Hydrobiologia 136, 5–20 (1986).

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Hydrology, hydraulics, and geomorphology of the Upper Mississippi River System

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Keywords: Upper Mississippi River, hydrology, hydraulics, geomorphology, sediment transport, dredging

Abstract

The Upper Mississippi River system has been modified with locks, dams, dikes, bank revetments, channel modifications, and dredging to provide a nine-foot navigation channel. These activities have changed the river's characteristics. The historical changes in the hydrologic, hydraulic, and geomorphic characteristics were assessed and related to navigational development and maintenance activities in the Upper Mississippi River system. The hydrologic, hydraulic, and geomorphic features studied include river discharges, stages, sediment transport, river position, river surface area, island surface area, and river bed elevation. Water and sediment transport effects on dredging were also estimated. It was found that the general position of the Upper Mississippi River system has remained essentially unchanged in the last 150 years except for specific man-made developments in the river basin. The stage, velocity, sediment transport, and river and island areas were altered by development of the 2.75-m navigation system. Dredging requirements are strongly related to mean annual water discharge. Years in which water discharges were great were generally the years during which large volumes of sediment needed to be dredged from the channel. The backwater areas are experiencing some deposition. With implementation of erosion-control measures in major tributaries and upland areas, better confinement of disposed dredged materials, and better maintenance practices, the sedimentation and pertinent problems in the main channel, as well as in the backwater areas, may be reduced with time.

Introduction

The Upper Mississippi River system extends from the Mississippi River headwater to its confluence with the Ohio River at Cairo, Illinois, a length of about 1 370 m (850 miles). The reach downstream of the mouth of the Missouri River is quite often called the Middle Mississippi, while the reach above the Missouri River is called the Upper Mississippi River.

This river system has undergone development for navigation for more than 150 years. At present, the Upper Mississippi River from St. Paul, Minnesota, to Alton, Illinois, is controlled by 27 locks and dams to maintain a 2.75-m (9-ft) navigation channel, supplemented by dikes, closing dams, and periodic dredging at various locations. The Middle Mississippi River is free-flowing; however, it has also undergone extensive improvement for navigation purposes.

Man's activities have affected the Upper and Middle Mississippi River in different ways. The historical changes in the hydrologic, hydraulic, and geomorphic characteristics were assessed and related to navigational development and maintenance activities. The results are presented in this paper, along with a comparison of the changes between the Upper and Middle Mississippi River segments.

Geomorphology of the Upper Mississippi River

Development of the Upper Mississippi River

For more than 150 years, the Upper Mississippi River (Fig. 1) has been continuously developed for navigation purposes. As early as 1824, the federal government initiated navigational improvements on the Upper Mississippi River. The work consisted of removing snags, shoals, and sandbars, excavating rock to eliminate rapids, and closing off sloughs to confine flows to the main channel. These activities helped create adequate depths for navigation during periods of low-water flow.

The first comprehensive improvement of the river for navigation was authorized by the River and Harbor Act of June 18, 1878, to develop a 1.37-m (4.5-ft) channel from St. Paul, Minnesota, to the mouth of the Missouri River. The 1.37-m channel was maintained by dams constructed at the river's headwaters, bank revetments, closing dams, and longitudinal dikes. These dikes were built of rock, brush, and sand, and their crests stood 1.83-m (6-ft) above the 1864 low-water level. By 1907, the 1.37-m channel had been achieved.

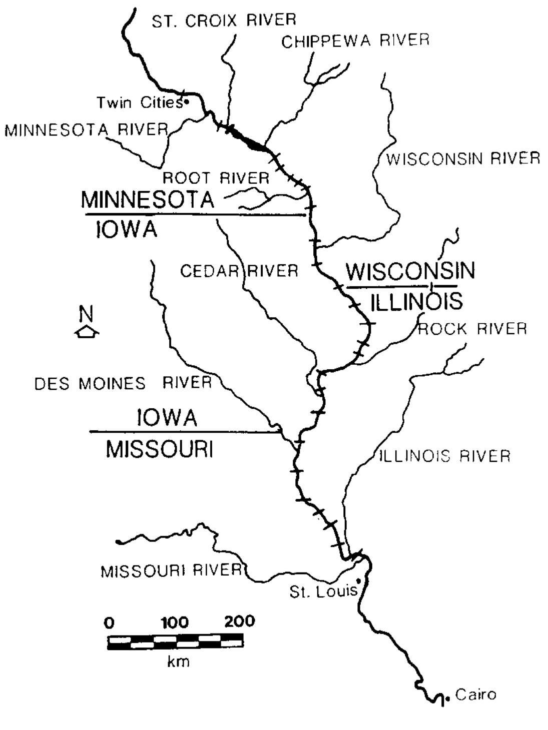


Fig. 1. Upper Mississippi River basin showing major tributaries and locations of the locks and dams (——).

In 1907, a 1.83-m (6-ft) channel was authorized by the River and Harbor Act of March 21, 1907. The additional depth was attained primarily by the construction of rock and brush dikes and the extension of existing dams. Low dikes extended radially from the shore into the river to constrict low-water flows. Dike construction was extensive in the Upper Mississippi River. For example, between 1878 and 1930, 143 dikes, with a total length of more than 29 km (18 miles), were constructed in the 16.9-km (10.5-mile) reach of Pool 4.

In 1930, when the 1.83-m (6-ft) navigation channel was 82 percent complete, a 2.75-m (9-ft) channel was authorized by the River and Harbor Act of July 3, 1930. The 2.75-m navigation-channel project was based on the concept of complete flow regulation by a series of locks and dams. The project was completed in 1940, and with supplemental dredging, a 2.75-m navigation channel has been maintained from St. Paul to St. Louis. Locations of locks and dams are shown in Fig. 1.

The Upper Mississippi River has been altered by the effects of two very different types of river-control structures: dikes and lock and dams.

Effects of developments

Maps and photographs made by the U.S. Army Corps of Engineers (COE), U.S. Geological Survey (USGS), Soil Conservation Service (SCS), and state and county agencies provide a record of channel changes throughout the period of Man's influence on the river. The 1850's township plat, made by counties, is considered representative of river morphology prior to the 1.37-m channel project between 1878 and 1907. The 1890 and 1929 COE maps show the river morphology close to completion of the 1.37-m and 1.83-m channel projects, respectively. River characteristics after completion of the 2.75-m channel project are shown on the 1938 COE map and on aerial photographs taken in 1939 and 1973. The effects of navigation-channel development on river characteristics were evaluated for Pools 4 through 9 (Simons *et al.*, 1976; Simons & Chen, 1979) and Pools 24 through 26 (Simons *et al.*, 1975), based on data obtained from these maps and aerial photographs, and from stage and discharge data at selected USGS gaging stations. The results of anlysis were interpreted to assess the general effects of river development on the Upper Mississippi River. The geomorphic and hydraulic features studied include stages and discharges, river position, river surface area, island surface area, number of islands, river-bed surface area, surface widths, water depth, side channels, and river-bed elevations.

Response to construction of low dikes

The general impacts caused by construction of low dikes on the Upper Mississippi River geomorphology consisted of the following.

