PROPAGATION AND COMPOSITION OF THE FLOOD WAVE

ON THE UPPER MISSISSIPPI RIVER 1.9.9.3

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Field Hydrologist making streamflow
measurements (U.S. Geological Survey)

PROPAGATION AND COMPOSITION OF THE FLOOD WAVE ON THE UPPER MISSISSIPPI RIVER, 1993

By John A. Moody

Floods in the Upper Mississippi River Basin, 1993

U.S. GEOLOGICAL SURVEY CIRCULAR 1120–F

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FOREWORD

During spring and summer 1993, record flooding inundated much of the upper Mississippi River Basin. The magnitude of the damages—in terms of property, disrupted business, and personal trauma—was unmatched by any other flood disaster in United States history. Property damage alone is expected to exceed $10 billion. Damaged highways and submerged roads disrupted overland transportation throughout the flooded region. The Mississippi and the Missouri Rivers were closed to navigation before, during, and after the flooding. Millions of acres of productive farmland remained under water for weeks during the growing season. Rills and gullies in many tilled fields are the result of the severe erosion that occurred throughout the Midwestern United States farmbelt. The hydrologic effects of extended rainfall throughout the upper Midwestern United States were severe and widespread. The banks and channels of many rivers were severely eroded, and sediment was deposited over large areas of the basin's flood plain. Record flows submerged many areas that had not been affected by previous floods. Industrial and agricultural areas were inundated, which caused concern about the transport and fate of industrial chemicals, sewage effluent, and agricultural chemicals in the floodwaters. The extent and duration of the flooding caused numerous levees to fail. One failed levee on the Raccoon River in Des Moines, Iowa, led to flooding of the city's water treatment plant. As a result, the city was without drinking water for 19 days.

As the Nation's principal water-science agency, the U.S. Geological Survey (USGS) is in a unique position to provide an immediate assessment of some of the hydrological effects of the 1993 flood. The USGS maintains a hydrologic data network and conducts extensive water-resources investigations nationwide. Long-term data from this network and information on local and regional hydrology provide the basis for identifying and documenting the effects of the flooding. During the flood, the USGS provided continuous streamflow and related information to the National Weather Service (NWS), the U.S. Army Corps of Engineers, the Federal Emergency Management Agency (FEMA), and many State and local agencies as part of its role to provide basic information on the Nation's surface- and ground-water resources at thousands of locations across the United States. The NWS has used the data in forecasting floods and issuing flood warnings. The data have been used by the Corps of Engineers to operate water diversions, dams, locks, and levees. The FEMA and many State and local emergency management agencies have used USGS hydrologic data and NWS forecasts as part of the basis of their local flood-response activities. In addition, USGS hydrologists are conducting a series of investigations to document the effects of the flooding and to improve understanding of the related processes. The major initial findings from these studies will be reported in this Circular series as results become available.

U.S. Geological Survey Circular 1120, *Floods in the Upper Mississippi River Basin, 1993*, consists of individually published chapters that will document the effects of the 1993 flooding. The series includes data and findings on the magnitude and frequency of peak discharges; precipitation; water-quality characteristics, including nutrients and man-made contaminants; transport of sediment; assessment of sediment deposited on flood plains; effects of inundation on ground-water quality; flood-discharge volume; effects of reservoir storage on flood peaks; stream-channel scour at selected bridges; extent of flood-plain inundation; and documentation of geomorphologic changes.

Gordon P. Eaton

Director

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot
kilometer (km)	0.6214	mile
	Area	
square kilometer (km^2)	0.3861	square mile
	Volume	
cubic meter (m^3)	35.31	cubic foot
	Velocity	
meter per second (m/s)	3.281	foot per second
cubic meter per second (m^3/s)	35.31	cubic foot per second
kilometer per day (km/d)	0.6214	mile per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Mean discharge: In this report, "mean discharge" is the arithmetic mean of individual daily mean discharges during a period, usually the period of record of the stream-gaging station.

Propagation and Composition of the Flood Wave on the Upper Mississippi River, 1993

By John A. Moody

Abstract

The historic flood of 1993 affected the entire 1,358-kilometer reach of the upper Mississippi River from Minneapolis, Minnesota, to Cairo, Illinois, but had no unusual effect on the lower Mississippi River from Cairo to the Gulf of Mexico. The flood was preceded by heavy (200 percent of normal) spring rains that saturated the ground in much of Minnesota, Iowa, Illinois, and Wisconsin. The flooding began in June along the upper 200 kilometers of the river. Intense rains that continued into summer caused the Minnesota River in Minnesota and the Chippewa and the Black Rivers in Wisconsin to contribute simultaneously near-record discharges to the upper Mississippi River from June 22 to 25. The maximum discharge in the flood wave, which propagated downstream at about 0.58 meter per second, was five to seven times the daily mean discharge at stream-gaging stations on the upper Mississippi River. As the flood wave propagated southward, the rains shifted southward in concert. The phase or propagation speed of the flood wave was influenced largely by hydrologic factors, such as tributary inflow and flood-plain storage, rather than by hydraulic factors, such as water depth, channel width, and channel roughness. The Iowa and the Des Moines Rivers contributed near-record discharges to the Mississippi in early July. A record (greater than 100-year recurrence interval) discharge of 12,300 cubic meters per second occurred on the Mississippi River at Keokuk, Iowa, on July 10. This part of the flood wave probably passed St. Louis, Missouri, on July 20, but was not the major flood peak there; by late July, the rains had shifted further southward into Missouri and central Illinois, which caused the Missouri and the Illinois Rivers to contribute about 20,900 and 2,220 cubic meters per second, respectively, to the upper Mississippi River at St. Louis from July 29 to July 31. Not all of this water passed Thebes, Illinois (about 70 kilometers upstream from Cairo, where the last downstream-gaging and sampling station on the upper Mississippi River is located), because water left the channel of the upper Mississippi River upstream from Thebes through failed levees and by seepage through and under the levees that did not fail and was stored temporarily on the flood plain. The maximum discharge at St. Louis (29,700 cubic meters per second) occurred on August 1; however, the maximum discharge at Thebes (27,700 cubic meters per second) did not occur until August 7, which was about 4 days later than the normal travel time of 2 days.

