Colorado, January, 1974.

Starrett, W.C., "Man and the Illinois River," in River Ecology and Man, proceedings from International Symposium on River Ecology and the Impact of Man, University of Mass., 1971, Oglesby, R.T., Carlson, C.A., McCann, J.A., eds., Academic Press, New York, 1972, pp. 131-169.

Thornbury, W.D., Regional Geomorphology of the United States, John Wiley & Sons, New York, 1965.

Toffaleti, F.B., "Definitive Computation of Sand Discharge in Rivers," Journal of the Hydraulics Division, ASCE, Vol. 95, No. HY1, Proc. Paper 6350, January, 1969.

Trollope, A., North America, Alfred Knopf, New York, 1951.

Tucker, S.J., "Indian Villages of the Illinois Country," Vol. 2 Scientific Papers, Illinois State Museum, Part 1 Atlas, Springfield, Illinois, 1942.

Twain, M., Life on the Mississippi, Harper Bros., New York, 1951.

Tweet, R., "A History of the Rock Island District," U.S. Army Engineer District, Rock Island, Illinois, unpublished manuscript, 1974.

Upper Mississippi River Basin Coordinating Committee, "Upper Mississippi River Comprehensive Basin Study," Vols. 1,2,3,5 and 6, June, 1972.

U.S. Army Corps of Engineers, "Tainter Gates in Open Channels--Discharge Coefficients, Hydraulic Design Charts 320-4 to 320-8/1," Corps of Engineers Hydraulic Design Criteria, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Miss. 1959.

U.S. Army Engineer District, St. Louis, Post Flood Report, Mississippi and Illinois River Basins, 1974 Floods, Corps of Engineers, St. Louis, Missouri, 1974.

U.S. Army Engineer District, St. Louis, Regulating Mississippi River Navigation Pools, Corps of Engineers, St. Louis, Missouri, 1968.

U.S. Army Engineer District, St. Louis, Stages and Discharges of the Mississippi River and Tributaries in St. Louis District, Corps of Engineers, St. Louis, Missouri, 1965-1967.

U.S. Geological Survey, Surface Water Supply of the United States, Part 5 - Hudson Bay and Upper Mississippi River Basin, Part 6 - Missouri River Basin above Sioux City, Iowa, USGS Water Supply Paper, 1932-1960.

U.S. Geological Survey, Surface Water Records of Illinois and Missouri, 1961-1973.

APPENDIX A

FLOOD RANKS IN THE STUDY REACH

TABLE A1

TOP TEN FLOOD DISCHARGES AND STAGES
MISSISSIPPI RIVER AT ALTON

FLOOD DISCHARGES

Rank	Discharge cfs	Year
1	573,000	1858
2	565,000	1851
3	535,000	1973
4	460,000	1844
5	437,000	1943
6	412,000	1881
7	399,000	1903
8	391,000	1888
9	380,000	1965
10	377,000	1960

Period of record: 1844 to 1973

FLOOD STAGES

Rank	Stage ft above msl	Year
1	432.11	1973
2	432.10	1844
3	429.91	1943
4	429.47	1951
5	429.40	1947
6	429.33	1944
7	429.30	1903
8	428.20	1858
9	427.90	1851
10	427.10	1922

Period of record: 1844 to 1973

TABLE A2

TOP TEN FLOOD DISCHARGES AND STAGES
MISSISSIPPI RIVER AT KEOKUK

FLOOD DISCHARGES

Rank	Discharge cfs	Year
1	360,000	1851
2	344,000	1973
3	327,000	1965
4	314,000	1888
5	306,000	1892
6	293,000	1881
7	289,500	1960
8	271,000	1880
9	270,000	1903
10	265,000	1951

Period of record: 1851 to 1973

FLOOD STAGES

Rank	Stage ft above msl	Year
1	501.20	1973
2	499.97	1965
3	499.47	1960
4	498.79	1851
5	498.40	1944
6	498.13	1951
7	498.03	1947
8	497.48	1888
9	497.10	1929
10	497.10	1929

Period of record: 1851 to 1973

TABLE A3

TOP TEN FLOOD DISCHARGES AND STAGES
ILLINOIS RIVER AT MEREDOSIA

FLOOD DISCHARGES

Rank	Discharge cfs	Year
1	123,000	1943
2	105,000	1926
3	102,000	1973
4	102,000	1944
5	94,800	1970
6	93,100	1922
7	91,100	1962
8	90,800	1933
9	77,800	1951
10	77,200	1950

Period of record: 1921 to 1973

FLOOD STAGES

Rank	Stage ft above msl	Year
1	446.70	1943
2	444.70	1973
3	443.29	1944
4	442.00	1926
5	441.53	1933
6	441.50	1927
7	441.21	1922
8	440.90	1844
9	440.50	1970
10	440.20	1962

Period of record: 1844 to 1973

APPENDIX B

MATHEMATICAL MODEL OF THE PRINCIPAL PHYSICAL PROCESSES OF THE RIVER

TABLE OF CONTENTS

	Page
LIST OF TABLES	B3
LIST OF FIGURES	B4
PART I: INTRODUCTION	B5
PART II: THEORETICAL ANALYSIS	B6
PART III: NUMERICAL ANALYSIS	B11
PART IV: CALIBRATION OF THE MATHEMATICAL MODEL	B20
General	B20
Model Calibration	B20
PART V: OPERATION OF THE MATHEMATICAL MODEL	B33
General Model Operation	B33
Mathematical Model Prediction	B33
Dredging	~~B39~~ B40
PART VI: LIMITATION OF THE MATHEMATICAL MODEL	B47

LIST OF TABLES

Table		Page
B1	River Sections in the Mathematical Model. . .	B21
B2	Physical Data and Operation Method of Dams 24, 25, and 26	B24
B3	Change in Bankfull Cross-Sectional Area in the Mississippi River from 1939 to 1971	B31
B4	Change in Average Riverbed Elevations in the Mississippi River from 1939 to 1971	B32
B5	Typical Hydrographs	B37

LIST OF FIGURES

Figure		Page
B1	Definition sketch of an alluvial channel. . .	B8
B2	Network for the implicit method	B12
B3	Schematic diagram of the study river reach. .	B12
B4	Flow chart of the mathematical model.	B19
B5	Mathematical model reproduction of 1965 water surface profile in the Upper Mississippi River	B28
B6	Mathematical model reproduction of 1967 water surface profile in the Upper Mississippi River	B29
B7	Mathematical model reproduction of 1965 water surface profile in the Lower Illinois River	B30
B8	Mathematical model reproduction of 1967 water surface profile in the Lower Illinois River	B30
B9	Water surface profiles in the Upper Mississippi River during a flood routing. . .	B34
B10	Water surface profiles in the Lower Illinois River during a flood routing.	B35
B11	Bed elevation changes in the Upper Mississippi River during a flood routing.	B36
B12	Peak discharge frequency curve.	B38
B13	Flow volume frequency curve	B38
B14	Riverbed level changes during the year after dredging and disposing.	B41
B15	Average riverbed elevation changes with time in a crossing and its downstream pool area (2-year annual hydrograph).	B42
B16	Average riverbed elevation changes one year after dredging and/or disposing, or without dredging (2-year annual hydrograph)	B43
B17	Average riverbed elevation changes one year after dredging and/or disposing, or without dredging (1-year annual hydrograph)	B45

PART I: INTRODUCTION

The mathematical model was developed by formulating the unsteady flow of sediment-laden water with the one-dimensional partial differential equations representing the conservation of mass for sediment, and the conservation of mass and momentum for sediment-laden water. The effects of locks and dams and the interactions between the Mississippi River and its main tributaries on the geomorphology of rivers and adjacent lands were considered in the modeling. The model can be used to study the impacts of the effects of different operational schemes for the locks and dams, the effects of the pools on the behavior and form of the tributary rivers, the impact of changes in the delivery of sediment and water to the study reach on the morphology of the river and adjacent lands, and the impacts of dredging and dredged material disposal on the hydraulic response and sedimentation patterns in the main channel.

A detailed description of the mathematical model is given in the following sections. In Part II the theoretical background of the mathematical model is described and the governing partial differential equations are formulated. The numerical analysis of these equations by a linear implicit method is outlined in Part III. The calibration of the mathematical model and its operations are presented in Parts IV and V, respectively. The limitations of the model are discussed in Part VI.

PART II: THEORETICAL ANALYSIS

The one-dimensional differential equations of gradually varied unsteady flow in natural alluvial channels can be derived based on the following assumptions:

1. The channel is sufficiently straight and uniform in the reach so that the flow characteristics may be physically represented by a one-dimensional model.
2. Hydrostatic pressure prevails at every point in the channel.
3. The water surface slope is small.
4. The density of the sediment-laden water is constant over the cross section.
5. The resistance coefficient is assumed to be the same as that for steady flow in alluvial channels and can be approximated from resistance equations applicable to alluvial channels or from field data.

The three basic equations derived (Chen, 1973)* are:

the sediment continuity equation

$$\frac{\partial Q_s}{\partial x} + p\,\frac{\partial A_d}{\partial t} + \frac{\partial AC_s}{\partial t} - q_s = 0 \tag{1}$$

the flow continuity equation

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} + \frac{\partial A_d}{\partial t} - q_\ell = 0 \tag{2}$$

and the flow momentum equation

$$\frac{\partial \rho Q}{\partial t} + \frac{\partial \beta\rho QV}{\partial x} + gA\,\frac{\partial \rho y}{\partial x} = \rho gA\,(S_o - S_f + D_\ell)$$

or

$$\frac{\partial \rho Q}{\partial t} + V\,\frac{\partial \beta\rho Q}{\partial x} + \beta\rho V\,\frac{\partial Q}{\partial x} - \beta\rho V^2 T\,\frac{\partial y}{\partial x} + gA\,\frac{\partial \rho y}{\partial x}$$

$$= \rho gA(S_o - S_f + D_\ell) + \beta\rho V^2 A_x^y \tag{3}$$

where

x = horizontal distance along the channel

t = time

Q_s = sediment discharge

---

*References in the appendix are given in the literature cited section following the main text.

p = volume of sediment in a unit volume of bed layer given by ρ_b/ρ_s

ρ_b = bulk density of sediment forming the bed

ρ_s = density of sediment

A_d = volume of sediment deposited on channel bed per unit of length of channel, the value of which is negative when bed erosion occurs

A = water cross-sectional area

C_s = mean sediment concentration on a volume basis given by Q_s/Q

Q = flow discharge

q_s = lateral sediment flow per unit length of channel, a positive quantity indicates inflow and a negative value denotes outflow

q_w = lateral water flow per unit length of channel, a positive quantity indicates inflow and a negative value denotes outflow

q_ℓ = lateral flow per unit length of channel, given by $q_s + q_w$

ρ = density of sediment-laden water given by $\rho_w + C_s(\rho_s - \rho_w)$

ρ_w = density of water

β = momentum coefficient

V = mean flow velocity

T = $\partial A/\partial y$

y = flow depth

g = acceleration of gravity

S_o = bed slope

S_f = friction slope

D_ℓ = dynamic contribution of lateral discharge given by $q_\ell V_\ell/Ag$

V_ℓ = velocity component of lateral inflow in the main flow direction

A_x^y = departure from a prismatic channel given by $(\partial A/\partial x)_y$

h = water surface elevation

z = riverbed elevation

Δz = change in riverbed elevation

B = top width

Figure B1 is a definition sketch of an alluvial channel.

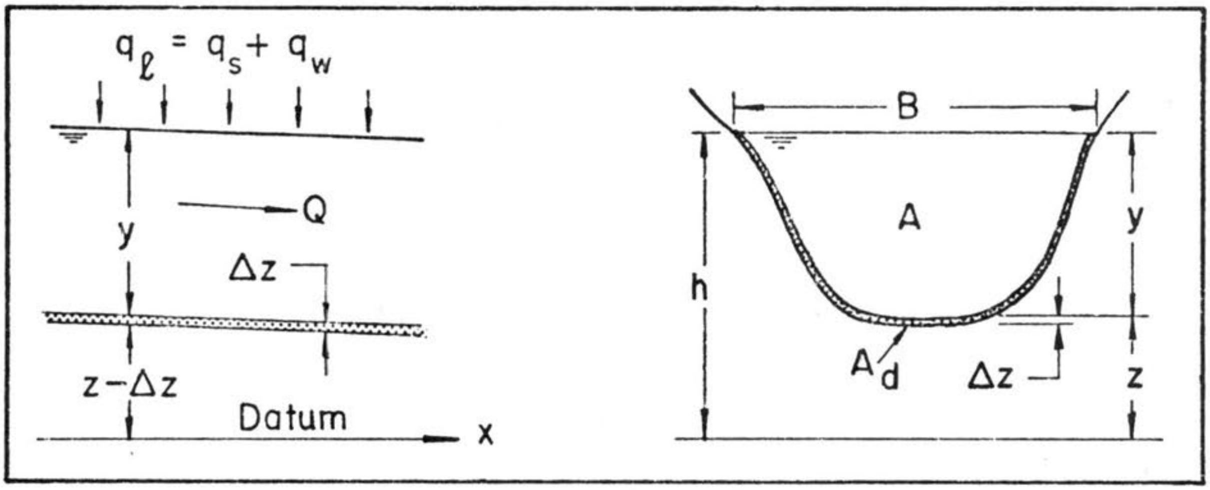


Figure B1. Definition sketch of an alluvial channel

The three equations contain three basic unknowns Q, y, and A_d. The other variables in the equations must be expressed as a function of the three unknowns in order to obtain a solution. These functions are given by the following supplementary equations which describe the physical properties of the prototype.