Discharges and stages. Examination of stage and discharge records collected by the USGS at Prescott, Wisconsin (Pool 3); Winona, Minnesota (Pool 6); McGregor, Iowa (Pool 10); Keokuk, Iowa (Pool 20); Hannibal, Missouri (Pool 22); and Alton, Illinois (Pool 26), indicates that low dikes did not significantly alter flood stages. Low dikes were unable to restrict high flows enough to increase stages, because the dikes were low compared to the high-water stage.

River position. The position of the Upper Mississippi River did not change appreciably after construction of low dikes. The attachment of some islands to the river bank caused only local changes. These attachments resulted from sediment deposition in dike fields. For example, Maple Island, a large island in Pool 25, gradually joined the Illinois flood plain between 1891 and 1929. By 1929, Island 29 in Pool 4 also became attached to the Minnesota flood plain (Fig. 2). The same situation occurred in many other pools in the Upper Mississippi River.

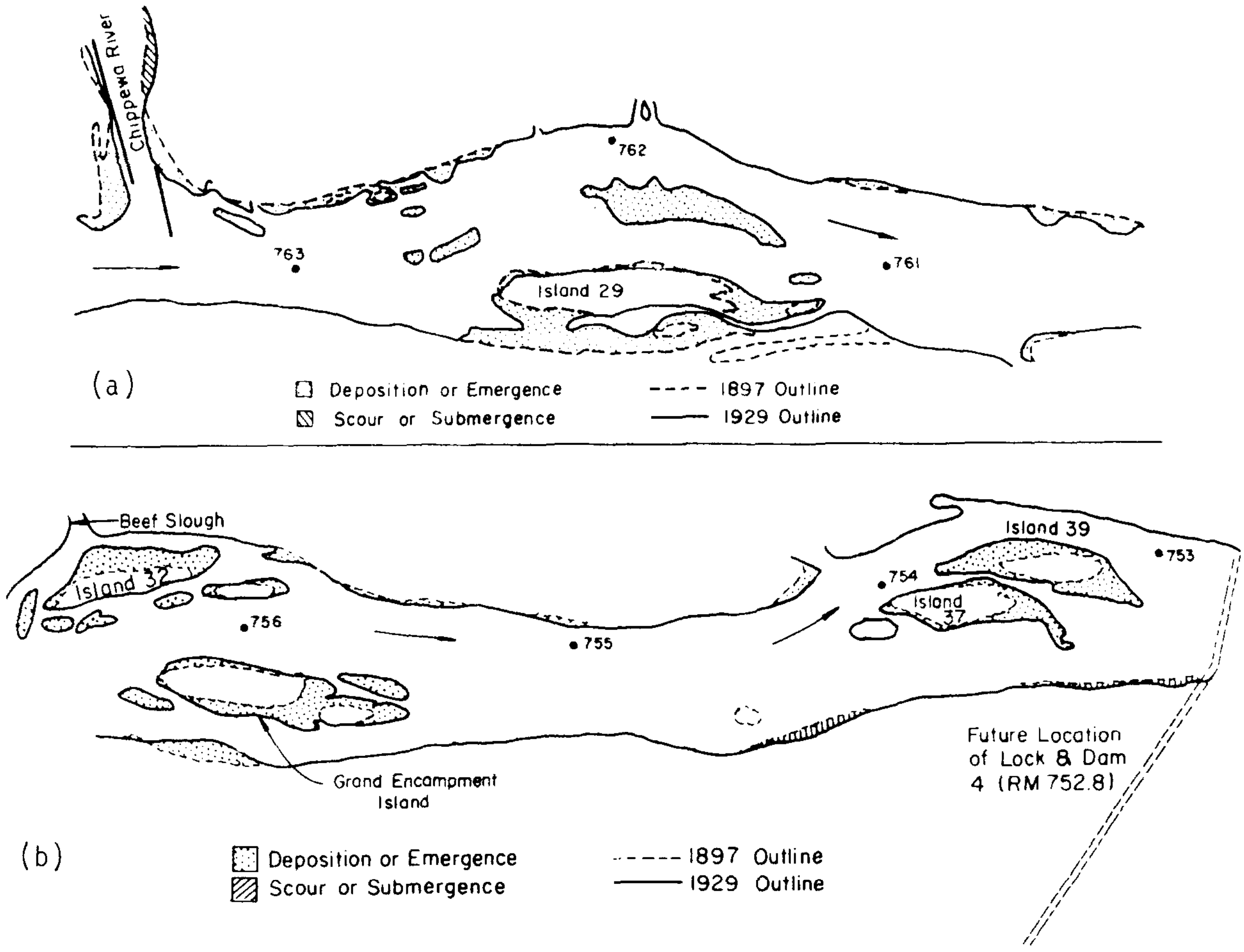


Fig. 2. Effect of dikes on river geometry in Pool 4 reach below Lake Pepin in Upper Mississippi River: (a) upper one-third; (b) lower one-third.

Surface areas. The following definitions of surface area were used in this study. The surface area of a river is the area between the river banks and includes the area of islands. The banks are defined as the location where the land-type vegetation ceases. The islands are defined as areas with land-type vegetation that lie within the channel banks and area separated from the mainland by water. The river-bed area is defined as the river surface area less the area of the islands.

After construction of dikes, the surface area of the Upper Mississippi River generally decreased, while the island area increased. These changes were primarily the result of sediment deposition in dike fields (e.g., Fig. 2). For example, the river surface area of Pool 4 below Lake Pepin decreased from 12.6 km^2 (4.86 square miles) in 1897 to 12.0 km^2 (4.65 square miles) in 1929. Surface areas of Pool 24 decreased from 57.5 km^2 (22.2 square miles) to 52.6 km^2 (20.3 square miles), a decrease of about 9 percent. During this same period, the island area in Pool 4 below Lake Pepin increase from 0.73 km^2 (0.28 square miles) to 1.27 km^2 (0.49 square miles), and in Pool 24 island area increased from 12.8 km^2 (4.93 square miles) to 13.7 km^2 (5.27 square miles). Increase in island area was due to the enlargement of some existing islands, as well as the formulation of new islands. The number of islands increased from 17 to 23 in Pool 4 below Lake Pepin and from 50 to 65 in Pool 25. The increased island area resulted in a reduction of river-bed area from 11.87 km^2 (1897) to 10.73 km^2 (1929) in Pool 4 and from 44.7 km^2 to 38.9 km^2 in Pool 25, thereby constricting the river channel and increasing the low-flow depth of the navigation channel.

Surface width. The river surface width is the distance between the vegetated banks measured perpendicular to the direction of flow in the river. The surface widths have changed in the same manner as the river surface areas. In general, average surface width decreased by about 30 m (100 ft) to 90 m (300 ft) during the period of dike construction.

River-bed elevation. During the period of dike construction, the river-bed degraded about 0.5 m (1.6 ft) in major portions of the Pool 4 reach below Lake Pepin and in Pools 5 through 9. However, the river-bed in Pools 24, 25, and 26 aggraded slightly, approximately 0.2 m (0.8 ft) on an average. This aggregation could have resulted from seasonal floods. The low dike fields were mainly designed to constrict the low-flow channel. At high flow, these low dikes were under water without significantly reducing the area of flow. The dikes served as roughness elements that increase resistance to flow and enhance deposition. The dike fields encourage bed degradation during low flow and aggradation during high flow. Because the 1929 maps were surveyed a short time after the high flow, the aggradation in Pools 24, 25, and 26 could be due to the seasonal deposition. There are no sufficient data to verify this seasonal change in the river-bed elevation.