INTRODUCTION

Flood waves that move down the upper Mississippi River, which ends at the confluence with the Ohio River at Cairo, Illinois, are confined and altered by human and natural processes. Starting in Minneapolis, Minnesota, a moderate flood cannot propagate as a free wave under normal conditions because the free surface of the river is controlled by a drop of 96 meters (m) through a series of stairstep pools created by backwater from 29 navigation dams that regulate the 1,050-kilometer (km) reach of the river to its confluence with the Missouri River near St. Louis, Missouri (fig. 1). Between Minneapolis and Clinton, Iowa (532 km), the flood plain is narrow and confined by high bluffs on either side; the average depth of the river is 2 m. Downstream from Clinton to St.

Figure 1. Upper Mississippi River and some of its tributaries.

Louis (518 km), the flood plain widens, and a series of levees of different heights has been built by Federal, State, and local agencies. The levees normally confine a moderate flood wave to a narrow channel within the wider flood plain; the average depth of the river is 3 m. From St. Louis to Cairo (315 km), where the Ohio River joins the upper Mississippi River, the Mississippi is channelized by using lateral dikes and revetments to maintain an average depth of 7 m. Because there are no navigation dams on this reach of the river, flood waves can propagate freely.

The flood of June through August 1993, however, was not a moderate flood. For floods this large, the gates in the navigation dams are raised out of the water, which prevents damage to structures and machinery at the dam, and the river surface more closely resembles a natural, smoothly changing surface than a series of stairsteps.

Flows from tributaries also affect the timing and shape of a flood wave, depending upon the proportion of the tributary's discharge to the discharge of the main river. The mean discharge of the upper Mississippi River, which receives a large percentage of its water from its many tributaries (fig. 2; table 1), increases from 225 cubic meters per second (m^3/s) near Anoka, Minnesota, at an average rate of 4.2 m^3/s per river kilometer. In contrast, the mean discharge of the lower Mississippi River (downstream from the confluence with the Ohio River), which has fewer significant tributaries, increased from 13,500 m^3/s near Cairo at an average rate of only 1.6 m^3/s per river kilometer.

Purpose and Scope

This report describes the propagation of the flood wave of 1993 through the engineered channel of