1. The geometric properties of cross sections are expressed as a function of stage from the known channel geometry.

2. The mean bed slope

   $$S_o = - \partial z/\partial x \tag{4}$$

   in which the initial bed elevation is known and its change is related to the variable A_d.

3. The friction slope S_f is a function of flow and channel characteristics. The resistance functions such as Manning's or Chezy's equations can be employed to relate S_f to the basic unknowns.

4. The lateral inflow q_ℓ consists of two components, $q_{\ell 1}$ and $q_{\ell 2}$, induced by natural and manmade activities, respectively. For overbank flow, the natural-induced lateral inflow is related to the change of water surface elevation Δh over a time period Δt

$$q_{\ell 1} = - \frac{A_f}{\Delta x \Delta t} \Delta h \tag{5}$$

where A_f = the surface area of the floodplain and Δx = length of the floodplain along the main channel. Equation 5 is formulated from the assumption that the transverse water surface (normal to the main flow direction) is horizontal and the amount of infiltration and evaporation is negligible. The lateral sediment inflow q_s has its natural and man-induced components, q_{s1} and q_{s2}, in which

$$q_{s1} = q_{\ell 1} C_b \tag{6}$$

and C_b = sediment concentration at or near the river bank.

5. The sediment discharge can be estimated from field surveys and/or from the available theories.

To account for the effects of locks and dams, the following equations are utilized to simulate sediment-laden water flowing through the locks and dams:

$$Q_{s_{NL}} = Q_{s_{NL+1}} \tag{7}$$

$$Q_{NL} = Q_{NL+1} \tag{8}$$

$$Q = CW a \sqrt{2g(h_{NL} - h_{NL+1})} \tag{9}$$

where

C = gate discharge coefficient

a = the height of the gate opening

W = the width of the gate

h = the stage (water surface elevation)

NL and NL+1 = the sections above and below the lock and dam respectively.

The interaction between the Upper Mississippi River and its tributaries can be simulated by the following continuity and energy equations:

$$Q_{NC+1} = Q_{NC} + Q_N \tag{10}$$

$$Q_{s_{NC+1}} = Q_{s_{NC}} + Q_{s_N} \tag{11}$$

$$z_{NC} + y_{NC} + \frac{V_{NC}^2}{2g} = z_{NC+1} + y_{NC+1} + \alpha_{NC} \frac{V_{NC+1}^2}{2g} + h_{f_{NC}} \qquad (12)$$

$$z_N + y_N + \frac{V_N^2}{2g} = z_{NC+1} + y_{NC+1} + \alpha_N \frac{V_{NC+1}^2}{2g} + h_{f_N} \qquad (13)$$

where

α = the correction factor for energy loss

h_f = the energy head loss given by $S_f \Delta x$

NC, NC+1 and N = the sections in the Mississippi River above and below the confluence and the section at the mouth of its tributary, respectively.

Equations 1 through 13 govern the flow and sediment movement in the study reach. Changes in flow and channel characteristics can be assessed from the solution of these equations. Because of the non-linearity of these equations, the only feasible method of solution is by numerical methods.

PART III: NUMERICAL ANALYSIS

Equations 1 through 3 and 7 through 13 can be solved by a linear-implicit method using a digital computer. The finite-difference approximations employed to express the values and the partial derivatives of a function f within a four-point grid (Fig. B2) formed by the intersections of the spacelines x_i and x_{i+1} with the time lines t^j and t^{j+1} are given by

$$f \approx \frac{1}{2}(f_i^j + f_{i+1}^j) \tag{14}$$

$$\frac{\partial f}{\partial x} \approx \frac{1}{\Delta x}(f_{i+1}^{j+1} - f_i^{j+1}) \tag{15}$$

and

$$\frac{\partial f}{\partial t} \approx \frac{1}{2\Delta t}[(f_i^{j+1} - f_i^j) + (f_{i+1}^{j+1} - f_{i+1}^j)] \tag{16}$$

in which f represents Q, A, y, etc. All the variables are known at all nodes of the network on the time line t^j. The unknown values of the variables on the time line t^{j+1} can be found by solving the system of linear algebraic equations formulated by substitution of the finite-difference approximations 14, 15, and 16 into Eqs. 1 through 3 and 7 through 13. The schematic diagram shown in Fig. B3 explains the solution scheme.

As Eqs. 14, 15, and 16 are substituted into Eqs. 1, 2, and 3, or 7, 8, and 9 by assuming $\partial A_d/\partial z = \partial A/\partial y = T$ and employing the first order Taylor series expansion (e.g., $Q_s^{j+1} \approx Q_s^j + (\partial Q_s/\partial Q)^j(Q^{j+1} - Q^j) + (\partial Q_s/\partial y)^j(y^{j+1} - y^j) + (\partial Q_s/\partial z)^j(z^{j+1} - z^j)$), three linear algebraic equations are formed. They can be written as

$$K_{k1}\,Q_i + K_{k2}\,y_i + K_{k3}\,z_i + K_{k4}\,Q_{i+1} + K_{k5}\,y_{i+1} + K_{k6}\,z_{i+1} = E_k \tag{17}$$

$$K_{m1}\,Q_i + K_{m2}\,y_i + K_{m3}\,z_i + K_{m4}\,Q_{i+1} + K_{m5}\,y_{i+1} + K_{m6}\,z_{i+1} = E_m \tag{18}$$

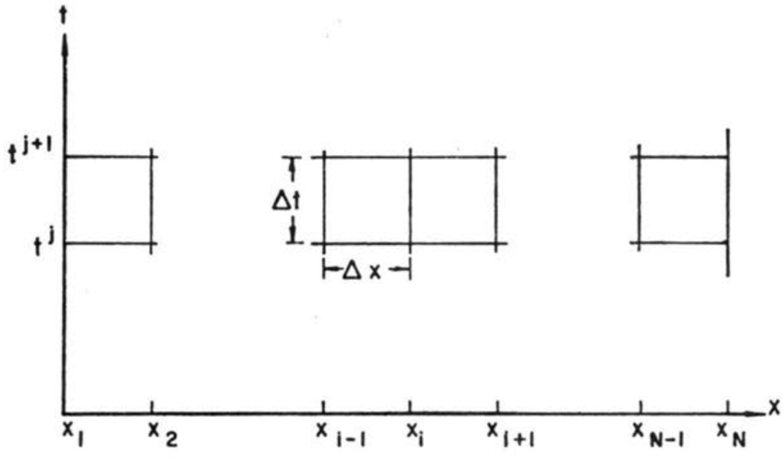


Figure B2. Network for the implicit method

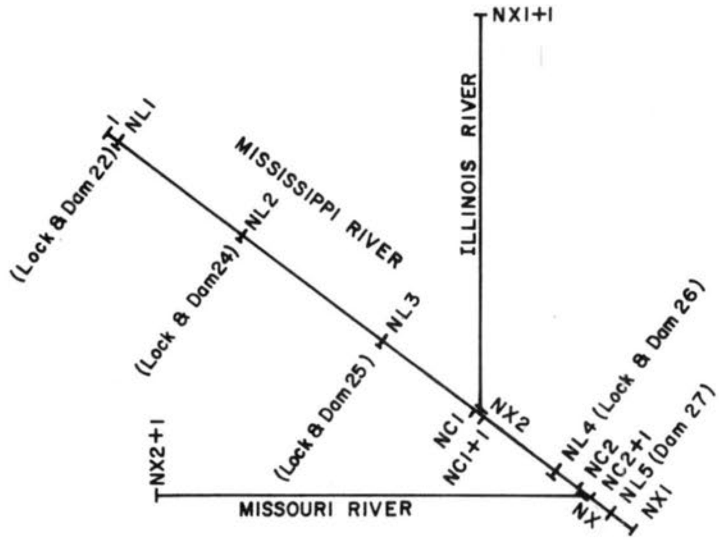


Figure B3. Schematic diagram of the study river reach

$$K_{n1}\,Q_i + K_{n2}\,y_i + K_{n3}\,z_i + K_{n4}\,Q_{i+1} + K_{n5}\,y_{i+1} + K_{n6}\,z_{i+1} = E_n \qquad (19)$$

where k = 3i, m = 3i+1, and n = 3i+2 when applied to the grid formed by sections i and i+1. The coefficients, K and E, are functions of variables evaluated at the time step t^j and therefore are known. To ensure the stability of the scheme, the fraction slope S_f is taken on the time line t^{j+1} by employing a first order Taylor series expansion.

There are six unknowns in Eqs. 17, 18, and 19 at the time step t^{j+1} which cause the system to be indeterminate. However three unknowns are common for any two neighboring rectangular grids. Consequently, there are

$$[(NC1-1) + (NC2-NC1-1) + (NX1-NC2-1) + (NX2-NX1-1) + (NX-NX2-1)]$$

or

$$(NX-5)$$

sets of three equations containing 3(NX) unknowns. Fifteen additional equations supplied by six upstream boundary conditions (one sediment and one flow discharge hydrograph at the upstream section of the Mississippi River, the Illinois River, and the Missouri River, respectively), one downstream boundary condition (a stage-discharge relationship at Sec. NX1), and eight confluence equations (four equations for the confluence of the Mississippi and the Illinois Rivers and four equations for the confluence of the Mississippi and Missouri Rivers) make this system of equations mathematically determinable. All 15 equations can be expressed in the form of the following linear algebraic equations.

1. The flow discharge

   $Q_i = f(t)$

   can be written as

$$K_{m4}\,Q_i + K_{m5}\,y_i + K_{m6}\,z_i = E_m \qquad (20)$$

in which $K_{m4} = 1$, $K_{m5} = K_{m6} = 0$, $E_m = f(t)$. The subscript i denotes the upstream boundary sections 1, (NX1+1), or (NX2+1), and $m = 3(i-1)+1$. Figure B3 shows the schematic locations of these sections.

2. The sediment discharge hydrograph

$$Q_{si} = f_2(t)$$

can be approximated by

$$f_2(t^{j+1}) = f_2(t^j) + \left(\frac{\partial Q_s}{\partial Q}\right)_i^j (Q_i^{j+1} - Q_i^j) + \left(\frac{\partial Q_s}{\partial y}\right)_i^j (y_i^{j+1} - y_i^j)$$

$$+ \left(\frac{\partial Q_s}{\partial z}\right)_i^j (z_i^{j+1} - z_i^j)$$

or rearranged as

$$K_{n4} Q_i + K_{n5}\, y_i + K_{n6}\, z_i = E_n \qquad (21)$$

in which the subscript $i = 1$, (NX1+1), or (NX2+1), and $n = 3(i-1)+2$.

3. The rating curve

$$Q_{NX1} = f_3(h_{NX1})$$

can be approximated by

$$Q_{NX1}^{j+1} = Q_{NX1}^j + \left(\frac{\partial f_3}{\partial y}\right)_{NX1}^j (y_{NX1}^{j+1} - y_{NX1}^j)$$

$$+ \left(\frac{\partial f_3}{\partial z}\right)_{NX1}^j (z_{NX1}^{j+1} - z_{NX1}^j)$$

or rearranged as

$$K_{3(NX1),1} Q_{NX1} + K_{3(NX1),2} y_{NX1} + K_{3(NX1),3} z_{NX1}$$

$$= E_{3(NX1)} \qquad (22)$$

4. The confluence equations 10 to 13 can be linearized as

$$P_{28}\, Q_{NC+1} + P_{29}\, Q_{NC} + P_{30}\, Q_N = P_1 \qquad (23)$$

$$P_{31}\, Q_{NC+1} + P_{32}\, y_{NC+1} + P_{33}\, z_{NC+1} + P_{34}\, Q_{NC} + P_{35}\, y_{NC}$$

$$+ P_{36}\, z_{NC} + P_{37}\, Q_N + P_{38}\, y_N + P_{39}\, z_N = P_2 \tag{24}$$

$$P_{14}\, Q_{NC} + P_{15}\, y_{NC} + P_{16}\, z_{NC} + P_{17}\, Q_{NC+1} + P_{18}\, y_{NC+1}$$

$$+ P_{19}\, z_{NC+1} = P_{20} \tag{25}$$

$$P_{21}\, Q_N + P_{22}\, y_N + P_{23}\, z_N + P_{24}\, Q_{NC+1} + P_{25}\, y_{NC+1}$$

$$+ P_{26}\, z_{NC+1} = P_{27} \tag{26}$$

in which the coefficient P is a function of known variables, and the subscript N denotes the confluence sections NX2 or NX.