Response to construction and operation of locks and dams

In 1938 and 1939, the first hydrographic survey of the Upper Mississippi River subsequent to construction of locks and dams was made by the COE. This survey provides a picture of the immediate response of the river to construction of the locks and dams. During the record floods of 1973, the U.S. Army Corps of Engineers (St. Paul, Rock Island, and St. Louis Districts) obtained aerial photographs and the 1973 topographic survey data. These data were used to assess the long-term response of the river to locks and dams.

Discharges and stages. Viewed in longitudinal water-surface profile, the locks and dams on the Upper Mississippi River 2.75-m channel project form a series of steps in a river stairway (Fig. 3). The locks and dams regulate river flows to maintain the minimum 2.75-m depth required for navigation. In Fig. 3, the lower irregular line depicts the riverbed; the dotted line represents low water before lock and dam construction; the intermediate stepped line indicates minimum pool water-surface levels maintained by the locks and dams; and the upper line depicts the water surface as it would appear under conditions of higher flow. At high flow, the stages for the selected high-flow discharges have, in general, slightly decreased with time after the operation of locks and dams. The reason is that the submergence of parts of the flood plain after construction and operation of locks and dams destroys overbank vegetation, and in turn, increases the river-bed area (the flow carrying portion of the

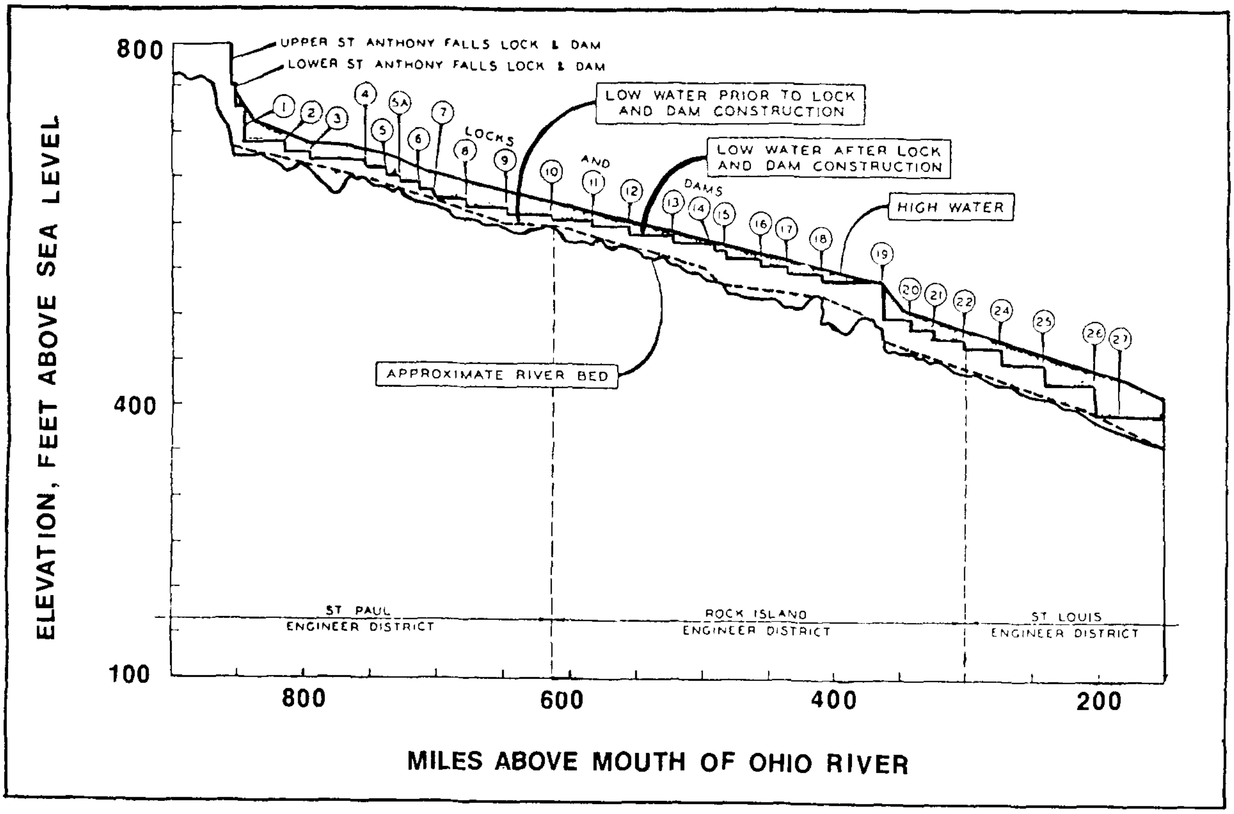


Fig. 3. Navigation stairway, see text for explanation.

river). This results in a lower stage for a given discharge during floods (e.g., Fig. 4).

The locks and dams changed the character of the river. The permanent change in water levels submerged the dikes constructed during the 1.37-m and 1.83-m channel projects. Pools and a stable low-water level upstream of dams were created by the dams.

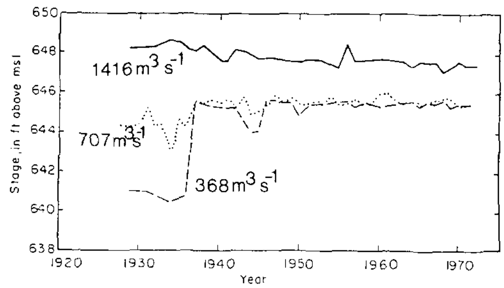
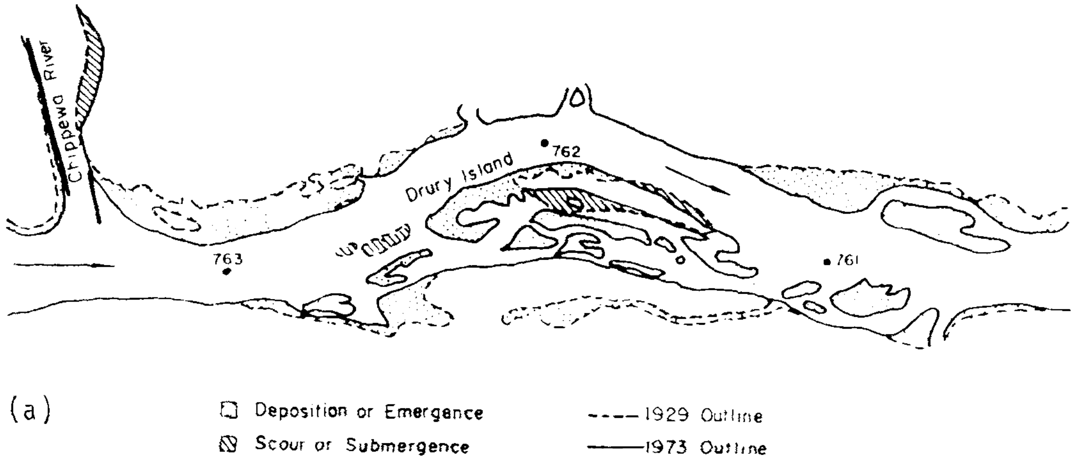


Fig. 4. Specific stage diagram at Winona, Minnesota.