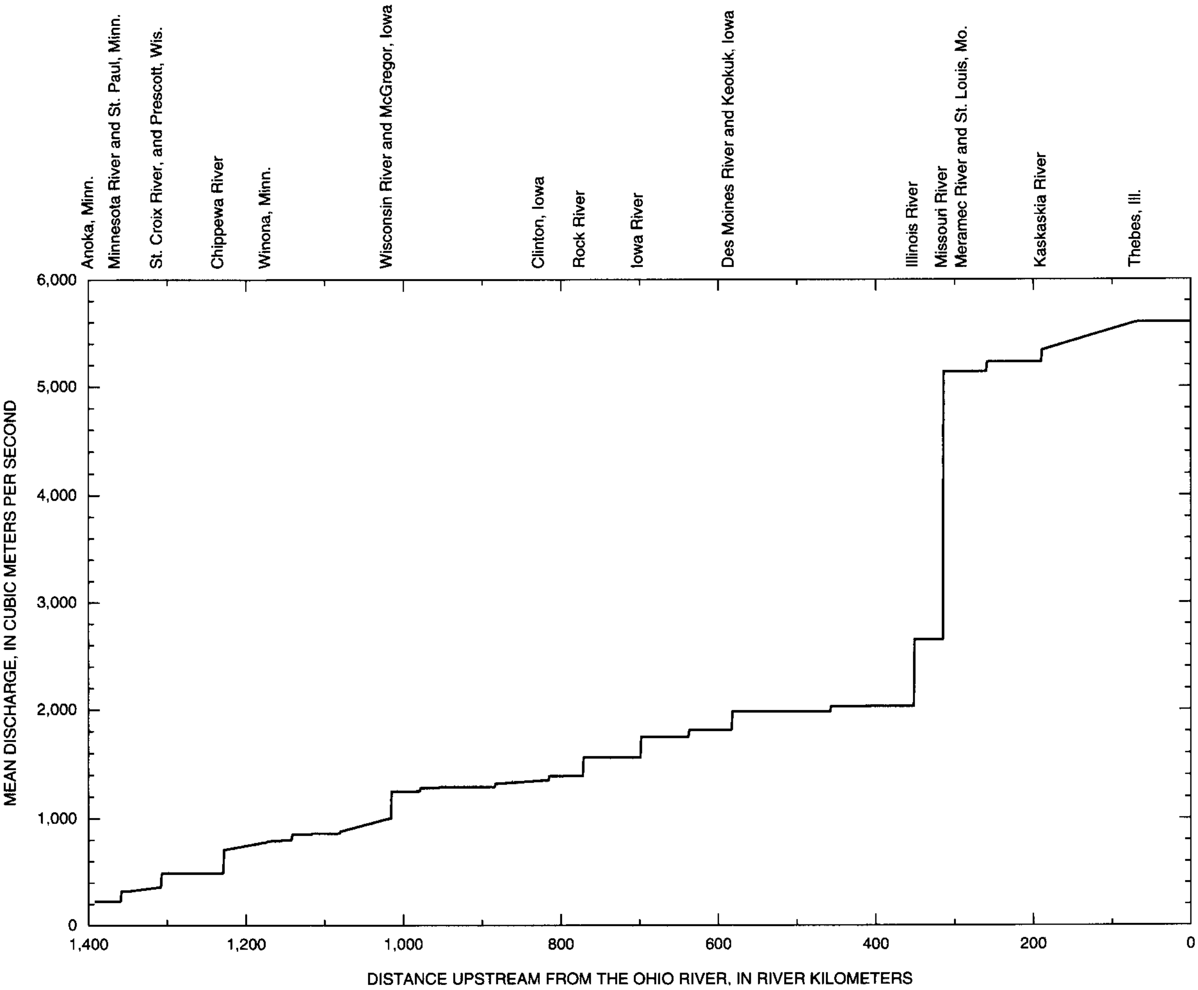


Figure 2. Mean discharge of the upper Mississippi River in relation to distance upstream from the confluence of the upper Mississippi River with the Ohio River. See footnote in table 1 for references that give the period of record for the mean discharges shown here.

Table 1. Drainage areas, mean discharges, and 1993 flood discharges for the upper Mississippi River and some of its tributaries

[km, kilometer; km^2, square kilometer; m^3/s, cubic meter per second; na, does not apply. Mean discharge is given for the stream-gaging station closest to the mouth of the tributary; distances upriver from the Mississippi–Ohio River confluence are measured to the mouth of the tributary. See Parrett and others (1993) for other flood discharges]

Stream-gaging stations	Distance upriver from Mississippi and Ohio River confluence (km)	Drainage area (km^2)	Period of record	Percentage of mean discharge of Mississippi River downstream from mouth of tributary (percent)	Mean discharge (m^3/s)	Maximum daily mean discharge for June through August (m^3/s)	Estimated travel time to next downstream Mississippi River stream-gaging station[1] (days)
Mississippi River near Anoka, Minn.	1,391	49,500	1931–88	na	225	974	2
Minnesota River near Jordan, Minn.	1,358	42,000	1934–88	34	107	2,570	2
St. Croix River at St. Croix Falls, Wis.	1,307	17,700	1902–89	25	122	558	2
Mississippi River at Prescott, Wis.	1,306	116,000	1928–89	na	486	3,680	3
Chippewa River at Durand, Wis.	1,228	23,300	1928–89	28	216	2,400	1
Mississippi River at Winona, Minn.	1,168	153,300	1928–88	na	788	4,810	6
Trempealeau River at Dodge, Wis.	1,154	1,670	1913–19 1934–89	1.5	12.2	145	6
Black River near Galesville, Wis.	1,141	5,400	1931–89	5.8	49.3	1,540	6
Root River near Lanesboro, Minn.[2]	1,116	3,290	1912–88	1.2	10.1	214	5
Upper Iowa River near Dorchester, Iowa.	1,080	1,990	1936–89	1.8	15.6	231	4
Wisconsin River at Muscoda, Wis.	1,015	26,900	1902–03 1913–89	22	246	1,670	3
Turkey River at Garber, Iowa.[3]	978	4,000	1913–89	2.3	26.7	456	3
Grant River at Burton, Wis.	954	700	1934–89	0.4	4.7	111	2
Platte River near Rockville, Wis.	947	370	1934–89	0.2	2.8	73.9	2
Maquoketa River near Maquoketa, Iowa.	883	4,020	1913–89	2.4	29.0	827	1
Mississippi River at Clinton, Iowa.	823	221,700	1873–1989	na	1,350	6,230	4
Wapsipinicon River near DeWitt, Iowa.	815	6,030	1934–89	3.1	43.2	609	4
Rock River near Joslin, Ill.	771	24,700	1939–88	11	176	986	4
Iowa River at Wapello, Iowa.	698	32,400	1914–89	11	197	3,000	2

Table 1. Drainage areas, mean discharges, and 1993 flood discharges for the upper Mississippi River and some of its tributaries—Continued

Stream-gaging stations	Distance upriver from Mississippi and Ohio River confluence (km)	Drainage area (km^2)	Period of record	Percentage of mean discharge of Mississippi River downstream from mouth of tributary (percent)	Mean discharge (m^3/s)	Maximum daily mean discharge for June through August (m^3/s)	Estimated travel time to next downstream Mississippi River stream-gaging station[1] (days)
Skunk River at Augusta, Iowa.	637	11,100	1914–89	4.2	68.8	1,300	1
Mississippi River at Keokuk, Iowa.	586	308,200	1878–1989	na	1,810	12,100	4
Des Moines River at Keosauqua, Iowa.	582	36,400	1904–05 1912–89	8	165	3,060	4
Illinois River at Meredosia, Ill.	351	69,700	1938–88	24	620	2,220	2
Salt River near New London, Mo.	457	6,400	1922–89	1.8	48.2	317	1
Missouri River at Hermann, Mo.	314	1,358,000	1897–1989	46	2,290	20,900	1
Mississippi River at St. Louis, Mo.	289	1,805,000	1861–1989	na	5,140	29,700	2
Meramec River near Eureka, Mo.	259	9,810	1903–06 1921–89	1.8	89.0	918	1
Kaskaskia River near Venedy Station, Ill.	189	11,400	1969–88	2	107	252	1
Mississippi River at Thebes, Ill.	70	1,847,000	1932–89	na	5,600	27,700	0

[1] Institute of River Studies, 1983. Travel times from river kilometers 289 to 938 averaged about 0.7 m/s; this speed was extrapolated and used from river kilometers 938 to 1,228. Travel times between river kilometers 1,306 and 1,391 were based on information furnished by Joseph Hess, U.S. Geological Survey, Minnesota District. The extrapolation of travel times was supported by the conservation of mass calculations (with errors of about 10 percent) for Mississippi River stream-gaging sites.