Equations 17 through 26 constitute a system of 3(NX) linear algebraic equations in 3(NX) unknowns. Any of the standard methods, such as the Gaussian elimination method or the matrix inversion method, can be used for its solution. A double-sweep method is applied here for solving this system of linear equations (Chen, 1973). This method offers two advantages. First, the computations do not involve any of the many zero elements in the coefficient matrix, which saves considerable computing time. Second, the required computer core storage is reduced significantly from that required from a 3(NX) x 3(NX) matrix to that required for a 3(NX) x 6 matrix, a desirable feature of the matrix solution technique when the matrix is large and the computer storage capacity is limited.

The principles of the double-sweep method can be explained by the following example. Consider a river reach being divided into three sections and the linear equations derived are

$$K_{1,4}Q_1 + K_{1,5}y_1 + K_{1,6}z_1 = E_1 \tag{27}$$

$$K_{2,4}Q_1 + K_{2,5}y_1 + K_{2,6}z_1 = E_2 \tag{28}$$

$$K_{3,1}Q_1 + K_{3,2}y_1 + K_{3,3}z_1 + K_{3,4}Q_2 + K_{3,5}y_2$$

$$+ K_{3,6}z_2 = E_3 \tag{29}$$

$$K_{4,1}Q_1 + K_{4,2}y_1 + K_{4,3}z_1 + K_{4,4}Q_2 + K_{4,5}y_2$$

$$+ K_{4,6}z_2 = E_4 \tag{30}$$

$$K_{5,1}Q_1 + K_{5,2}y_1 + K_{5,3}z_1 + K_{5,4}Q_2 + K_{5,5}y_2$$

$$+ K_{5,6}z_2 = E_5 \tag{31}$$

$$K_{6,1}Q_2 + K_{6,2}y_2 + K_{6,3}z_2 + K_{6,4}Q_3 + K_{6,5}y_3$$

$$+ K_{6,6}z_3 = E_6 \tag{32}$$

$$K_{7,1}Q_2 + K_{7,2}y_2 + K_{7,3}z_2 + K_{7,4}Q_3 + K_{7,5}y_3$$

$$+ K_{7,6}z_3 = E_7 \tag{33}$$

$$K_{8,1}Q_2 + K_{8,2}y_2 + K_{8,3}z_2 + K_{8,4}Q_3 + K_{8,5}y_3$$

$$+ K_{8,6}z_3 = E_8 \tag{34}$$

$$K_{9,1}Q_3 + K_{9,2}y_3 + K_{9,3}z_3 = E_9 \tag{35}$$

Equations 27 and 28, Eqs. 29 to 34, and Eq. 35 have the form of the upstream boundary equations 20 and 21, of the interior equations 17 to 19, and of the downstream boundary equation 22, respectively.

Equations 27 and 28 with 3 unknowns can be reduced to

$$Q_1 = L_{1,2} + L_{1,3}\, z_1 \tag{36}$$

and

$$y_1 = L_{2,2} + L_{2,3}z_1 \tag{37}$$

where the coefficient L is a function of K and E. Substituting Eqs. 36 and 37 into the first three interior equations, 29 to 31, yields

$$L_{3,3}z_1 + L_{3,4}Q_2 + L_{3,5}y_2 + L_{3,6}z_2 = M_3 \tag{38}$$

$$Q_2 = L_{4,2} + L_{4,3}z_2 \tag{39}$$

and

$$y_2 = L_{5,2} + L_{5,3}z_2 \tag{40}$$

Equations 27 to 31 are reduced to Eqs. 36 to 40. The same procedure can be repeated to reduce the next three interior equations, 32 to 34, by substituting Eqs. 39 and 40 into them yielding

$$L_{6,3}z_2 + L_{6,4}Q_3 + L_{6,5}y_3 + L_{6,6}z_3 = M_6 \tag{41}$$

$$Q_3 = L_{7,2} + L_{7,3}z_3 \tag{42}$$

and

$$y_3 = L_{8,2} + L_{8,3}z_3 \tag{43}$$

The coefficients L and M in Eqs. 36 to 43 can be computed by recurrence equations and therefore can be easily programmed. The procedure of using the recurrence equations to compute the values of the coefficients in Eqs. 36 to 43 is called the "forward-sweep."

Equations 42 and 43 derived from the forward-sweep can be combined with Eq. 35 to form a set of 3 equations in 3 unknowns. The values of Q_3, y_3 and z_3 can be easily determined. Thereafter, the values of z_2, Q_2, y_2, z_1, Q_1, and y_1 can be determined backward from Eqs. 41 to 36. The recurrence equations can be easily formulated for programming. This procedure of using the recurrence equations to compute the values of unknowns is called the "backward-sweep." The whole procedure is designated as the "double-sweep" method. The method can be extended to solve a set of linear equations formulated for any number of sections in a channel reach.

The double-sweep method is used to solve the set of linear equations formulated in the study river reach. The forward-sweep is started from Section 1 to NC1 and from Section (NX1+1) to NX2 (Fig. B3). This results in four equations in the form of Eqs. 42 and 43. With the aid of the four confluence equations 23 through 26, a set of eight linear equations in nine unknowns is formed at the confluence. Two equations in the form of Eqs. 42 and 43 can then be derived for Section (NC1+1). The forward-sweep can be extended across the confluence to the Illinois River to Section (NC1+1) and then continued to Section NC2. This forward-sweep meets with the other branch of forward-sweep (from Section NX2+1 to NX) at the confluence with the Missouri River. By employing the other four confluence equations, the forward-sweep is utilized across the confluence to reach the downstream boundary section at NX1. By solving the resulting two equations (containing unknowns only at Section NX1) from the forward-sweep and the downstream boundary equation, the unknowns Q_{NX1}^{j+1}, y_{NX1}^{j+1} and z_{NX1}^{j+1} can be computed. The unknown variables at the other sections can then be solved by the backward-sweep. After the flow condition at each node section on the time line t^{j+1} is computed, the computation is moved to the next time step. A flow chart is given in Fig. B4 to show the principal programming steps.

The change of sediment area over a time step from t^j to t^{j+1} is given by

$$\Delta A_d = T(z^{j+1} - z^j) \tag{44}$$

where ΔA_d is assumed to be uniformly distributed over the channel width when formulating the finite-difference equations 17 through 26. However, to directly solve for A_d, the finite-difference equations may be derived in terms of Q, y, and A_d. A certain distribution of ΔA_d can then be assumed from theoretical or empirical information.

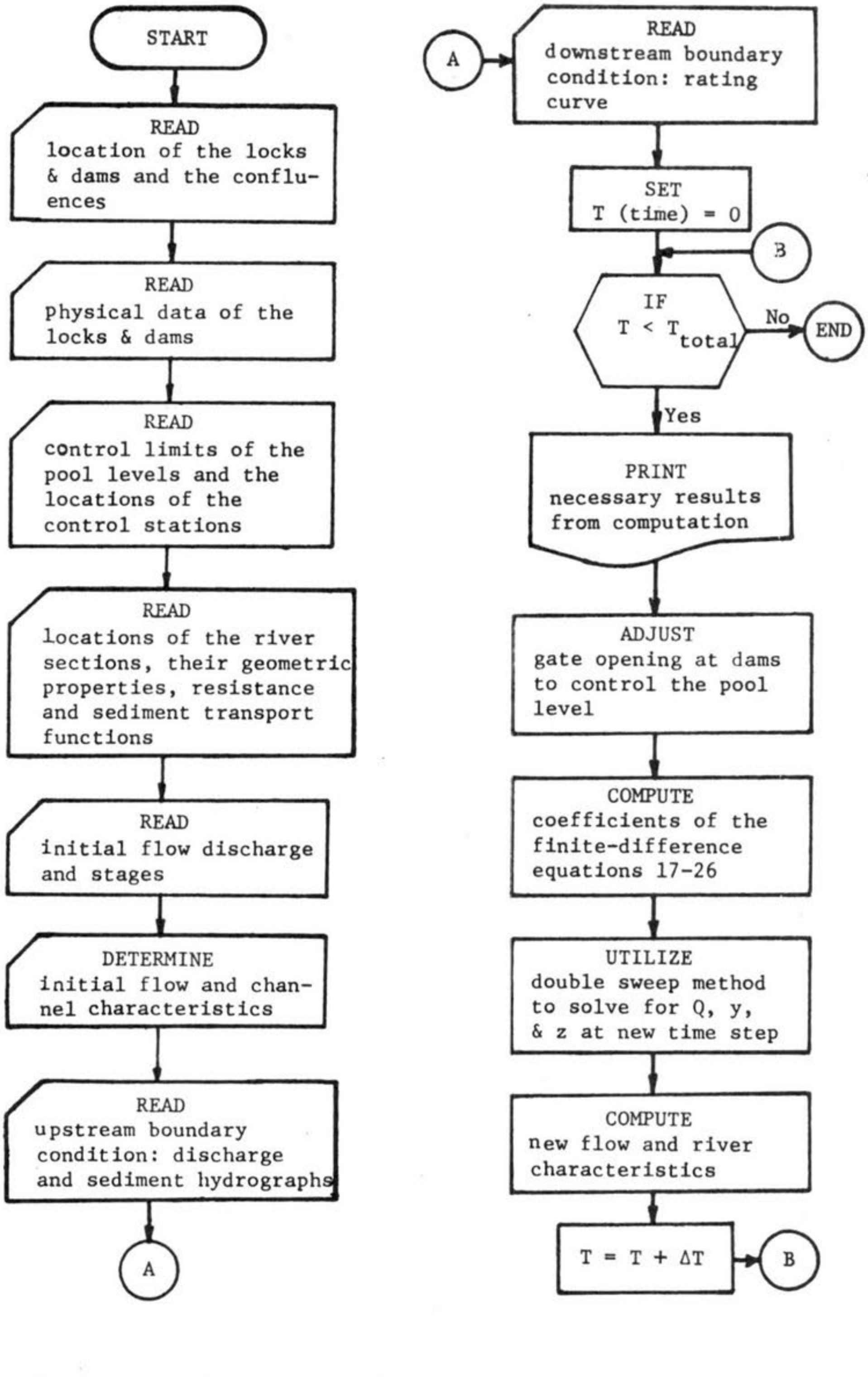


Figure B4. Flow chart of the mathematical model

PART IV: CALIBRATION OF THE MATHEMATICAL MODEL

General

The calibration of a mathematical model involves evaluating and modifying supplementary relations to basic equations from the field data and/or theories such that the mathematical model would reproduce the historical response of the modeled river system. This is similar to the calibration of a physical model.

Hydrographic maps of the modeled river reach, hydrographs of stage, flow, and sediment discharge data, and geological and physical properties of the bed and bed material are needed to perform the calibration of the mathematical model. From this, the geometric properties of the river reach and the relations for S_f, Q_s, q_ℓ, and V_ℓ can be evaluated. If part of data is not available, relations based on experimental, empirical, or theoretical approaches can be used. The resistance function for S_f and the sediment transport function for Q_s must be tested and modified to accomplish the model calibration until the historical data along the river reach can be reproduced by the mathematical model.

Model Calibration

The mathematical model of the river system being studied includes the Upper Mississippi River from above Locks and Dam 22 (RM 304.8) to St. Louis (RM 179.6), the Lower Illinois River from RM 80 to the mouth of the Illinois River, and the Lower Missouri River from Hermann (RM 97.9) to the mouth of the Missouri River (Figs. 1 and B3). The river reach was divided into 75 sections with space increments ranging from 0.4 mile at a lock and dam to 20 miles in the Missouri River. A list of the river sections is given in Table B1. The available field data that were used to calibrate the mathematical model include:

1. The 1939 and 1971 hydrographic maps of the river reach.
2. The 1932 to 1973 discharge hydrographs of the Mississippi River at Keokuk, Iowa (RM 364.2), and at St. Louis, Missouri (RM 179.6 above mouth of Ohio River); of the Des Moines River at Keosauqua, Iowa (RM 50.6 above mouth of Des Moines River); of the Illinois River at Meredosia, Illinois

Table B1

River Sections in the Mathematical Model

Section	Location (river miles)	Remarks*
MI 1	304.8	Upstream boundary (MI)
MI 2	301.4	Locks and Dam 22 (upper)
MI 3	301.0	Locks and Dam 22 (lower)
MI 4	298.5	
MI 5	297.5	
MI 6	294.7	
MI 7	290.0	
MI 8	285.0	Pool 24 control point
MI 9	280.0	
MI 10	273.6	Locks and Dam 24 (upper)
MI 11	273.0	Locks and Dam 24 (lower)
MI 12	270.0	
MI 13	269.0	
MI 14	268.0	
MI 15	267.1	
MI 16	265.9	
MI 17	265.0	
MI 18	263.0	
MI 19	260.0	Pool 25 control point
MI 20	255.1	
MI 21	253.0	
MI 22	251.0	
MI 23	247.2	
MI 24	241.8	Locks and Dam 25 (upper)
MI 25	241.1	Locks and Dam 25 (lower)
MI 26	238.0	
MI 27	236.5	
MI 28	234.6	
MI 29	233.1	
MI 30	229.8	
MI 31	227.9	
MI 32	226.5	
MI 33	225.0	
MI 34	223.7	
MI 35	222.5	

*In Fig. B3, NL1 = 2, NL2 = 10, NL3 = 24 and NC1 = 36. MI denotes the river section in the Mississippi River.