River position. The river inundation area has changed noticeably, mainly due to inundation of large sections of flood plain upstream of locks and dams (e.g., Fig. 5b). However, the general river position has remained the same.

Surface areas. In general, the river surface areas upstream of locks and dams increased due to inundation of the flood plain after construction of locks and dams. For example, from 1929 to 1973, the river surface areas in the lower one-fourth reach of Pool 24 increased from 14.2 km^2 (5.49 square miles) to 15.1 km^2 (5.82 square miles) and in the lower one-third reach of Pool 4 below Lake Pepin from 4.35 km^2 (1.68 square miles) to 9.51 km^2 (3.67 square miles) as shown in Fig. 5b. However, the surface area decreased further upstream because of sediment deposition. For example, the surface areas in the upper one-fourth reach of Pool 24 decreased from 13.5 km^2 (5.22 square miles) to 13.3 km^2 (5.13 square miles) and in the upper one-



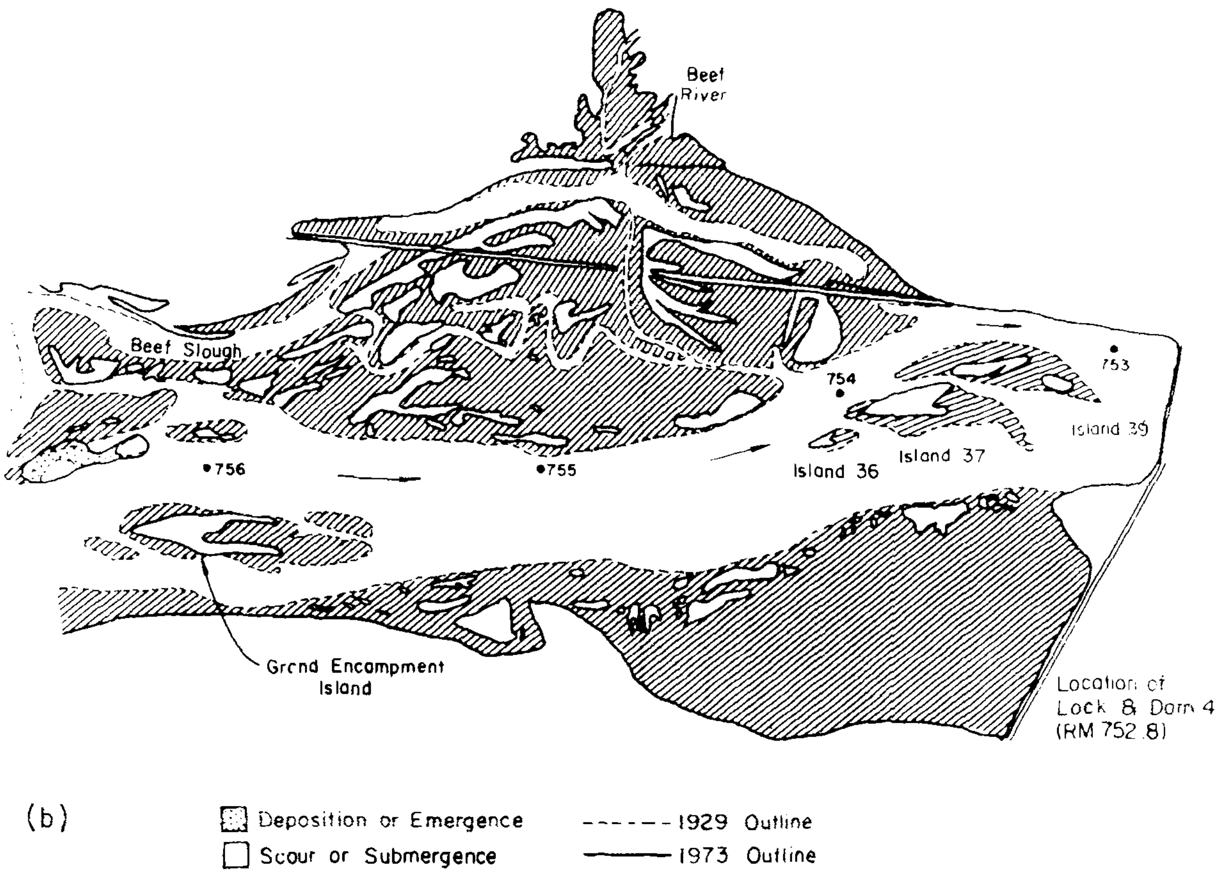


Fig. 5. Effect of Lock and Dam 4 on river geometry in Pool 4 reach below Lake Pepin in Upper Mississippi River: (a) upper one-third; (b) lower one-third.

third of Pool 4 below Lake Pepin from 3.25 km^2 (1.25 square miles) to 2.98 km^2 (1.15 square miles) as shown in Fig. 5a. Conversely, the island areas decreased immediately upstream of locks and dams and increased further upstream; also, the total number of islands in all pools increased. The number of islands in Pool 4 below Lake Pepin increased from 23 to 121 after construction of Lock and Dam 4. This decrease in island areas and increase in number of islands upstream of locks and dams was caused by submerging low areas on the flood plain and on the larger islands to form new chutes and lakes. For example, this island area in the lower one-third reach of Pool 4 below Lake Pepin decreased from 0.88 km^2 (0.34 square miles) to 0.42 km^2 (0.16 square miles).

Surface width. The surface width of the river upstream of locks and dams increased after construction of locks and dams because of inundation of flood plains. This width decreased further upstream because of sediment deposition in these areas. For example, the surface width in the lower one-third of Pool 4 below Lake Pepin increased from 780 m (2 550 ft) in 1929 to 1 700 m (5 560 ft) in 1973 and the surface width in its upper one-third reach reduced from 580 m (1 890 ft) to 530 m (1 740 ft).

River-bed elevation. In general, the river bed degraded immediately below locks and dams due to trapping of sediment in its upstream pool; it aggraded immediately above locks and dams because of a backwater effects. For example, the average river-bed elevation in the lower one-third of Pool 4 aggraded 0.40 m (1.3 ft) and in the upper one-third, it degraded 0.67 m (2.2 ft) when comparing the 1929 and 1973 COE's hydrograph survey data.

Flood plains and backwaters. Prior to the creation of the 2.75-m navigation channel, the flood plain adjacent to the Upper Mississippi River was heavily wooded. Hundreds of lakes, ponds, and deep sloughs were scattered through the wooded area. In general, these lakes and marshes were flooded during the spring but dried out in the summer and fall with little marsh and aquatic development.

Much of the flood plain was changed with the creation of navigation pools. The relatively stable water levels in the navigation pools converted a portion of the flood plain from wooded islands and dry marshes into an excellent marsh and aquatic habitat. After more than 50 years of operation, sediment was slowly deposited in the marshes.