[2] 1912–14, 1916–17, 1941–85, and 1987–88. [3] 1913–16, 1919–27, 1929–30, and 1932–89.

the upper Mississippi River from Minneapolis to Thebes, Illinois, and the effects of tributary inflow and flood-plain storage on this flood wave. The composition of this flood wave, in terms of contributions from tributaries, is described for five U.S. Geological Survey stream-gaging stations between Minneapolis and Thebes—Prescott, Wisconsin, Winona, Minnesota, Clinton and Keokuk, Iowa, and St. Louis.

Flood Wave

The shape of the upper Mississippi River flood wave of 1993 was not the simple, solitary flood wave commonly depicted in textbooks, but was a composite shape that resulted from the summation of many separate tributary flood waves. The length of the composite flood wave was essentially the length of the upper Mississippi River, or 1,358 km (fig. 3*A*). The water surface of the composite flood wave for June 25 dropped sharply (600 km upstream from the Ohio River; fig. 3*A*); this was caused by the hydroelectric power dam at Keokuk, which always controls the flow of the river (fig. 4). This composite flood wave comprised three secondary peaks that can be seen when the average river slope of 91×10^{-6} is removed (fig. 3*B*). The daily mean discharge of some tributaries was routed into and down the upper Mississippi River at an assumed average water speed of about 0.7 meter per second (m/s) (Institute of River Studies, 1983). The shapes of the tributary discharge flood waves for June 25 had abrupt increases at the mouth of the tributary (fig. 3*C*). The summation of the tributary discharges in the upper Mississippi River upstream from Keokuk had a shape similar to the composite flood wave (fig. 3*B*). The composite flood wave for August 1 (date of peak discharge at St. Louis at river kilometer 289) distinctly showed the inflow of the floodwaters from the Missouri River (fig. 3*B*). On August 1, numerous drops in the elevation of the water surface were evident as the river flowed through navigation dams between 800 and 1,358 km upstream from the Ohio River. By this time, some dams were operational and were again regulating the river.

Flood-Wave Routing

Many methods for routing a flood wave assume unsteady flow in an open channel and no significant tributary inflow, but these two assumptions are not applicable to the upper Mississippi River. During low water conditions when the river is regulated by navigation dams, a flood wave cannot propagate freely through an open channel. However, flood waves can propagate freely in an open channel during high water conditions when the navigation dams no longer control the water level. During spring and late fall 1992, when the water discharge was closer to mean conditions, the periods of high water or open channel typically lasted a few days and occurred only in short reaches of the river between some dams. During summer 1993, the periods of open channel were longer and encompassed the entire reach of river from Minneapolis to Cairo, with the exception of the hydroelectric power dam at Keokuk (fig. 4). Tributary inflow to the upper Mississippi River was significant and had two effects on the flood wave. First, tributary inflow produced several secondary peaks and increased the magnitude of the maximum discharge flood peak as distance increased downstream (fig. 5). This contrasts with the assumption made by many routing methods that there is a single flood peak and that the magnitude of the peak is constant or decreases in the downstream direction (Gilcrest, 1950; Lawler, 1964). Second, the wave-propagation speed (phase speed or speed of the stage or discharge peak) was determined by the tributary inflows rather than the hydraulic characteristics of the channel.