Table B1 (Continued)

Section	Location (river miles)	Remarks*
MI 36	220.6	Ill. River enters at 218.0
MI 37	218.0	Pool 26 control point
MI 38	212.5	
MI 39	209.0	
MI 40	207.7	
MI 41	203.4	Locks and Dam 26 (upper)
MI 42	202.5	Locks and Dam 26 (lower)
MI 43	200.5	
MI 44	195.7	Mo. River enters at 195.5
MI 45	195.2	
MI 46	190.6	Dam 27 (upper)
MI 47	189.9	Dam 27 (lower)
MI 48	184.8	
MI 49	179.6	Downstream boundary (MI)
IL 50	80.0	Upstream boundary (IL)
IL 51	76.0	
IL 52	71.0	
IL 53	66.0	
IL 54	61.0	
IL 55	56.0	
IL 56	51.0	
IL 57	46.0	
IL 58	41.0	
IL 59	36.0	
IL 60	31.0	
IL 61	26.0	
IL 62	21.0	
IL 63	16.0	
IL 64	11.0	
IL 65	6.0	
IL 66	1.4	Downstream boundary (IL)
MO 67	97.9	Upstream boundary (MO)
MO 68	80.0	
MO 69	60.0	
MO 90	50.0	

*In Fig. B3, NL4 = 41, NL5 = 46, NC2 = 44, NX1 = 49, NX2 = 66 and NX = 75. IL and MO denote the river sections in the Illinois River and the Missouri River, respectively.

Table B1 (Concluded)

Section	Location (river miles)	Remarks*
MO 71	40.0	
MO 72	30.0	
MO 73	20.0	
MO 74	10.0	
MO 75	0.8	

*In Fig. B3, NL4 = 41, NL5 = 46, NC2 = 44, Nx1 = 49, Nx2 = 66 and Nx = 75. IL and MO denote the river sections in the Illinois River and the Missouri River, respectively.

(RM 70.8 above mouth of Illinois River); and of the Missouri River at Hermann, Missouri (RM 97.9 above mouth of Missouri River) (U.S. Geological Survey, 1932 to 1960 and 1961 to 1973).

3. The 1965 to 1967 discharge hydrographs of the Mississippi River at Saverton, Missouri (RM 301.0), and at Alton, Illinois (RM 202.7), (U.S. Army Engineer District, St. Louis, 1965 to 1967).

4. The 1965 to 1967 stage hydrographs of the Mississippi River at 18 gaging stations between Hannibal, Missouri (RM 309.9) and St. Louis; of the Illinois River at 5 gaging stations below Meredosia; and of the Missouri River at Hermann (U.S. Army Engineer District, St. Louis, 1965 to 1967).

5. The 1949 to 1967 yearly averaged sediment data in the Mississippi River at Hannibal and St. Louis, and in the Missouri River at Hermann (Jordan, 1968).

6. The sediment discharge in the Mississippi River at St. Louis (Colby, 1964).

7. The physical data and the regulation method of Dams 24, 25, and 26 are given in Table B2.

Using this information, the following supplementary relations were evaluated at all 75 sections in the modeled river reach:

1. The geometric properties of the river sections including cross-sectional areas, top widths, bed elevation, and floodplain surface area were estimated from the hydrographic maps. The cross-sectional area and the top width were expressed as a function of stage. The floodplain surface area was assumed not to vary with stage.

Table B2

Physical Data and Operation Method of Dams 24, 25, and 26

	Dam 24	Dam 25	Dam 26
General			
Location-river mile	273.4	241.4	202.9
Normal upper pool elevation (ft, Amsl)	449.0	434.0	419.0
Dam			
Length of movable section (clear opening, in ft)	1200	1140	1440
Tainter gates	15@80'x 25'	14@60'x25'	30@40'x30'
Roller gates	None	3@100'x25'	3@80'x25'
Elevation of gate sills:			
Tainter gates	424.0	409.0	389.0
Roller gates	--	409.0	394.0
Operation			
Control point (river mile)	Louisiana (282.9)	Mosier Ldg. (260.3)	Grafton (218.0)
Control elevation	448.8 - 449.5	434.0 - 435.8	418.0 - 420.0
Flow at beginning of drawdown (cfs)	80,000	70,000	108,000
Flow at open river	152,000	92,500	212,000
Minimum elevation at open river (upper gage)	445.5	429.7	414.0

2. The Manning equation was employed to relate the friction slope to the flow and channel characteristics. The Manning roughness coefficients were determined from the steady water surface profiles for given discharges, where the stage-discharge relationships were assessed from the stage and the discharge hydrographs measured or computed at the gaging stations in the river reach being studied. The Manning roughness coefficients were expressed as functions of stage. In general, the Manning coefficient decreases with increase in stage. Typical values vary from 0.033 with low flow to 0.024 with high flow.

3. Sediment discharge is related to the flow and channel characteristics by a sediment transport function. By fitting the available data obtained from Colby (1964) and Jordan (1968) the following relations were established:

$$C_s = KV^{3.4} D^{-1} \tag{45}$$

$$Q_w = 3.53 \times 10^{-13} Q^{2.752} \tag{46}$$

where

C_s = mean concentration of bed-material load on a volume basis,

K = empirical coefficient varied from 0.000005 to 0.000015,

D = hydraulic depth and,

Q_w = discharge of wash load in cfs.

4. For overbank flow, the natural-induced lateral flow $q_{\ell 1}$ was assessed from Eq. 5. On the rising limb of the hydrograph, the water carries sediment to the floodplain, depositing its coarse material along the river bank to raise the heights of natural levees. A triangular shape of natural levee was assumed with bottom angles 30 (face to the main channel) and 15 degrees. In this case, the quantity $q_{\ell 1}$ was negative and the lateral sand flow q_{s1} was determined from Eq. 6. The sediment concentration at or near the river bank was greater than the mean concentration calculated from Eq. 45. A factor of five times greater was assumed to obtain adequate natural levee height during calibration at the mathematical model. This factor is approximately equal to the averaged ratio between the sediment concentration at the river bank and the mean concentration during the overbank flow, assuming that the flow velocity at the river bank equals the mean velocity. During the falling limb, the water returns to the main channel carrying a negligible amount of sand, $q_{s1} \simeq 0$. Thus, the increase in the height of the natural levee over a period of time, $\Sigma\Delta t$, is

$$\Delta z_f = \left\{ \frac{-2\Sigma(q_{s1}\ \Delta t)}{p(\cot 15^\circ + \cot 30^\circ)} \right\}^{1/2} \tag{47}$$

Landward from the natural levees, the deposition of sediment (mainly silt and clay) on the floodplain was assessed by

$$\Delta z_w = - \frac{(\Sigma q_{\ell 1} C_w \Delta t)\Delta x}{p A_f} \quad (48)$$

where C_w was calculated from Eq. 46 by Q_w/Q for $q_{\ell 1} < 0$, and was assumed to equal zero when $q_{\ell 1} > 0$.

5. The gate discharge coefficient C in Eq. 9 was evaluated based on the design charts for tainter gates prepared by the U.S Army Engineers Waterways Experiment Station (U.S. Army Corps of Engineers, 1959). The relation for determining C is

$$C = C_t (h_s/a) \quad (49)$$

where h_s is the tailwater depth over gate sill in ft and C_t is defined by

$$C_t = k_1 (h_s/a)^{k_2} \quad (50)$$

in which

a. For $1.5 \leq h_s/a$, $k_1 = 0.90$ and $k_2 = - 1.11$.

b. For $1.0 \leq h_s/a < 1.5$, $k_1 = 1.50$ and $k_2 = -2.39$.

c. For $1.0 > h_s/a$, $k_1 = 1.50$ and $k_2 = 0$.

It was desired to reproduce the flow characteristics and geomorphic changes of the study reach from 1939 to 1971. Three 1939 to 1971 flow discharge hydrographs were used as upstream boundary conditions for the modeled reaches of the Mississippi, Illinois, and Missouri Rivers. They are the discharge hydrograph synthesized by adding flow discharges data at Keokuk, Iowa, on the Mississippi River and at Keosauqua, Iowa, on the Des Moines River; the discharge hydrograph recorded at Meredosia, Illinois, in the Illinois River; and the discharge hydrograph recorded at Hermann, Missouri, on the Missouri River. The corresponding sediment discharges delivered to the study reach were assumed equal to the sediment transport capacities of the upstream boundary channel sections calculated from Eq. 45.

When these discharge hydrographs were routed through the modeled river reach, the flow discharge, velocity, water surface and riverbed elevations, sediment discharge, bankfull cross-sectional area, open height of gates, and deposition on the floodplain at each section were calculated for each time step. The size of the time step varied from one to five days depending on the rate of change in flow discharge. A larger time step was used when the rate of change was small.

The calculated flow discharges, water surface and riverbed elevations, and bankfull cross-sectional areas were compared with measured data. Calibration continued through a large number of trials. Extensive efforts were made to modify the Manning roughness coefficients and the empirical coefficients in the sediment transport equation at each channel section until the known historical changes were reproduced.

The calculated 1965 and 1967 water surface profiles are compared with the measured stages in Figs. B5 through B8. These figures show an agreement between the measured and calculated values. In Tables B3 and B4 the calculated changes in bankfull cross-sectional areas and in average riverbed elevation (average of the riverbed elevations in the deepest 1000-ft width of river channel) between 1939 and 1971 are compared with the measured changes. Data in Table B3 shows an agreement between the measured and calculated changes in bankfull cross-sectional areas except in the lower part of Pool 25. The results in Table B4 are less satisfactory than the results in Table B3. The difference is due primarily to the assumption of a uniform distribution of sediment over the channel width. A better agreement could be obtained if a sediment distribution function were developed. Since the calculated trend agrees with the measured value and since the amount of sediment deposition on the floodplain from 1939 to 1971 appears reasonable, it was concluded that the mathematical model as calibrated was as good as the available field information, and could be employed to study the river's response to future development.

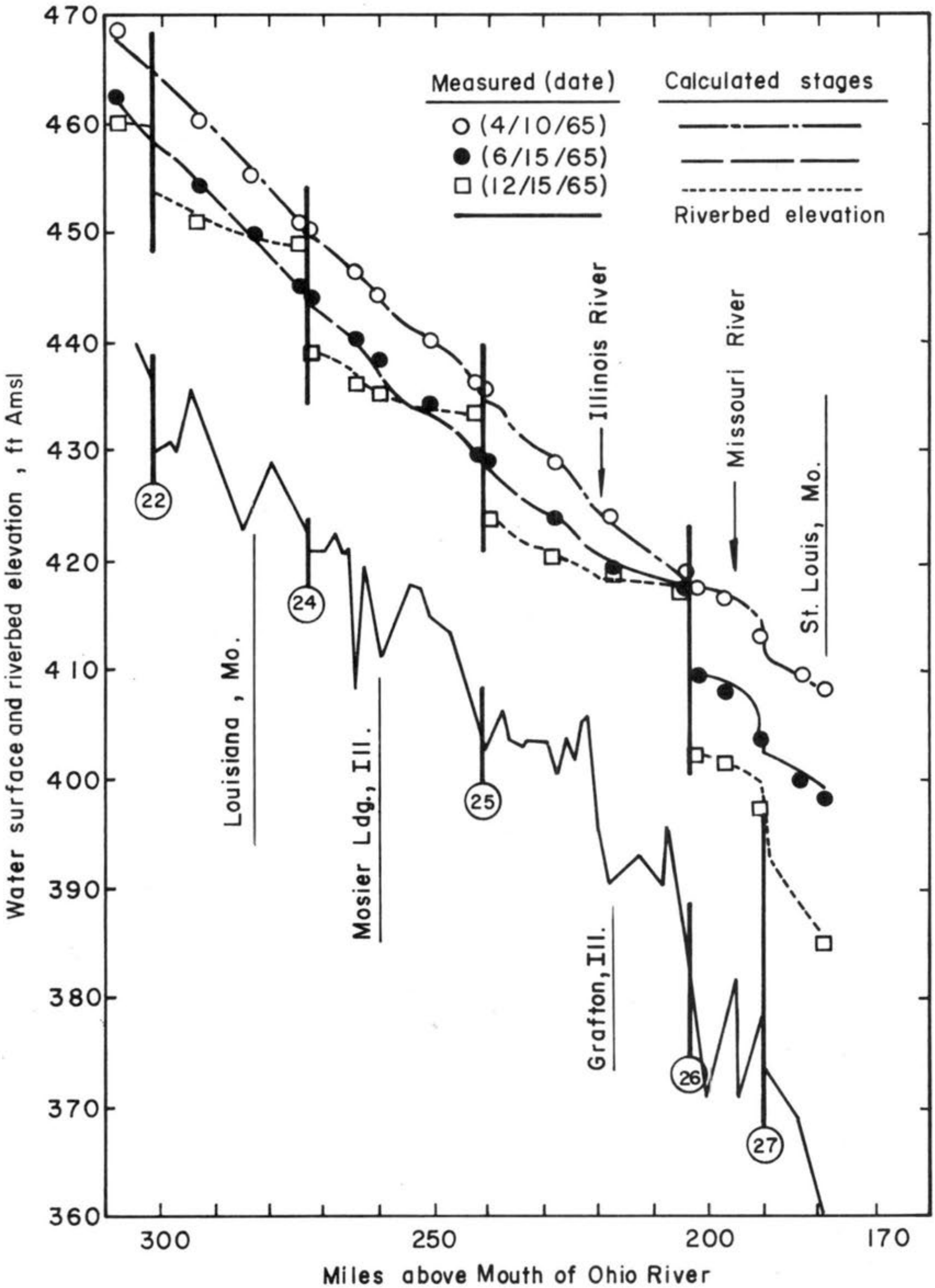


Figure B5. Mathematical model reproduction of 1965 water surface profile in the Upper Mississippi River