From 1975 to 1978, the Science and Education Administration (SEA) Sedimentation Laboratory, Oxford, Mississippi, conducted sediment sampling in Pools 4 through 10 in an effort to determine sedimentation rates in non-main channel areas where deposition of fine sediment is occurring. Cesium-137 sediment dating method along with spud and fathometer surveys were utilized to determine sedimentation rates.

An estimate of sedimentation rates based on the Cesium-137 survey is given in Table 1. The spud and fathometer survey data show somewhat different results. However, all the data clearly indicate that all non-main channel water areas in the study area are aggrading. Almost all the sampling sites are relatively shallow. Few of the backwater areas exceeded a depth of 3 m (10 ft) from 1975 to 1978. A sedimentation rate of 2.5 cm per year is equivalent to 2.5 m (8 ft) per century. In addition, the non-main channel surface water areas are decreasing due to encroachment of the flood plain because of sedimentation.

If the present rate of sedimentation in non-main channel areas is allowed to continue, most of the open-water areas of the backwater lakes will become marsh land within the next century. The main source of fine sediment is upland erosion. Local rehabilitative works may extend the existence of the Upper Mississippi backwater areas. However, prevention of sediment production at the source is the only solution for maintaining the existence of these backwater lakes (Soil Conservation Service 1979).

Table 1. Calculated sediment accumulation rates on non-main channel areas based on Cesium-137 sediment dating method.

Pool	Estimated rate of sedimentation (cm/year)	
	Since 1955	1963 – 1975
4	2.5	2.5
6	3.5	4.2
7	1.5	–
8	1.9	2.2
9	2.3	2.3
10	3.5	4.2

Dredging and sediment discharge

The importance of dredging in maintaining a navigable waterway in the Upper Mississippi River was recognized in the legislation that authorized the 2.75-m channel project. The River and Harbor Act of 1930 provided for a navigation channel 2.75 m deep to be established by constructing a series of locks and dams and to be maintained by channel dredging.

Comparing geomorphic data with dredging records provides a basis for determining those factors that influence dredging requirements in the Upper Mississippi River. Increased dredging volumes appear closely related to such factors as initial dredging requirements to make the transition from the 1.83-m channel to the 2.75-m channel, extended periods of abnormally low flow when lack of water becomes a controlling factor, extended period of unusually high flow, operational policies such as the practice of overdepth and overwidth dredging, and effectiveness and efficiency of dredging operations.

Mean annual volumes of dredged material from the dredging data provided by the COE, St. Paul District, were determined for each pool during different periods since 1933. In general, dredging requirements were greatest prior to 1944. For example, in Pool 4, the mean annual volume dredged was over 459 000 m^3 for the period from 1934 to 1944, while mean annual dredging volumes were less than 300 000 m^3 for succeeding periods. The larger dredging requirements prior to 1944 were necessary during the transition from the 1.83-m navigation channel to the 2.75-m channel. Dredging requirements after the completion of lock and dam construction are dependent on sediment deposition in the pools. The data indicate that dredging requirements are strongly related to mean annual water discharge. Years in which water discharges were great were generally the years during which large volumes of sediment needed to be dredged from the channel. Dredging requirements were also affected by the volumes dredged during previous years. Figures 6 and 7 show this trend in Pools 5 and 21. For example, in Pool 21 from 1956 through 1959, the mean annual flows were less than 1 360 m^3/sec (48 000 cfs) and less than 46 000 m^3 (60 000 cubic yards) were dredged during each of those four years. However, in 1960 the mean annual

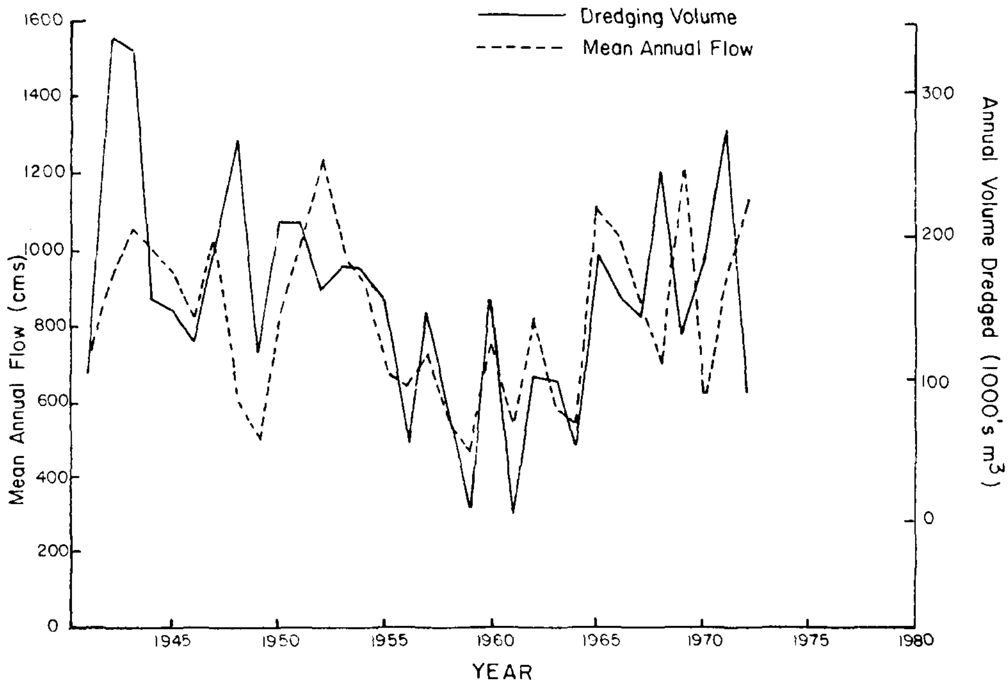


Fig. 6. Mean annual flows versus annual dredging volumes in Pool 5 (flow data from Winona, Minnesota).

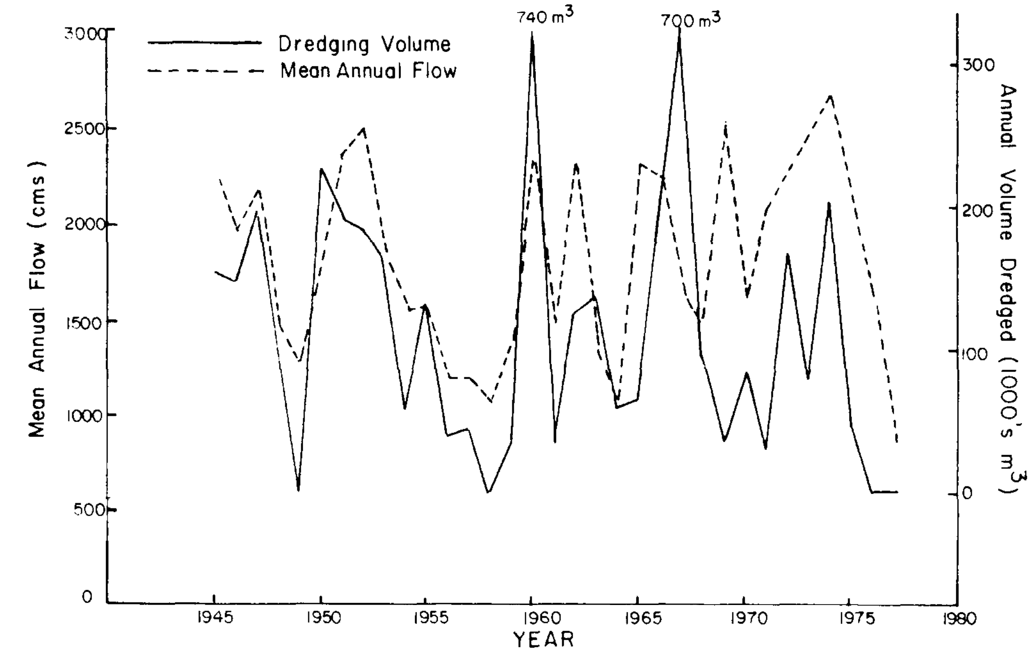


Fig. 7. Mean annual flows versus annual dredging volumes in Pool 21 (flow data from Keokuk, Iowa).