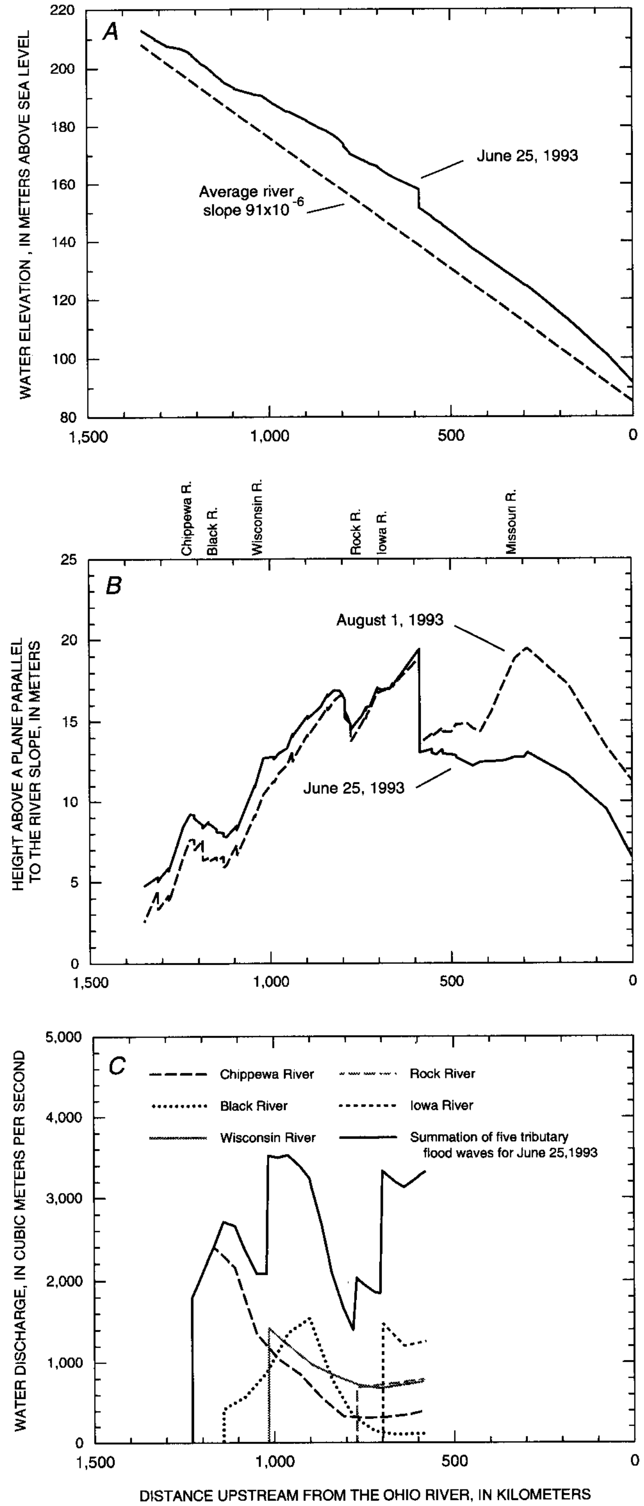


Figure 3. Composite flood wave on the upper Mississippi River. *A*, Shape of the flood wave for June 25 was based on water-level elevations from 78 stations. Data were furnished by the U.S. Army Corps of Engineers in the St. Paul, the Rock Island, and the St. Louis Districts; *B*, The water-level heights above an arbitrary plane with slope equal to the average river slope of 91 x 10^{-6}. The flood wave propagates downstream between June 25 and August 1, but its height at the hydroelectric dam at Keokuk, Iowa (at about 600 km), is held constant. The second large peak for August 1 is the Missouri River flood peak; *C*, Some individual discharge flood waves for tributaries upstream from Keokuk. They are plotted for June 25 by assuming that the daily mean discharge moves 0.7 meter per second. The summation of these tributary flood waves approximates the solid-line curve in *B*.