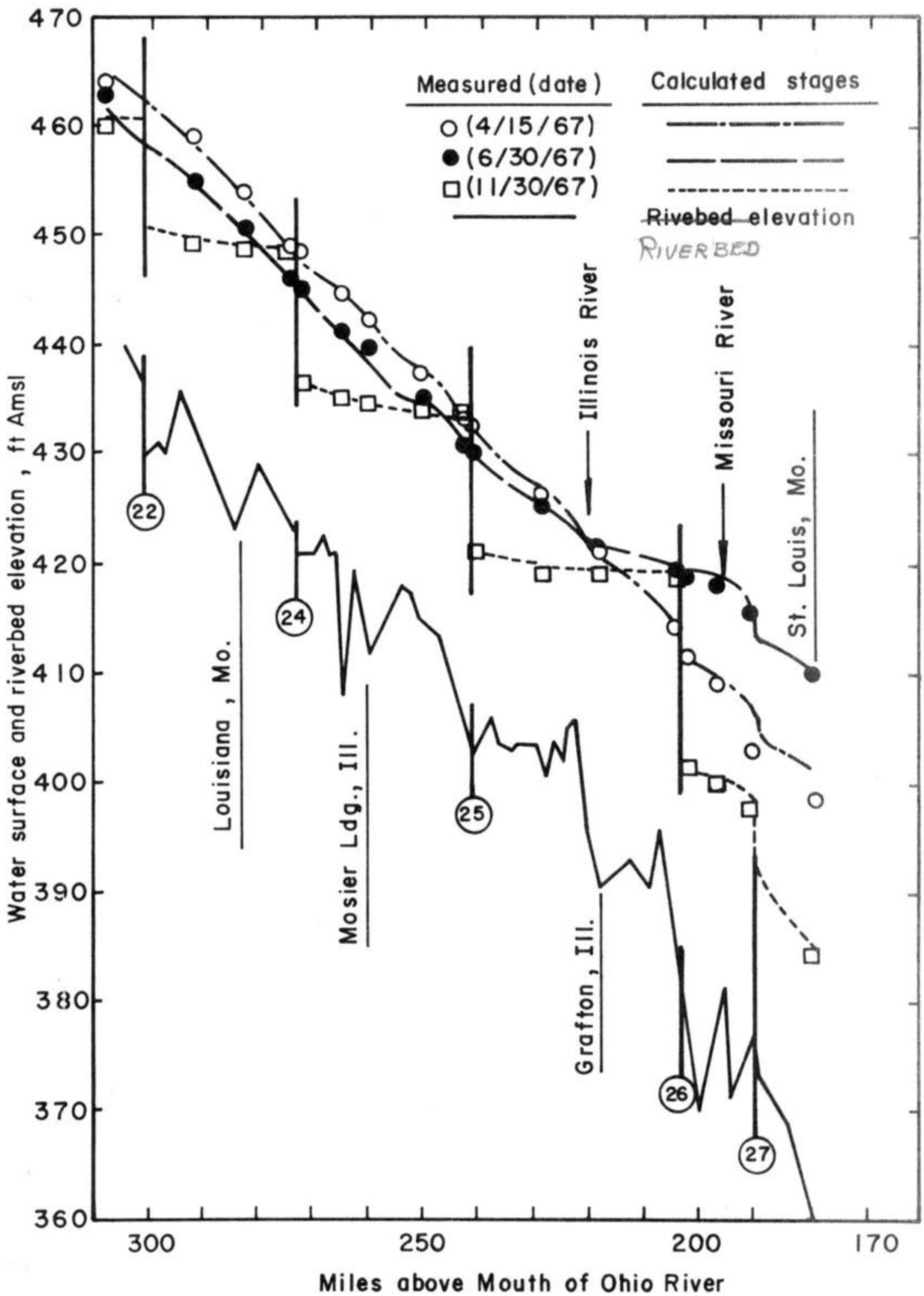


Figure B6. Mathematical model reproduction of 1967 water surface profile in the Upper Mississippi River

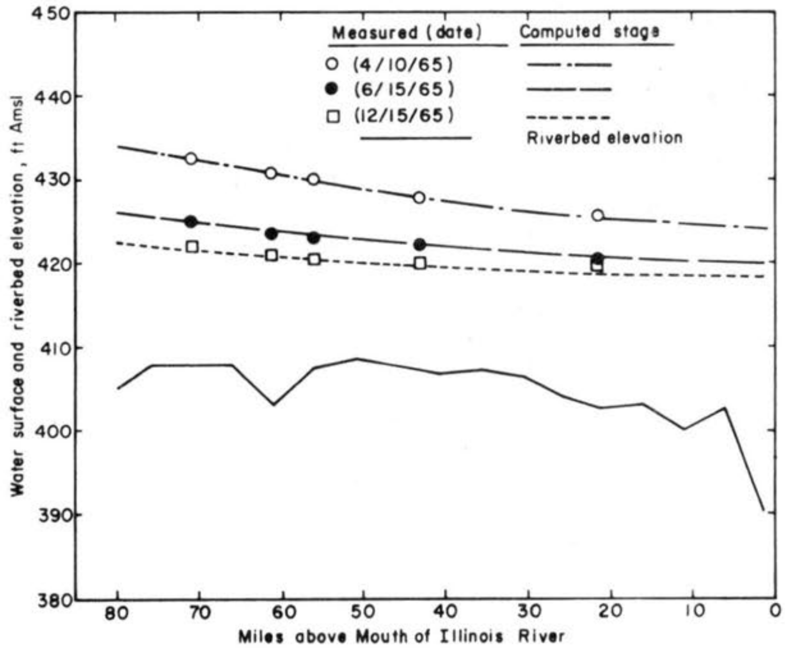


Figure B7. Mathematical model reproduction of 1965 water surface profile in the Lower Illinois River

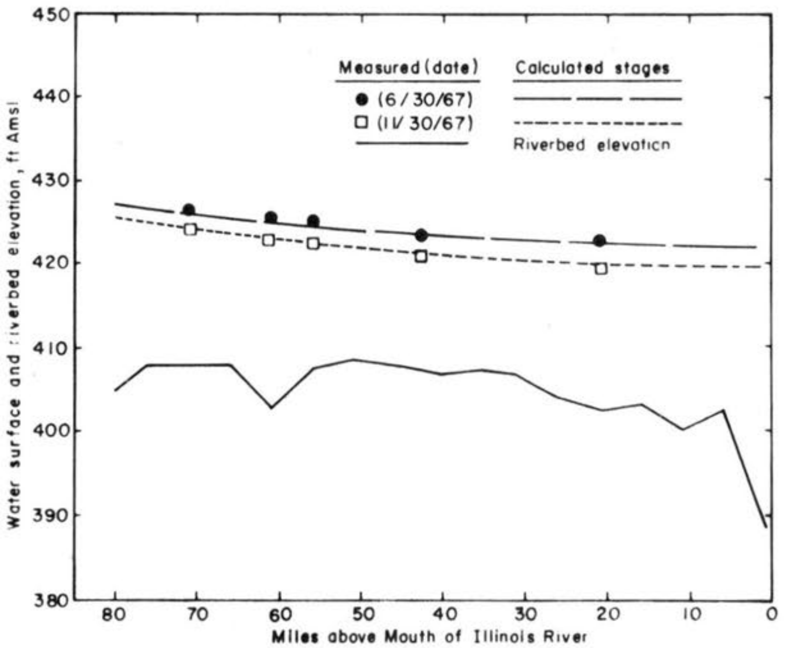


Figure B8. Mathematical model reproduction of 1967 water surface profile in the Lower Illinois River

Table B3

Change in Bankfull Cross-Sectional Area
in the Mississippi River from 1939 to 1971

Location	Bankfull Cross-sectional Area,* 100 ft^2		
	1939	Measured Change	Calculated Change
Pool 26:			
Below Illinois River	783	-44	-50
Middle third	546	-45	-25
Next eighth	521	-36	-33
Upper eighth	459	+34	+60
Pool 25:			
Lower quarter	500	-12	+11
Lower middle quarter	494	- 4	+20
Upper middle quarter	459	+20	+40
Next eighth	565	-68	-71
Upper eighth	470	+40	+31
Pool 24:			
Lower quarter	528	-85	-88
Lower middle quarter	425	-32	-30
Upper middle quarter	399	-25	-19
Upper quarter	396	-19	- 6

*Cross-sectional area at bankfull stage.

Table B4

Change in Average Riverbed Elevations
in the Mississippi River from 1939 to 1971

Location	Average Riverbed Elevation,* ft Amsl		
	1939	Measured Change	Calculated Change
Pool 26:			
Below Illinois River	390.2	-0.4	-0.9
Middle third	400.7	+0.1	+0.7
Upper quarter	405.7	-3.3	-0.9
Pool 25:			
Lower quarter	410.9	-2.7	-1.7
Middle half	414.5	+0.9	-1.0
Upper quarter	421.5	-2.5	-0.2
Pool 24:			
Lower quarter	424.7	+2.7	+2.9
Middle half	427.2	+2.0	+0.6
Upper quarter	430.8	+1.9	-0.4

*Average of the riverbed elevations in the deepest 1000-ft width of river channel.