flow was 2 320 m^3/sec (81 800 cfs), and the corresponding dredging requirement increased to 734 500 m^3 (960 000 cubic yards, Fig. 7). When flows are high, large quantities of sediment enter the Mississippi River from tributaries and from non-point sources throughout the drainage area. This sediment is transported to the pools and is deposited if the velocity is insufficient to retain the particles in suspension. The relation between discharge and dredging requirements becomes evident when mean annual volumes dredged for all pools are computed for different time periods and are plotted against the corresponding mean annual discharges (Fig. 8). After 1944, the total mean volume dredged from all pools was greatest for the period between 1965 to 1972 (3 430 000 m^3), while mean annual flow discharge was also greatest for this period at Alton, Illinois (Fig. 8).

In studying the relation between frequency and volume by location in Pools 24, 25 and 26, Lagasse (1975) found that the most troublesome reaches that require dredging are straight reaches located upstream of a pool's primary control point and divided by alluvial islands.

The dredged material is moved by hydraulic pipeline dredge and deposited along the bankline of the river channel in dike fields or on islands. This material may be moved again by subsequent floods. Water transport of sediments from a disposal site back to the river can increase local turbidity and may result in relocation of the dredged material to environmental sensitive portions of the river such as channels, marsh land, sloughs, or backwater areas. Because of the adverse impacts on selected environments caused by the dredging operation, it is desired to determine the minimum dredging required to maintain the navigable channel. This is one of the major tasks of the U.S. Army Corps of Engineers.

Summary

Improvement of the Upper Mississippi River for navigation has been underway for more than 150 years. The major improvement work includes construction of dikes, revetments, locks, and dams; operation of locks and dams; and dredging. All these man-made activities have changed the river's characteristics. The impacts on the geomorphology of the Upper Mississippi River are summarized in Table 2. In general, construction and operation of control structures supplemented by dredging have

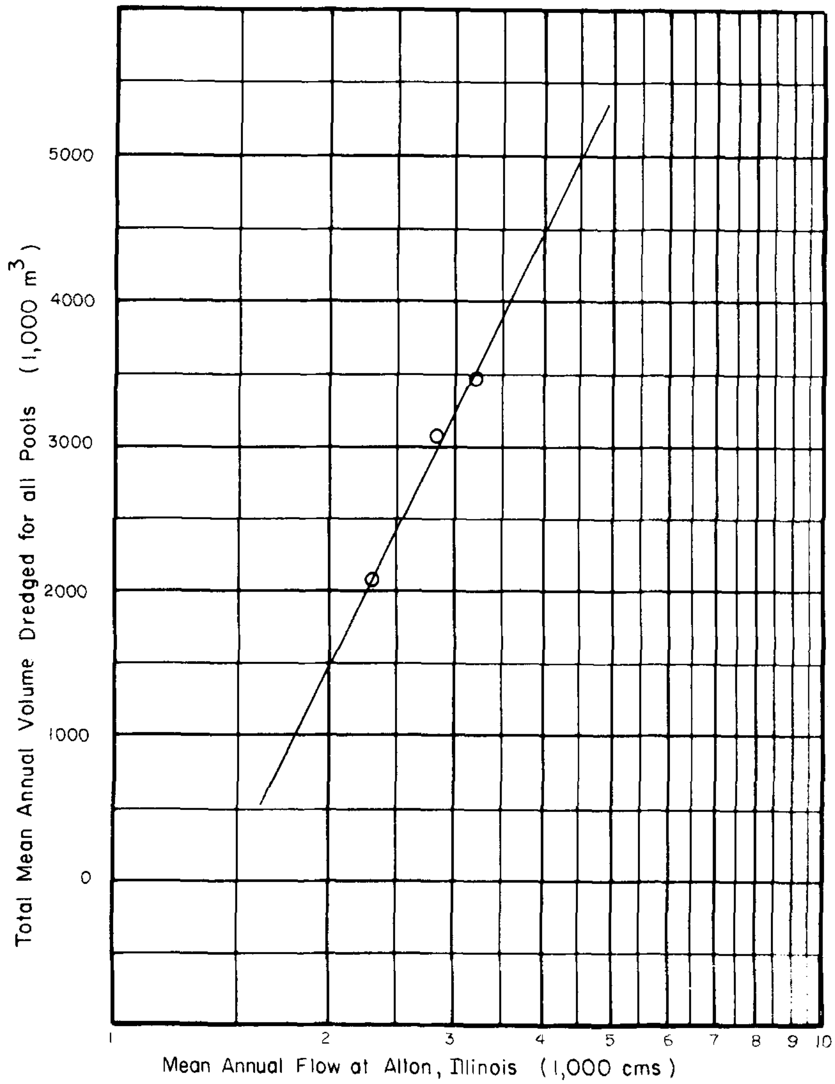


Fig. 8. Total mean annual volume dredged in the Upper Mississippi River versus mean annual flow at Alton, Illinois.

successfully maintained the low-water navigable channel. Also these improvements works have not significantly affected the high-flow stage and discharge relationship, indicating that these man-made structures have not increased the flooding problem. However, it is evident that lakes and backwater areas formed after construction of locks and dams are slowly being filled with sediment. Also, dredging required to maintain the navigable channel and disposal of dredged material have caused some adverse impacts on the environment. It is necessary to determine the minimum dredging requirement at each problem area and to evaluate the long-term impacts of maintaining the navigable waterway on the environment of the Upper Mississippi River. Based on the study of past geomorphic changes and with the aid of one-dimensional mathematical model simulation of future river responses, it is concluded that 50 years from now the river scene of the Upper Mississippi River will essentially be as it is today, if no major man-made changes are made.

Table 2. Response of Upper Mississippi River to construction of dikes and locks and dams.