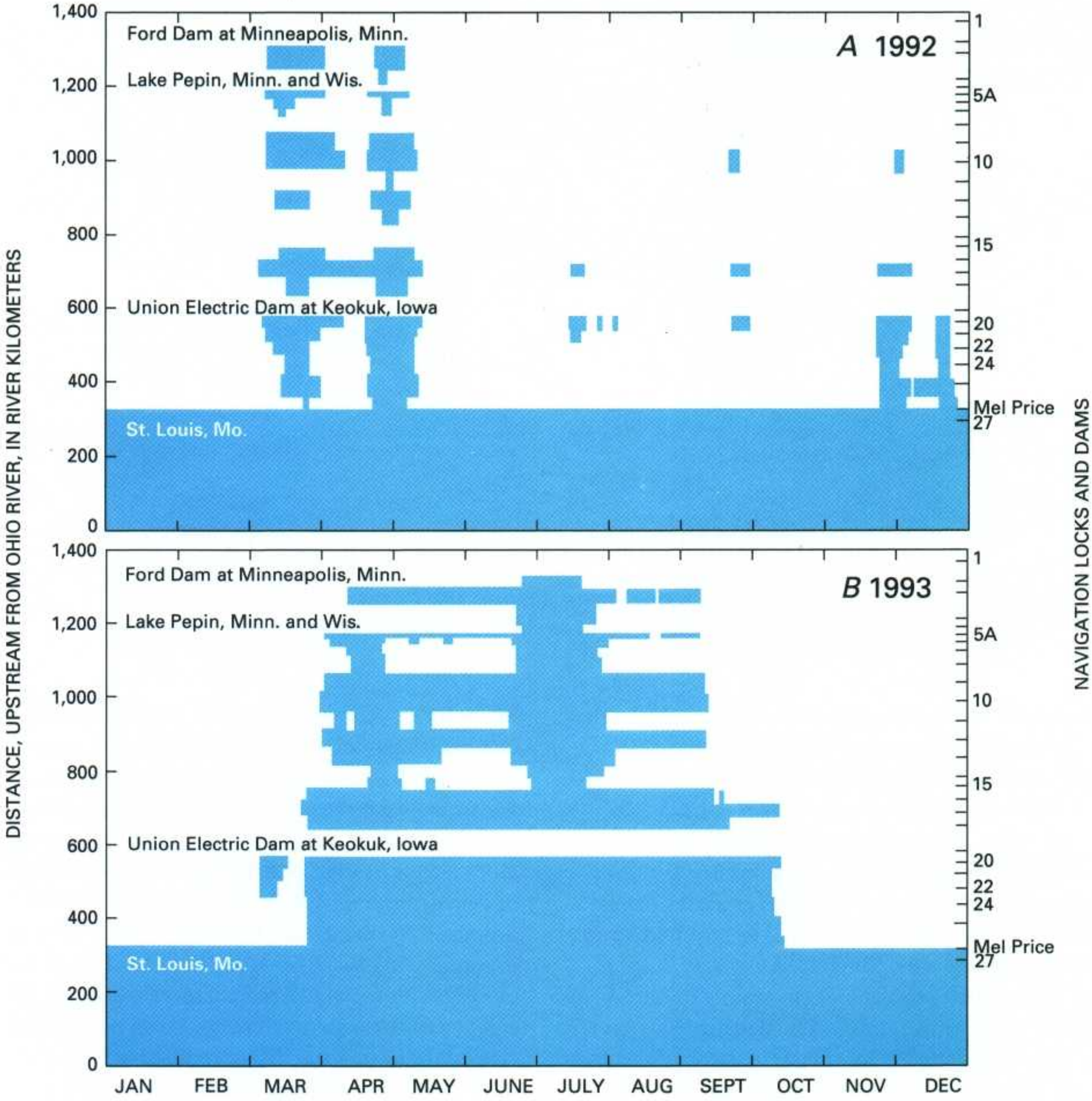


Figure 4. Periods of open channel for the upper Mississippi River. *A*, 1992; *B*, 1993. Blue represents times when all control gates in the navigation dam were out of the water. Information was furnished by U.S. Army Corps of Engineers in the St. Paul, the Rock Island, and the St. Louis Districts.

The flood-wave routing method used in this paper for the upper Mississippi River, therefore, assumed a steady, open-channel flow only from June through August 1993 and only along short reaches of the river between tributaries. The travel times within these reaches were based on field data published by the U.S. Army Corps of Engineers for the upper Mississippi River (table 1; Institute of River Studies, 1983) and the conservation of mass at upper Mississippi River stream-gaging stations. The steady open-channel flow was increased abruptly by inflow from tributaries or decreased abruptly by outflow to flood-plain storage. Following these abrupt gains or losses of water, steady open-channel flow was assumed to resume until the next tributary downstream entered the upper Mississippi River.

Acknowledgments

The discharge information used to prepare this report was provided by many U.S. Geological Survey personnel from the Minnesota, the Wisconsin, the Iowa, the Illinois, and the Missouri Districts. Although

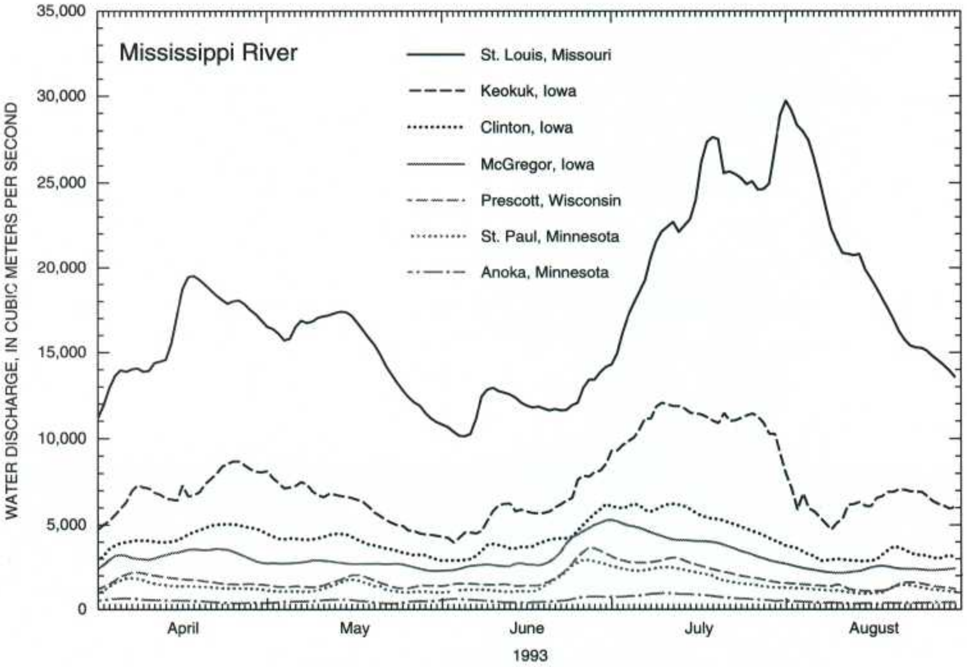


Figure 5. Daily mean water discharges at seven stream-gaging stations on the upper Mississippi River from April through August 1993.

working extra hours during the flood period, they still took time to satisfy numerous requests for the data required to make the calculations of percent composition of the flood wave.

The U.S. Army Corps of Engineers provided most of the stage information for at least 50 stations along the upper Mississippi River. Several requests required considerable time to fulfill or required searching of archived records. Some of these very helpful people were E.G. Eaton and K.W. Willus in the St. Paul District; W.H. Koelner, J.D. Bledsoe, B.J. Goodrum, G.F. Gitter, and K.W. Finch in the Rock Island District; D.M. Coleman, S.G. Farkas, and R.J. Kopsky, Jr., in the St. Louis District; and S.A. Lehr and H.W. Barton in the Memphis District.

The water-level information along Illinois Route 3 in Alexander County, Illinois, behind the East Cape Girardeau levee, was provided by K.L. Bartelsmeyer and B.G. Stout, Jr., of the Illinois Department of Transportation, Division of Highways.

Discussions with J.F. Sullivan of the Wisconsin Department of Natural Resources were instrumental in the conception of this chapter.

FLOOD-WAVE PROPAGATION

Hydrologic factors, such as tributary inflow or flood-plain storage, were more important than hydraulic factors, such as water depth, channel width, and channel roughness, in determining the flood-wave propagation speed. Water speed is not the same as wave-propagation speed. The wave-propagation speed was determined from the times and locations of maximum stages or discharges in the regulated reach of the upper Mississippi River. The general observed wave-propagation speed was 0.58 m/s for open-channel conditions during the 1993 flood (fig. 6). This compares closely with the wave-propagation speed of 0.52 m/s calculated from measurements given by Seddon (1900) for the upper Mississippi River flood of April 1881 when no navigation dams were present.