PART V: OPERATION OF THE MATHEMATICAL MODEL

General Model Operation

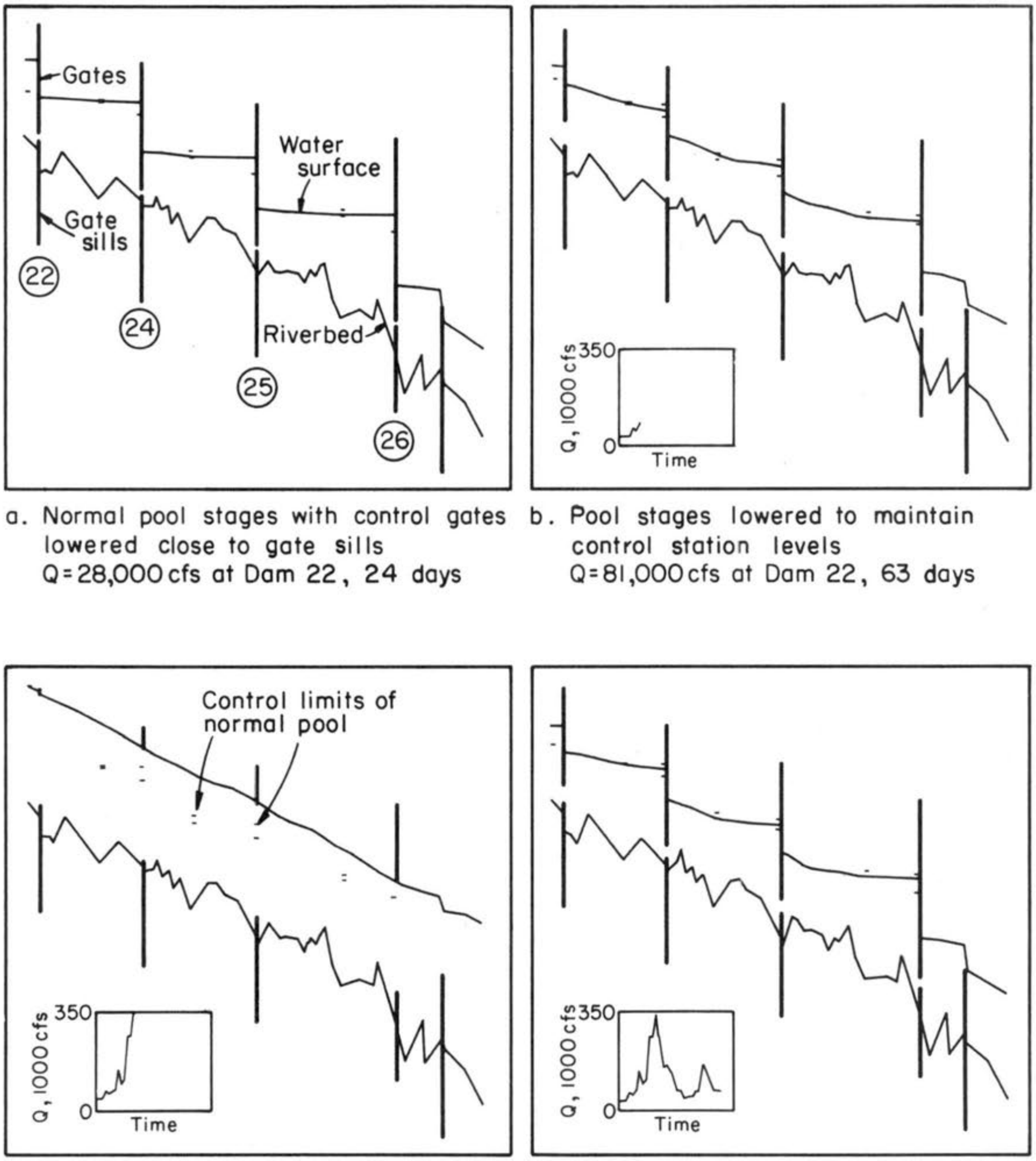
The calibrated mathematical model can be employed to assess the impacts of factors considered in this study. Typical results of routing a one-year hydrograph through the modeled river reach are given in Figs. B9, B10, and B11. The water-surface profile in the Upper Mississippi River for Q = 28,000 cfs at 24 days is shown in Fig. B9. To maintain the normal pool levels, the control gates are lowered close to the gate sills. As the inflow increases, the pool stage is lowered at the dam by gradually opening the gates to maintain the level at the control stations within the prescribed control limits (Table B2) as shown in Fig. B9. As inflow continues to increase, the gates are opened further to increase the outflow until the gates are then partially lowered into the water as required to restore the pool as shown in Fig. B9.

During the same flood routing, the water surface profiles in the Lower Illinois River were determined and some results are shown in Fig. B10. The dashed line in Fig. B10 depicts the water-surface profile without the backwater effect from Pool 26. Because of the regulation of Pool 26, the stage in the Illinois River near the confluence is raised, reducing the flow velocity and causing changes in river morphology.

Some changes in riverbed elevation in the Upper Mississippi River during the same flood routing are shown in Fig. B11. The difference between the solid and the dashed line indicates the changes in the riverbed elevation. It can be seen that the river bed does not continuously aggrade or degrade but fluctuates with a trend of aggradation or degradation.

Mathematical Model Prediction

What will Pools 24, 25, and 26 in the Upper Mississippi and Lower Illinois River look like 50 years from now? The answer may be obtained from the operation of the calibrated mathematical model of the present river system. Five major 50-year flow simulations were conducted



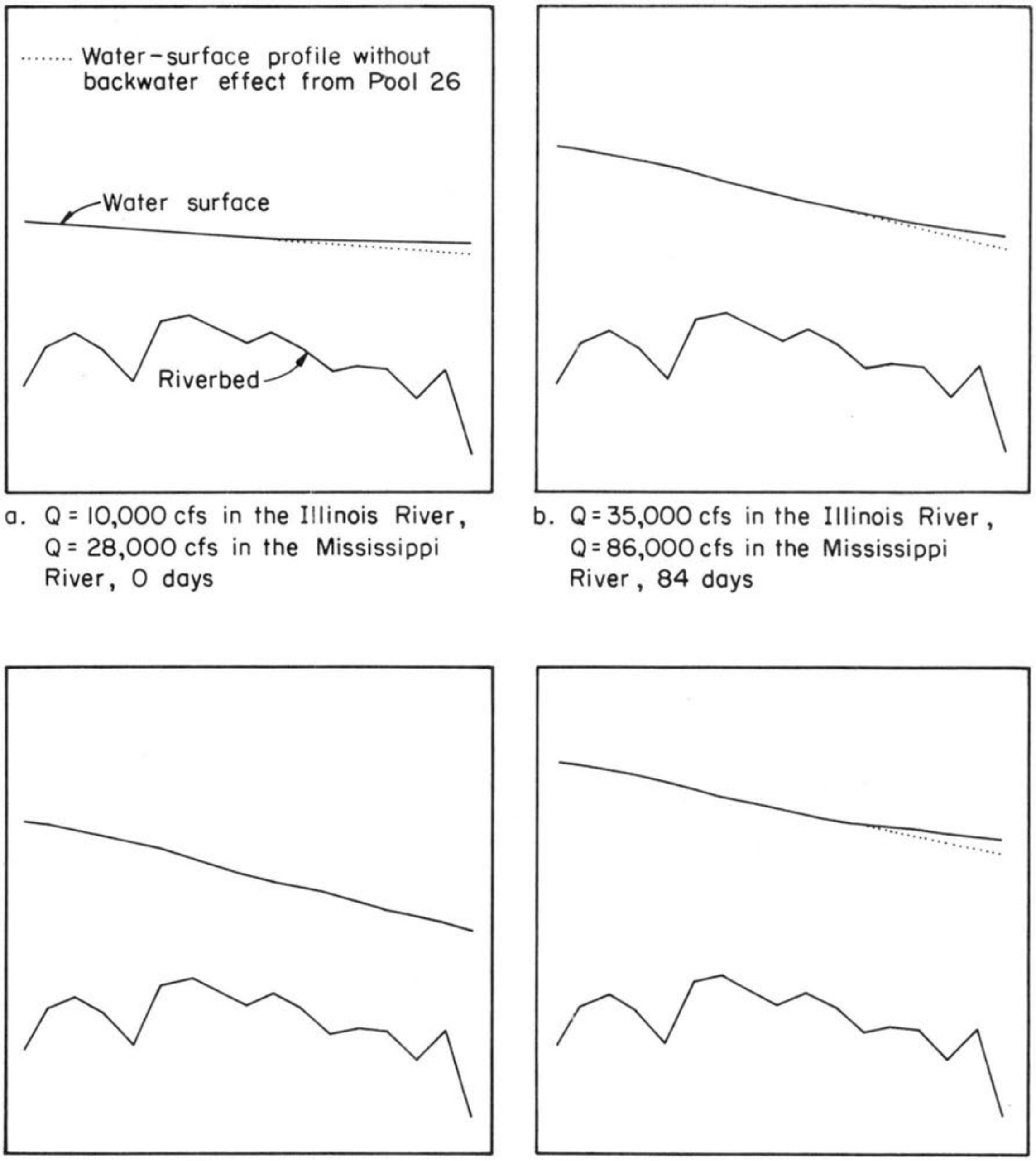
a. Normal pool stages with control gates lowered close to gate sills
Q=28,000 cfs at Dam 22, 24 days

b. Pool stages lowered to maintain control station levels
Q=81,000 cfs at Dam 22, 63 days

c. Gates entirely out of water at flood crest
Q=339,000 cfs at Dam 22, 117 days

d. Gates partially lowered to restore pools after flood recedes
Q=54,000 cfs at Dam 22, 324 days

Figure B9. Water surface profiles in the Upper Mississippi River during a flood routing



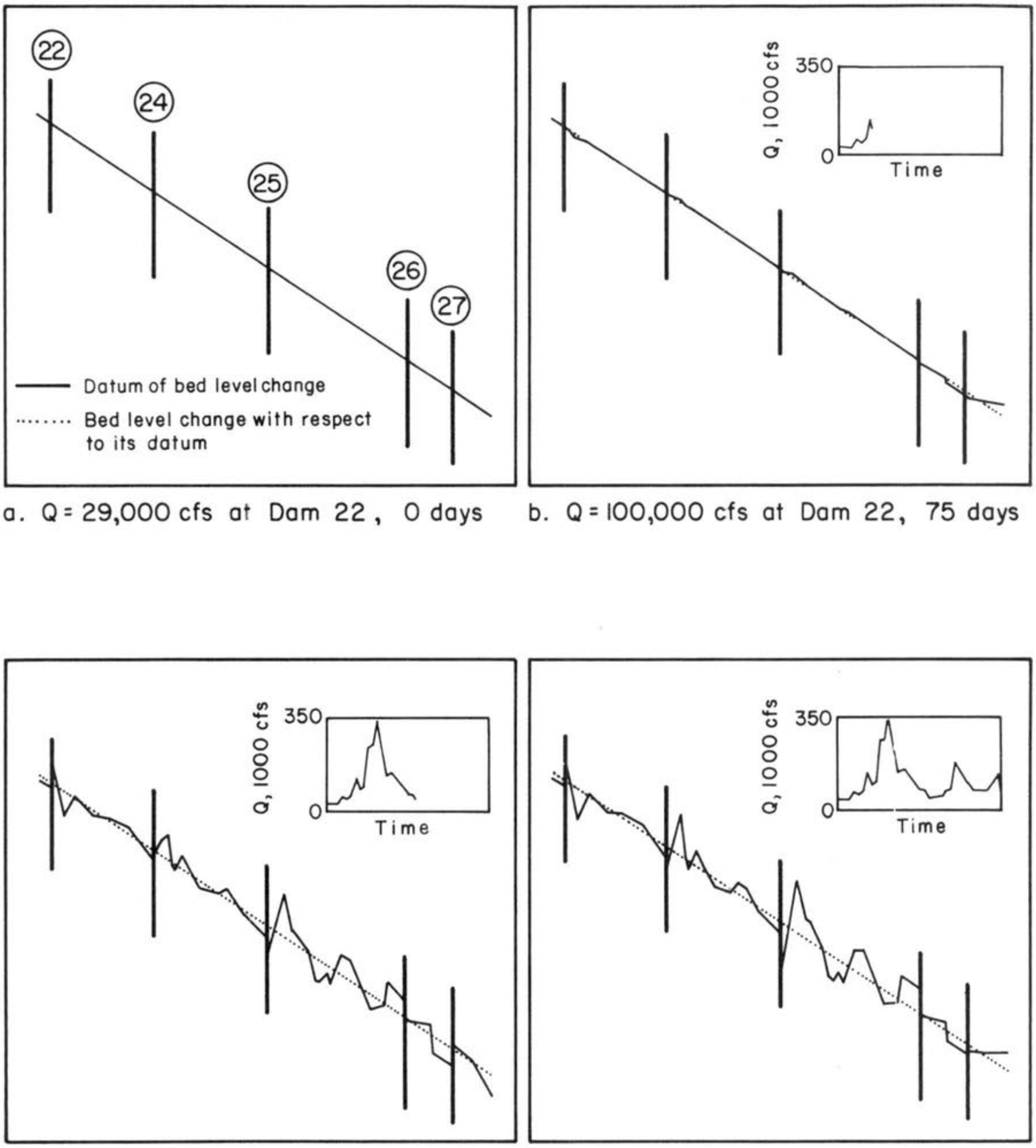
a. Q = 10,000 cfs in the Illinois River, Q = 28,000 cfs in the Mississippi River, 0 days

b. Q = 35,000 cfs in the Illinois River, Q = 86,000 cfs in the Mississippi River, 84 days

c. Q = 32,000 cfs in the Illinois River, Q = 96,000 cfs in the Mississippi River, 90 days

d. Q = 50,000 cfs in the Illinois River, Q = 299,000 cfs in the Mississippi River, 114 days

Figure B10. Water surface profiles in the Lower Illinois River during a flood routing



a. Q = 29,000 cfs at Dam 22, 0 days

b. Q = 100,000 cfs at Dam 22, 75 days

c. Q = 38,000 cfs at Dam 22, 207 days

d. Q = 51,000 cfs at Dam 22, 365 days

Figure B11. Bed elevation changes in the Upper Mississippi River during a flood routing using the mathematical model. An identical series of input flow rates was used for each simulation. This input series was developed from the peak discharges and flow volume frequency curves for the period 1932 to 1973 as follows:

1. The peak discharge and the flow volume frequency curves for the Mississippi River at Keokuk, the Illinois River at Meredosia, and the Missouri River at Hermann were constructed from the 1932 to 1973 flow data and are shown in Figs. B12 and B13.
2. The peak discharges and the flow volumes for return periods of 1, 2, 5, 10, and 50 years were determined from Figs. B12 and B13.
3. After examining the 1932 to 1973 flow data, the yearly flow having both the peak discharge and the flow volume closest to those determined from the frequency curves was selected to be the typical hydrograph for the specific return period. The yearly flows obtained are given in Table B5.