Features	River response	
	Construction of dikes	Construction of locks and dams
Stage	Not significantly changed	Low stage was raised to the minimum pool levels for navigation
Discharges	Not significantly changed	Not significantly changed
River position	Not appreciably changed	Not appreciably changed
River surface area	Reduced	Increased above lock and dam and decreased further upstream
Island area	Increased	Decreased above lock and dam and increased further upstream
Surface width	Reduced	Similar to river surface area change
Number of islands	Increased	Increased
River-bed elevation	Low-flow degradation	Degradation immediately below lock and dam and aggradation immediately above
Velocity	Increased at low flow and about same at high flow	Decreased at low flow and about same at high flow
Flood plain and backwater	Sediment deposition	Sediment deposition

Geomorphology of Middle Mississippi River

History of development

One of the first undertakings to improve conditions on the Middle Mississippi River was the removal of snags (sunken debris such as trees) that were hazardous to navigation. This work, performed by the U.S. Army Corps of Engineers, was authorized by Congress in May 1824. In the intervening years between 1824 and 1881, private landowners constructed some low-level levees along the river banks to prevent the flooding of their rich flood plain. On March 31, 1881, a comprehensive plan for regulation of the Middle Mississippi River was approved by Congress. The plan called for the continuous improvement of the navigation channel by reducing the width of the river to 760 m (2 500 ft). The Corps of Engineers started the work at St. Louis and continued downstream with construction of revetments and permeable timber pile dikes.

In 1879, the Illinois State Drainage and Levee Act was passed, clearing the way for organized levee districts to accomplish the needed works with the aid of state funds. However, in the Middle Mississippi, levee construction was not intensive until 1907. At that time, it began in earnest because the financing of levees was shifted from private landowners to government. Until this time, levees were not effective because of inadequate engineering and insufficient financial resources.

In 1927, the Corps of Engineers was authorized by Congress to obtain and maintain a 2.75-m (9-ft) deep, 91-m (300-ft) wide navigation channel for the Middle Mississippi River. This was achieved by the construction of dike fields to reduce channel width; however, the 2.75-m depth has been difficult to obtain, especially in areas where the main river flow crosses from one bank to the other. Adequate depths in troublesome channel crossings have been maintained by dredging, but dredging is only a temporary solution because the dredged sections generally fill again with sediment. On the other hand, the channel depth could be obtained throughout most of the river by further reducing its width. Therefore work was continued by the Corps of Engineers to obtain and maintain a minimum 2.75-m navigation channel between St. Louis and Cairo by extending the dikes into the river to contract the river width to 460 m (1 500 ft).

In 1973, almost the entire river from the mouth of the Missouri River north of St. Louis to Thebes Gap south of Cape Girardeau was lined with Corps of Engineers mainline levees on one bank or the other (Fig. 9). One hundred ninety-six km (122 miles) of bankline revetment prevent riverbank erosion (Degenhardt, 1973), and over 800 dikes, having a length of 146 km (91 miles), project from the river banks into the river channel. As an example, the dikes in a 25.8-km (16-mile) reach of the Middle Mississippi River total about 24.1 km (15 miles) in length.

River response to development

The objectives of flood protection and year-round river navigation have been met to a great extent on the Middle Mississippi River. However, the developments for flood protection and river navigation have produced a new river morphology and a different river behavior (Simons *et al.*, 1974). According to Rhodes (1972), in this century the Mississippi River has been 'dammed, leveed, jettied, and polluted til Huck Finn himself wouldn't recognize it'. The history of channel positions, river-bed areas, cross-sectional areas, and channel-bed elevation demonstrates how river morphology has been changing. Variations in water and sediment discharge, stage, and stage-discharge relations indicate how river behavior has been affected.

The changes in the form and behavior in the Middle Mississippi River are summarized on the basis of study results by Simons *et al.* (1974):

1. The position of the river in the valley is basically unchanged during the last century and, in the absence of earthquakes or great floods, it should remain so.
2. The surface area of the river has been greatly reduced since the 1880's. However, the present area may not be significantly less than the natural area if great floods had not occurred during the 19th century. For example, the river width at St. Louis was 945 m (3 100 ft) in 1803, increased to 1 280 m (4 200 ft) in 1850, and then reduced to 640 m (2 100 ft) in 1973.
3. The river flows are changed very little. Very large peak flows do not occur as frequently now as in the past. Annual minimum flow is not larger and mean annual flow is unchanged.
4. The mean annual maximum flood stage at St. Louis has increased slightly during the last 100 years, whereas the annual minimum stage has decreased significantly.
5. Except for depths greater than 6 m (20 ft), daily stages at St. Louis are lower now than in the past.
6. At all discharges, the depth of water in the river is greater now than before modification.
7. The change in river cross section has reduced the flow-carrying capacity of the channel for flows greater than bankfull. The levees have isolated the main channel from its flood plain and the dikes have constricted the main channel. Stages for flood discharges are higher now than in the past.

Although flood stages are now higher than under natural conditions, levees prevent flood damage when the Middle Mississippi River exceeds bankfull stage. Under natural conditions flood damage occurred whenever the river exceeded bankfull stage.

By encouraging deposition and tree and willow growth, the dikes have helped produce a stable low-water channel which is part of the world's largest inland water transportion system.

Summary and contrasts

The response of the Upper Mississippi River to the combined activities of contraction, dredging, and construction of locks and dams was compared with the response of the Middle Mississippi River to Man's activities. This comparison contrasts the response of a reach subjected to flow regulation by navigation dams with the response of a reach developed by open-river training works (contraction dikes and revetment).

Development for navigation on both the Upper and Middle Mississippi River between 1890 and