Tributary Inflow

The peak inflow from the tributaries of the upper Mississippi River upstream from the Illinois and the Missouri Rivers was nearly synchronous with the arrival of the flood wave from upstream because the areas of intense rainfall moved southward as the summer progressed (Wahl and others, 1993). This pattern of inflow contrasts with the inflow from the Illinois and the Missouri Rivers, which lagged behind the arrival of the upper Mississippi River flood wave by about 2 weeks and caused the wave-propagation speed to decrease from 0.58 to about 0.08 m/s (fig. 6). The average wave-propagation speed in the open-

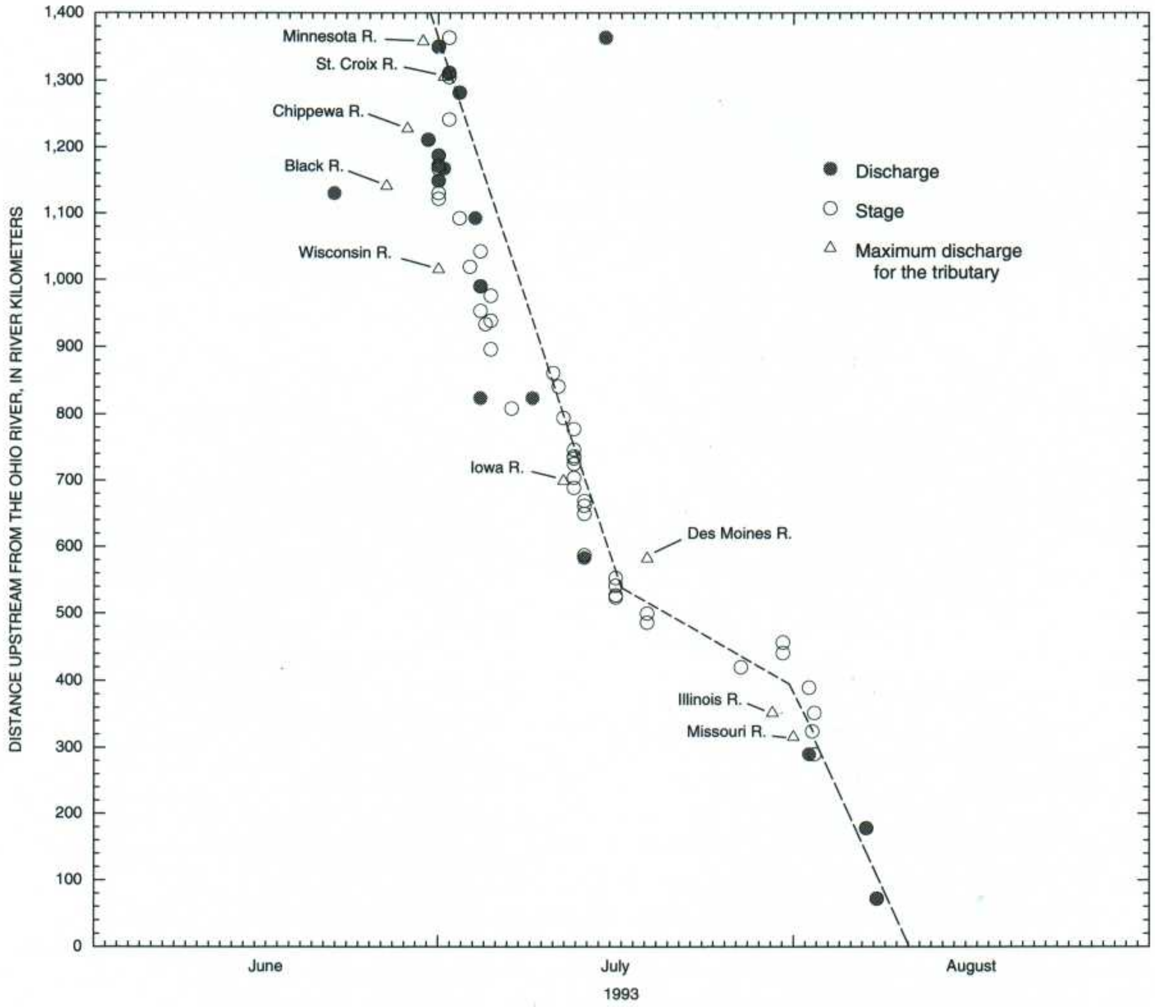


Figure 6. Times and locations of maximum stages and discharges during the 1993 flood on the upper Mississippi River. Maximum stages are shown by open circles, and maximum discharges, by solid circles. The times and locations of maximum discharges for the tributary are labeled. The three segments of the dashed line were fit visually to show the general trend. The slope of the three line segments is an estimate of the flood-wave propagation speeds and are equal to 0.58, 0.08, and 0.42 m/s.

channel reach from St. Louis to Thebes increased to about 0.42 m/s (fig. 6); this still was much less than the average of 1.6 m/s for previous high-water events in 1993 (table 2). Along some reaches, however (for example, 300–400, 700–800, 900–1,100, and 1,100–1,200 km upstream from the Ohio River), the wave-propagation speed was much higher than 0.58 m/s. This higher speed usually was caused by the arrival of the tributary inflow at the downstream end of a reach of the upper Mississippi River at the same time that the flood wave was arriving at the upstream end of the same reach. Consequently, the time of maximum stage or discharge coincided nearly simultaneously along the entire reach of the river and resulted in high wave-propagation speeds.