Table B5

Typical Hydrographs

Return Period in years	Terminology used	Year Duration Curve		
		Keokuk	Meredosia	Hermann
1	1-yr annual hydrograph	1958	1940	1931
2	2-yr annual hydrograph	1950	1965	1932
5	3-yr annual hydrograph	1962	1951	1970
10	10-yr annual hydrograph	1969	1970	1945
50	50-yr annual hydrograph	1973	1973	1951

4. The typical 1, 2, 5, 10, and 50-year floods were combined in random sequence into a 50-year series of flows. The resulting 50-year series contained one 50-year, five 10-year, ten 5-year, fourteen 2-year, and twenty 1-year floods. The input series of flow to Dam 22 was assumed equal to the sum of flow at Keokuk and at Keosauqua.

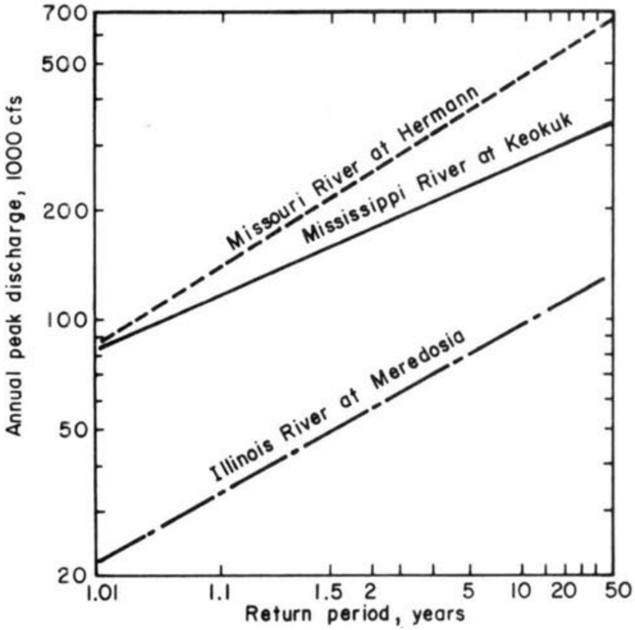


Figure B12. Peak discharge frequency curve

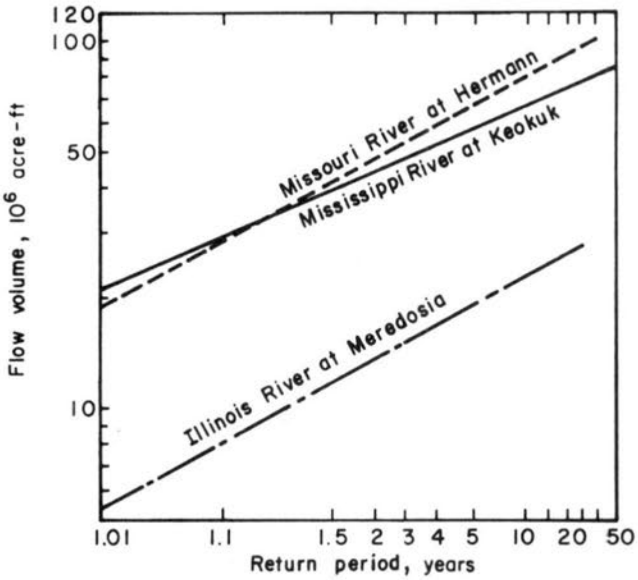


Figure B13. Flow volume frequency curve

From the study of the historical records of river flows, it was concluded that these flow series were adequate to represent the future river flow in the next 50 years.

The five major 50-year simulations conducted to assess future geomorphic changes were:

(1) present scheme of operation,

(2) holding the pool level 1 ft above the normal pool,

(3) holding the pool level 1 ft below the normal pool,

(4) zero sediment inflow into Pool 24, and,

(5) maximum sediment inflow into Pool 24.

Simulations (1) through (3) were conducted to assess the effects of different operational schemes for the locks and dams on the geomorphology of the study reach in the next 50 years. The effects of other alternative operational schemes can be determined in a similar way. Simulations (4) and (5) were performed to estimate the effects caused by the upper and lower limits of changes in the delivery of sediment to the study reach. From these two simulations and Simulation (1), the impact of changes in the delivery of sediment to the study reach on the morphology of rivers and adjacent lands in next 50 years were assessed. The effects of the pools on the behavior and form of the Illinois River were also estimated during the simulations.

Simulation (1) was performed by simply routing the 50-year series of flow through the model. To conduct the latter four simulations, some minor modifications of the control statements of the mathematical model were made. For Simulations (2) and (3), the control limits of the pool levels are raised 1 foot and lowered 1 foot, respectively. For Simulation (4), the sediment discharge entering Pool 24 was set to be zero. For Simulation (5), the gates at Dam 22 were raised entirely out of water at all times. The results of model predictions are presented in the text. A longer prediction period of the future geomorphic changes in the study reach may be assessed from the operation of the mathematical model, provided that the input flow discharge hydrographs are adequately synthesized.

Dredging

The mathematical model can be employed to study the effects of dredging on river morphology and hydraulics of the modeled river reach. Special attention has been given to the dredging problem in Pool 25. In this pool, one crossing which has required extensive dredging and the pool immediately downstream was identified and modeled by adding 18 more sections in the model between River Miles 269.0 and 265.0. This reduced the distance between neighboring sections to as small as 0.08 of a mile.

A dredge cut 3 ft deep and 950 ft long (from RM 268.91 to RM 268.72) was made in the crossing area over the channel width by assigning a suitable value to q_{s2}, the man-induced lateral sediment flow. The dredged material was disposed of in the downstream pool area (RM 268.46 to RM 268.28). This method of disposal is called the "thalweg disposal process." The cut was made at the beginning of the low-water season. The riverbed level changes in the modeled reach were computed during the next year for the 2-year annual hydrograph and are shown in Fig. B14.

The initial bed profile with dredge cut and disposal site is shown in Fig. B14. After a 129 day low-flow period, the bed level showed very small changes (Fig. B14). With the flood entering the river reach, the dredge cut was filled in rapidly and the bar at the disposal site was moved to the downstream crossing as shown in Fig. B14. After one year, both crossing and pool were back to the natural state. This phenomenon is illustrated more clearly in Fig. B15, which shows the changes in the riverbed elevation with time in the crossing and the pool areas. At one year after dredging, the bed changes are approximately equal to those without dredging. This result is supported by field experience and explains why many reaches require repeated dredging.

In general the river is not affected by disposal of dredged material within a year, except in the reach close to the disposal site (Fig. B16). If the dredged material were disposed on the adjacent floodplain or half on the floodplain and half in the downstream pool area, different bed configurations neighboring the dredge cut and disposal site would have resulted. When all the dredged material

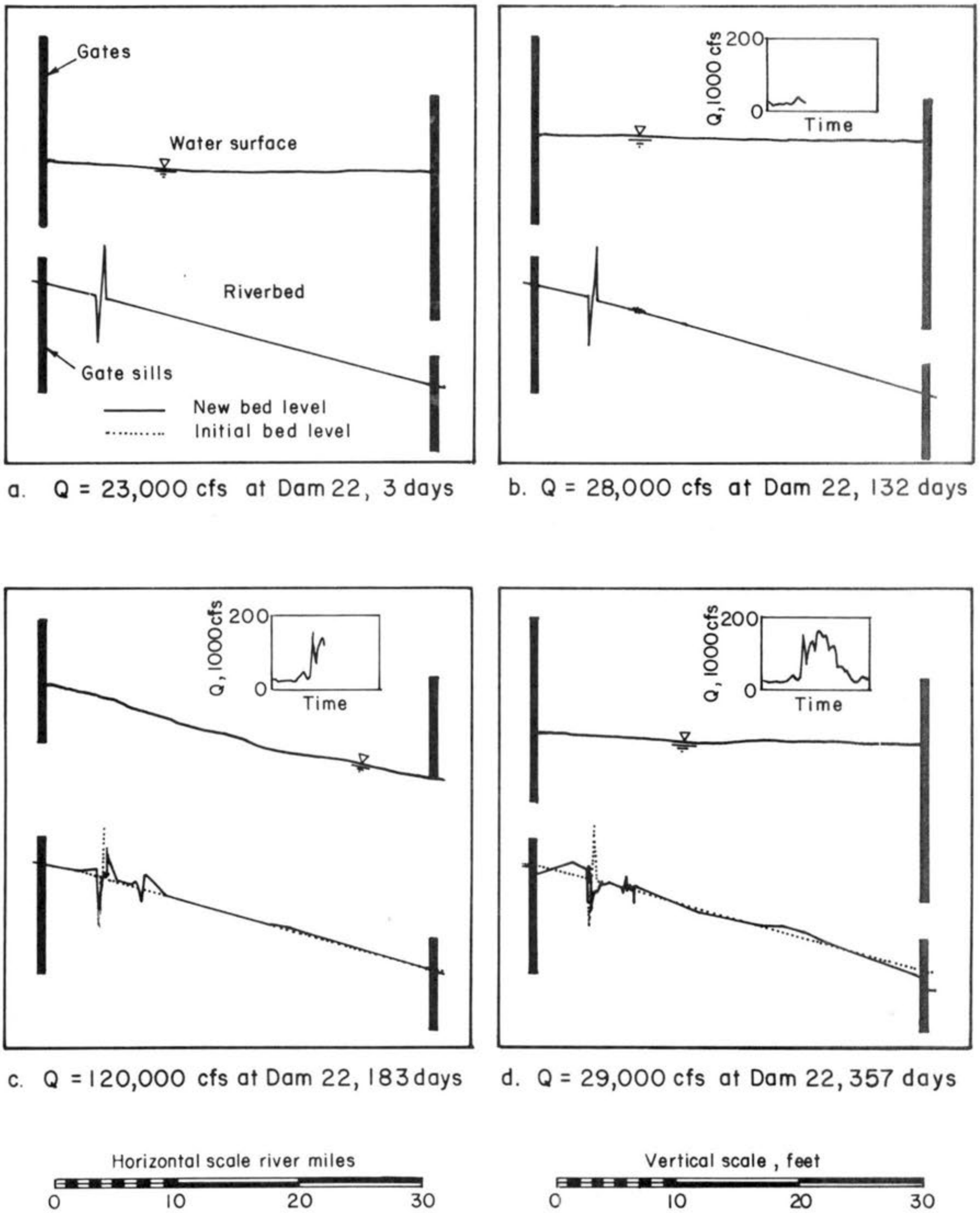


Figure B14. Riverbed level changes during the year after dredging and disposing

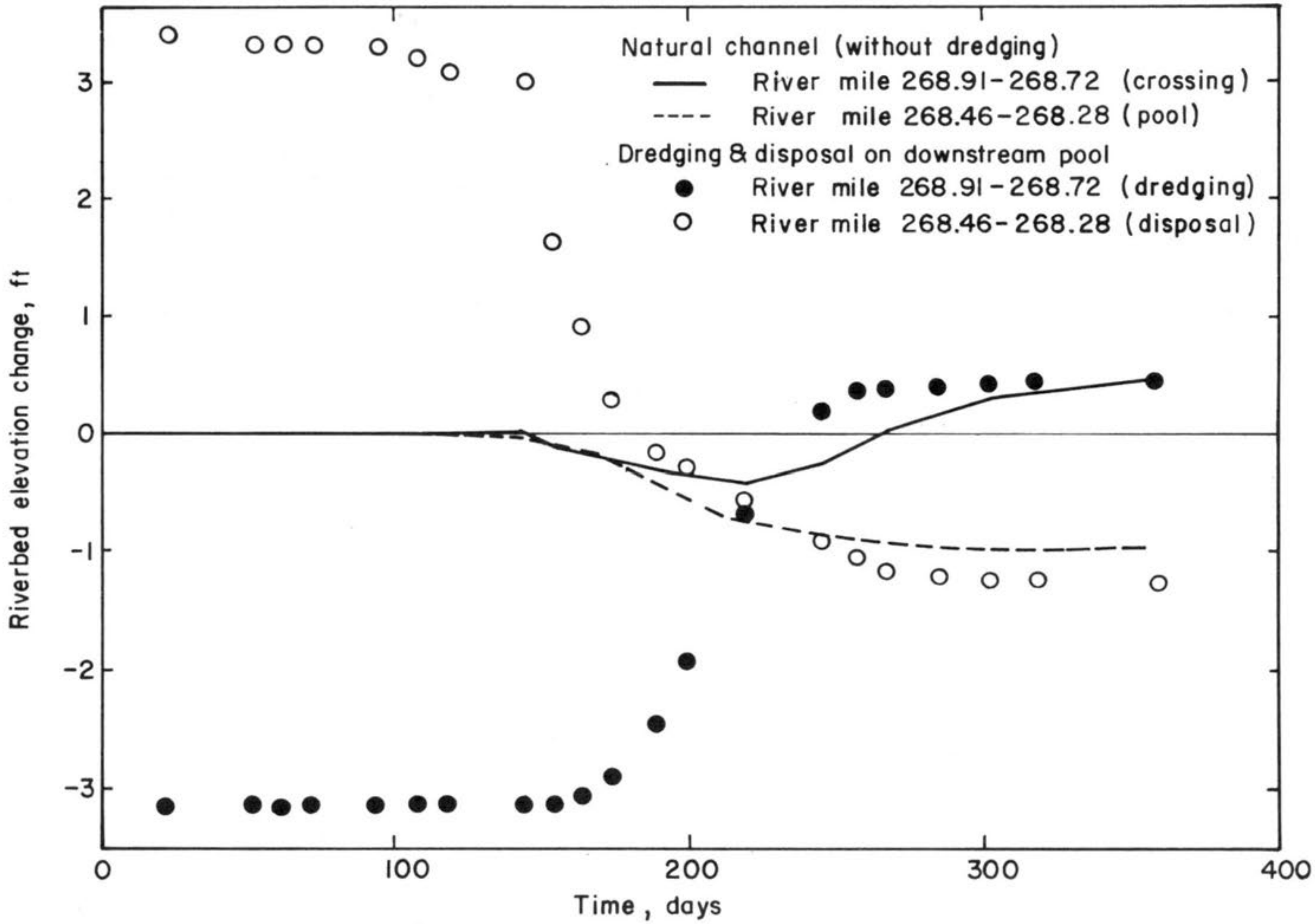


Figure B15. Average riverbed elevation changes with time in a crossing and its downstream pool area (2-year annual hydrograph)