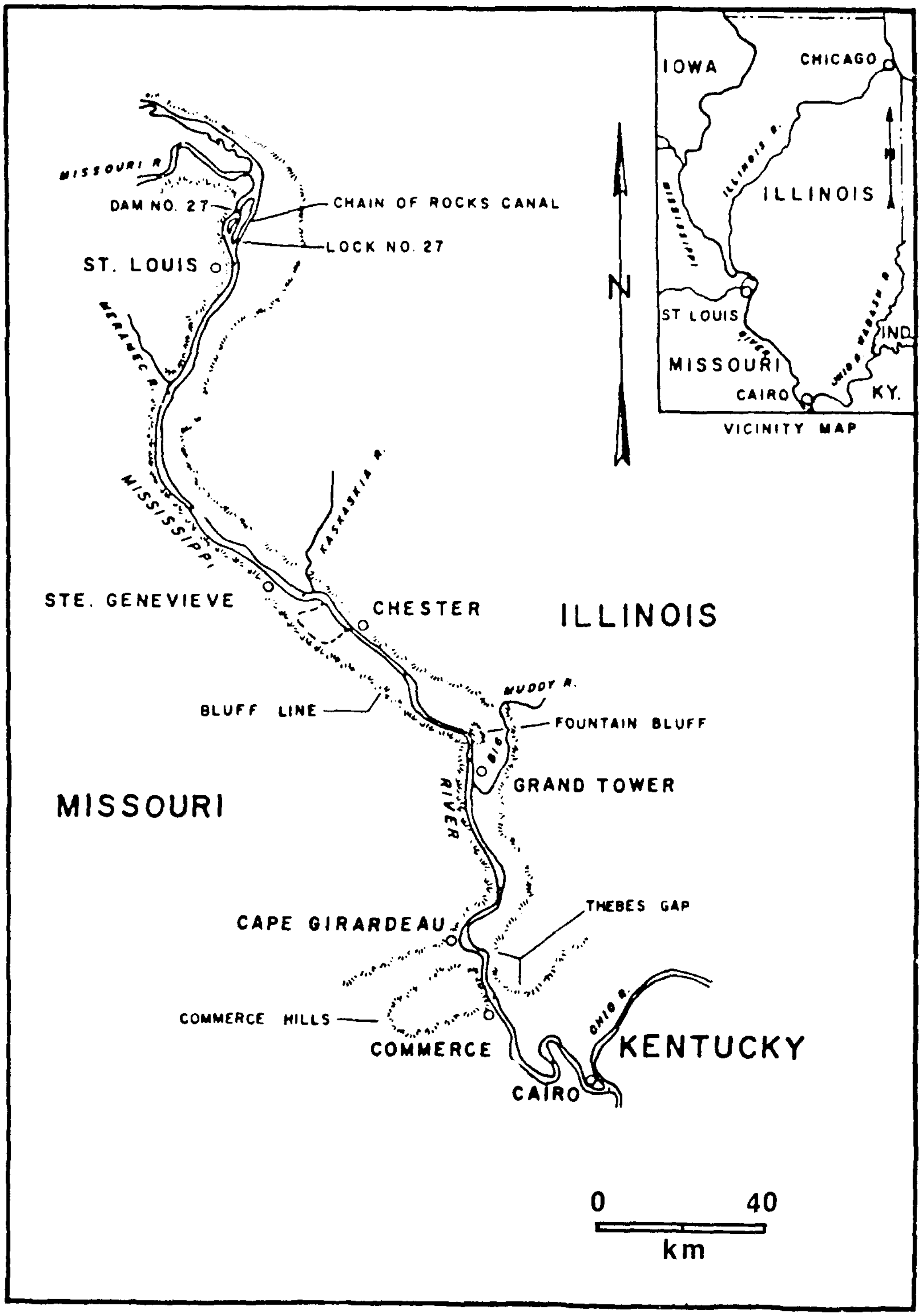


Fig. 9. The Middle Mississippi River in the St. Louis District (after Degenhardt, 1973).

1930 followed the same theme of contraction, revetment, and dredging where necessary to attain desired depth. After 1930, the U.S. Army Corps of Engineers continued to employ open-river training works and dredging on the Middle Mississippi to achieve a 2.75-m (9-ft) channel. On the upper river, however, the basic approach was changed to one of flow regulation by a system of navigation locks and dams, supplemented by dredging. While the response of the Middle Mississippi has been predictable, the response of the Upper Mississippi has been quite complex.

An analysis of river position based on a time-sequenced comparison of river banklines leads to the conclusion that the Mississippi between St. Paul and Cairo has not changed its position appreciably in the last 150 to 200 years. Using the change in river position as an indicator of stability, both the Upper and Middle Mississippi River are quite stable. In terms of degree of stability, several significant local changes in position on the Middle Mississippi (such as the Kaskaskia cutoff), indicate that the Middle Mississippi is somewhat less stable than the Upper Mississippi, but certainly far more stable than the Lower Mississippi.

The use of dikes to create a navigation channel produced a slight decrease in width between 1890 and 1930 on the upper river and a major decrease in width between 1890 and the present on the middle river. Although detailed conclusions relative to geomorphic and hydraulic change in specific reaches on the Upper Mississippi subsequent to 1940 require an analysis of the particular pool in question, general trends in Pools 4 through 9 and in Pools 24 through 26 appear reasonably representative of changes on the upper river following lock and dam construction. The immediate response to lock and dam construction was an increase in surface width throughout a pool; however, the long-term response has been a decrease in width immediately below a lock and dam and an increase in width just above a lock and dam.

The entire Mississippi above Cairo has experienced considerable within-channel change. These changes are reflected in variations in surface area, island area, and river-bed area. Because the length of the Mississippi above Cairo has not changed appreciably, surface-area change has generally mirrored the change in river width. Dike construction on the Middle Mississippi has produced significant decreases in island area and in river-bed area. On the Upper Mississippi, again, the response was more complex and was a function of position in a pool. Higher water levels immediately upstream of a lock and dam have produced decreased island area, while a lowering of bed elevations downstream of a lock and dam has resulted in lower stages and increased island areas.

Bed elevations on the Middle Mississippi have decreased throughout the period of dike construction. In a 22.5-km (14-mile) reach selected by the U.S. Army Corps of Engineers for detailed study, the river bed lowered almost 3.4 m (11 ft) between 1889 and 1966. The period of dike construction on the upper river (1880 to 1930) was one of slight aggradation of the river bed in Pools 24 through 26 and slight degradation in Pools 4 through 9. The limited effectiveness of the low dikes constructed on the upper river, and the concentration of construction effort toward the end of the era of dike construction, coupled with a natural tendency toward aggradation on the Upper Mississippi, contributed to this pattern of increasing bed elevations. This trend was reversed between 1930 and 1940 in the lower three pools of the navigation system, and general degradation has continued to the present in the lower two pools. Pool 24, however, has experienced general aggradation since 1940, indicating a tendency to trap incoming sediments from Pool 22 and the Salt River and to create a sediment-deficient condition in the downstream pools. Degradation has not been of the same magnitude as on the Middle Mississippi. Local exceptions to these trends include some aggradation immediately above locks and dams and local scour below.

Viewing the river in cross section provides an integrated picture of the effects of changes in width, surface area, and bed elevation. In particular, the response to dike construction is evident in the cross-sectional view. Flow area at St. Louis on the Middle Mississippi has progressively decreased until it is now only two-thirds that of the natural river. A similar decrease has occurred all along the Middle Mississippi wherever the channel has been contracted. On the Upper Mississippi, flow areas generally decreased during the period of dike construction and increased following lock and dam construction.

Geomorphic response of the Mississippi above Cairo to Man's activities is reflected in the hydraulic parameters of discharge and stage. Annual peak flood discharges on the upper river have remained, on the average, unchanged through the period of record. On the middle river, present-day peak floods are, on the average, slightly lower than in the past, reflecting the construction of storage dams on the Missouri River. Minimum flows have increased slightly above and below the mouth of the Missouri. The effect on river change has been more significant. At St. Louis, the decrease in both flow area and overbank storage has contributed to an increase in the annual maximum flood stage. Although present-day floods on the Middle Mississippi produce flood stages higher than similar discharges produced in the past, levees prevent flood damage when the river exceeds bankfull stage. Under natural conditions, flood damage occurred whenever the river exceeded bankfull stage.

On the Upper Mississippi, minimum stages have been strongly influenced by Man's development. In general, minimum stages have decreased at locations immediately below a lock and dam and have increased sharply at locations above a lock and dam shortly after first full pool was reached at each location. On the average, the annual maximum stages and discharges at Alton, Illinois, and Keokuk, Iowa, have remained unchanged in the last 100 years. This indicates that present-day floods on the upper river produce flood stages similar to the past.

Sediment data support the characterization of the Upper Mississippi as a relatively clear-water stream and the Mississippi below the Missouri as a heavy sediment carrier. A little over 10 percent of the suspended load at St. Louis is contributed by the Upper Mississippi. While 15 percent of the suspended load at St. Louis is sand, sediment data indicate that very little sand is moving in suspension in Pools 24, 25 and 26.

Sediment records on the Mississippi above Cairo are not of sufficient length to permit an accurate determination of the effect of development on sediment load. Available data do suggest that sediment loads have been decreasing in the recent past. The sediment trapping effect of the upstream pools of the Upper Mississippi lock and dam system have certainly been a contributing factor to the observed general degradation in the lower pools of the system.

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