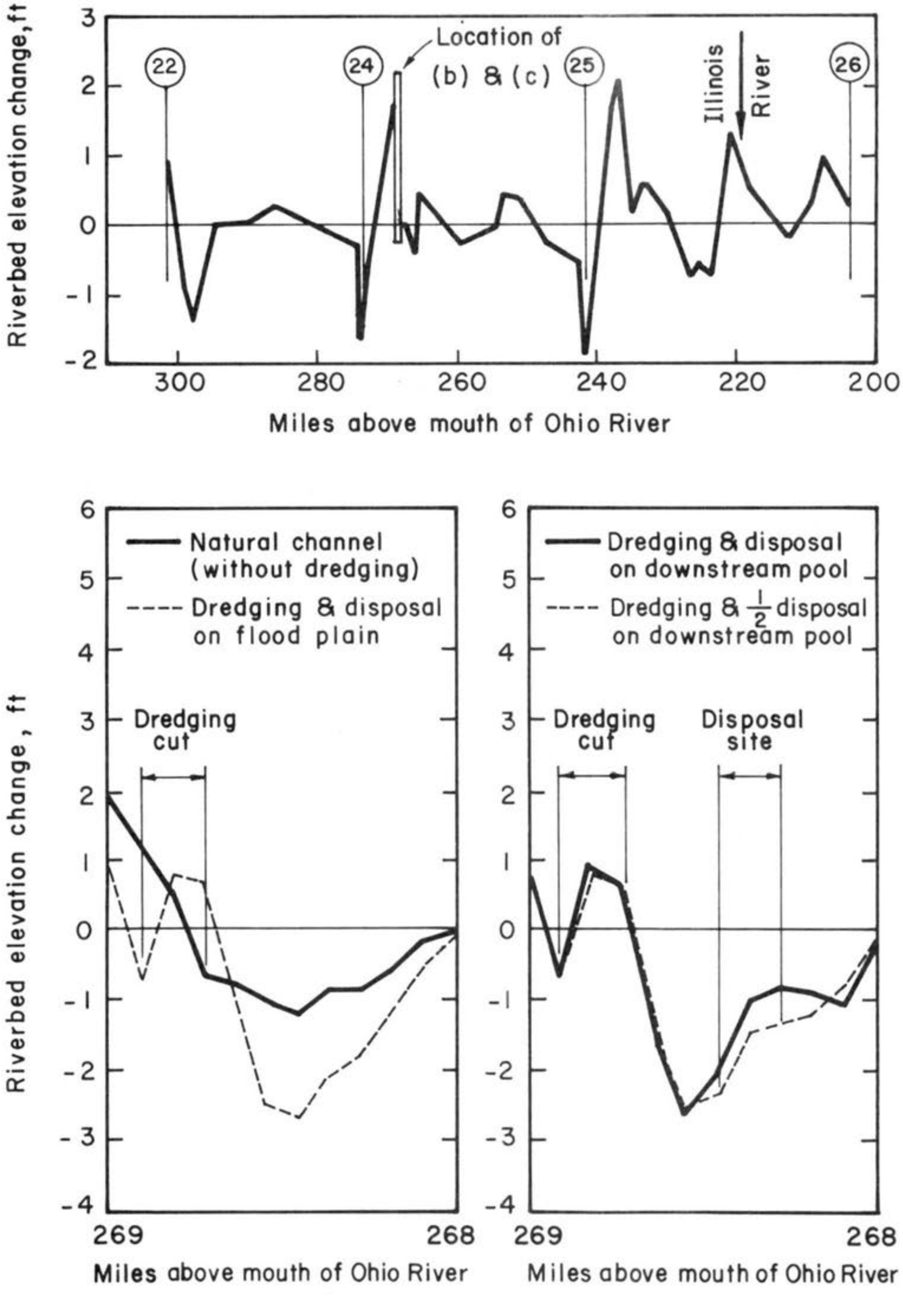


Figure B16. Average riverbed elevation changes one year after dredging and/or disposing, or without dredging (2-year annual hydrograph) was placed on the floodplain, the downstream pool during the following year deepened much more than if no dredging had been done (Fig. B16b). Disposing of half the dredged material in the downstream pool reduced the deepening of the pool area (Fig. B16c).

If the next annual hydrograph following the dredging was small, for example, 1-year annual hydrograph, the dredge cut would have remained essentially unchanged as shown in Figs. B17b and c. However, when the dredged material was disposed in the downstream pool area, this disposed sandbar was moved downstream to deposit on the next crossing and resulted in a 2-1/2 ft additional deposition than without thalweg disposal, causing inadequate water depths on the crossing. The height of deposition would have been reduced by 1 ft when only half of the dredged material was disposed in the downstream pool (Fig. B17c).

The model was also subjected to an annual hydrograph with a larger flow volume and a higher peak than the 2-year hydrograph to evaluate the impact of large floods on the thalweg disposal process. The 1973 flood hydrograph was used. Neither the dredged cut on the crossing nor the disposal bar in the pool persisted for long under the high sediment transport conditions of a flood of this magnitude. After 100 days into the hydrograph the bed elevation change closely approximated those expected under natural river conditions with no dredging.

The mathematical model study of the particularly troublesome reach of Pool 25 on the Upper Mississippi indicates that dredging from a crossing and disposing the dredged material in a downstream pool does constitute a feasible dredge disposal method. The process involves a degree of risk to the navigation channel downstream from the pool, particularly if dredging is followed by a small discharge hydrograph. However, at many locations the risks incurred by thalweg disposal would be outweighed by the potential environmental benefits of avoiding bankline disposal. Although conditions downstream of a proposed disposal site may preclude thalweg disposal at certain locations, in many cases disposing only a portion of the dredged material along the thalweg would still result in reduced environmental impacts. Consequently, the concept of thalweg disposal offers a viable alternative to both long-term and emergency disposal requirements.

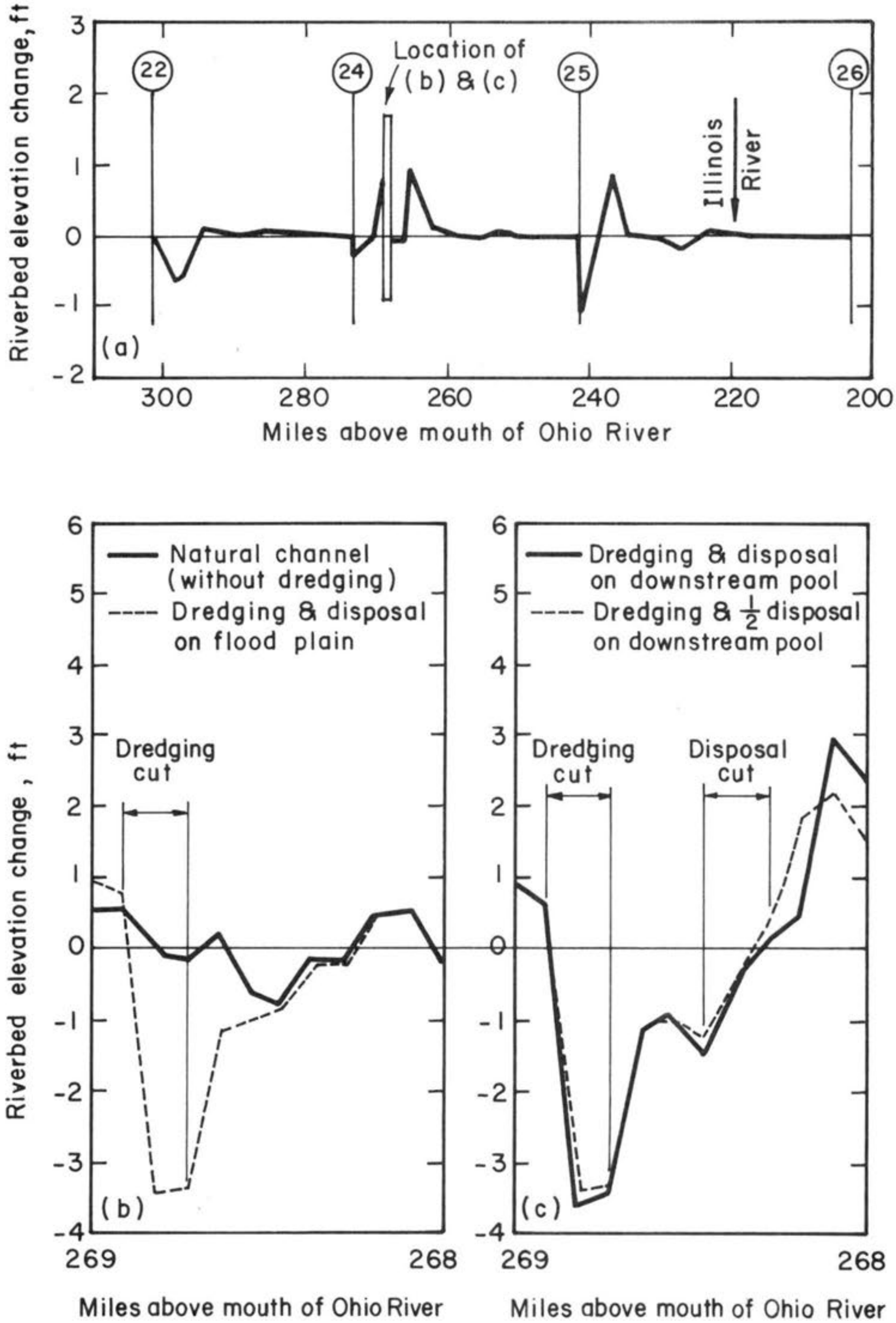


Figure B17. Average riverbed elevation changes one year after dredging and/or disposing, or without dredging (1-year annual hydrograph)

The results of this limited study are sufficiently promising to warrant additional investigation of the concept of thalweg disposal of dredged material.

PART VI: LIMITATION OF THE MATHEMATICAL MODEL

The mathematical model used in this study was one-dimensional. The model was effective in studying the short-term and long-term river responses to development in a long river reach. With the aid of two- or three-dimensional theories of sediment and velocity distributions and the concepts of lateral flows, the mathematical model can be employed to assess the impacts of the factors considered in this study. However, since the space increments were chosen to be relatively large to operate the mathematical model efficiently and since sediment was assumed to be uniformly distributed over the channel width, only the general pattern of the river geomorphology is considered in this study. To study a particular reach of river in detail, either the reach may be subdivided into a large number of segments to apply the mathematical model (e.g., study of the dredging problem) or a combination of the physical model and the mathematical model might be used.

Since there was no width predictor included in the mathematical model, the changes in channel width with time should be accepted as a known quantity or should be evaluated using qualitative geomorphic concepts.

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Colorado. State University, Fort Collins.
Environmental inventory and assessment of Navigation Pools 24, 25, and 26, Upper Mississippi and Lower Illinois Rivers; a geomorphic study, by D. B. Simons, S. A. Schumm, M. A. Stevens, Y. H. Chen [and] P. F. Lagasse. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Contract report Y-75-3)
Prepared for U. S. Army Engineer District, St. Louis, St. Louis, Missouri, under Contract No. DACW39-74-C-0148.
Includes bibliography.
1. Channel improvements. 2. Channel stabilization. 3. Geomorphology. 4. Illinois River. 5. Locks and Dams. 6. Mathematical model. 7. Mississippi River. 8. Navigation. I. Simons, D. B. II. Schumm, S. A., joint author. III. Stevens, M. A., joint author. IV. Chen, Y. H., joint author. V. Lagasse, P. F., joint author. VI. U. S. Army Engineer District, St. Louis. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Contract report Y-75-3)
TA7.W34c no.Y-75-3