An estimate of the wave-propagation speed for a simple kinematic wave in an open channel is the slope of the regression line for a plot of discharge as a function of cross-sectional area (Gilcrest, 1950). These estimates of the predicted kinematic wave-propagation speed for stations on the upper Mississippi River (table 2) generally differ from the speeds observed during the flood of 1993 and the speeds calculated from measurements during previous high-water events. This is because the significant tributary inflow, not the hydraulic factors, determined the propagation speed of the flood wave, and numerous levee breaks and seepage under and through the levees delayed the arrival of the flood wave downstream by removing water from the river and storing it on the flood plain.

Table 2. Flood-wave propagation speeds on the upper Mississippi River

[km, kilometer; m/s, meter per second; numbers following ± symbol are standard deviations]

Upper Mississippi River stream-gaging stations	Distance upstream from the Ohio River (km)	Wave propagation speed (m/s)		
		Predicted[1]	Observed 1993 flood[2]	Previous high water events[3]
Regulated river:				
Prescott, Wis.	1,306	0.92±0.73	0.58	
				No data.
Winona, Minn.	1,168	.91–1.4	.58	
				Do.
Pool 8, Wis./Minn.[4]	1,097–1,102	.69	.58	
				Do.
McGregor, Iowa	1,019	.88± .06	.58	
				0.59
Clinton, Iowa	823	2.3± .21	.58	
				1.86
Keokuk, Iowa	582	1.9± .15	.58	
Open river:				.65
St. Louis, Mo.	289	3.0± .30	.42	
				1.3±0.3
Chester, Ill.	177	2.1± .12	.42	
				1.9± .8
Thebes, Ill.	70	3.9± .28	.42	

[1] From the slope of a regression line of measured discharge as function of a cross-sectional area.

[2] From slope of dashed lines (fig. 6), which is an average over several stream-gaging stations but listed for each station as the same value.

[3] From measurements of historic high water events of various magnitude previous to the flood of 1993 in the regulated river reach (Institute of River Studies, 1983, Plate II) and for seven events previous to the flood of 1993 in the open-channel reach.

[4] Based on three measurements at different locations made on July 14 and October 18, 1991, and April 16, 1992.

Flood-Plain Storage

During the flood of 1993, water was stored on flood plains because of two mechanisms—levee breaks and levee seepage. No levee breaks occurred upstream from Clinton, a few occurred between Clinton and St. Louis, but the largest levee breaks occurred downstream from St. Louis and caused a delay in the arrival of the discharge flood peak at Thebes.

Levee Breaks

Among the most dramatic pictures seen on television and in the newspapers during the upper Mississippi River flood of 1993 were those of floodwaters raging through levee breaks and flooding adjacent flood plains. The floodwalls that protect St. Louis and East St. Louis, Illinois, held throughout the flood and confined the river to a narrow channel near the Gateway Arch at St. Louis. However, many levees failed downstream from St. Louis (table 3) and allowed water to flow onto the flood plain, thus decreasing the discharge of the river at Thebes where natural bluffs again confined the floodwaters to a narrow channel. The plot of water discharge at St. Louis (fig. 7) has been lagged 2 days (on the basis of the wave-propagation speed of previous high-water events in 1993) so that the two red shaded areas (in July and August) between the water-discharge graphs for St. Louis and Thebes represent the water volume stored on the flood plain between St. Louis and Thebes. These volumes of water stored on flood plains (fig. 7) between St. Louis and Thebes were estimated to be 1.36 x 10^9 m^3 during July and an additional 1.54 x 10^9 m^3 during August. The volume of water stored on flood plains also can be estimated by using the approximate area protected by the levees that broke and an assumed average depth (table 3). A generous estimate of the average depth is 6 m, but this is still not enough to account for all the water stored on the flood plain, which is based on the difference in

Table 3. Some levee breaks on the upper Mississippi River, July and August 1993

[km, kilometer; km^2, square kilometer; m^3, cubic meter; m, meter. Information between St. Louis, Missouri, and Thebes, Illinois, was provided by S.G. Farkas, U.S. Army Corps of Engineers, St. Louis District; information between Clinton and Keokuk, Iowa, was supplied by G.F. Gitter, U.S. Army Corps of Engineers, Rock Island District, November 1993]

Levee	Distance of levee break upstream from the Ohio River (km)	Date of break 1993	Approximate area protected (km^2)	Approximate volume of water stored on the flood plain for various assumed depths (10^9 m^3)		
				2-m deep	4-m deep	6-m deep
Clinton to Keokuk, Iowa						
Green Island	879–882	July 2	29	0.06	0.12	0.17
Henderson Co. No. 3	663–668	July 1	9	.02	.04	.05
Green Bay	623–637	July 10	55	.11	.22	.33
Keokuk, Iowa, to St. Louis, Missouri						
Meyer	550–576	July 9	40	0.08	0.16	0.24
Indian Grave South and North	531–550	July 13	69	.14	.28	.41
Sny	478–507	July 25	445	.89	1.78	2.67
St. Louis, Missouri, to Cairo, Illinois						
St. Genevieve	196	July 18	28	0.06	0.11	0.17
Kaskaskia	179	July 22	38	.08	.15	.23
Bois Brule	156	July 25	106	.21	.42	.64
Subtotal for July levee breaks.			174	0.35	0.68	1.04
Columbia	265	August 1	57	0.11	0.23	.34
Harrisonville[1]	249	August 2	188	.38	.75	1.13
Subtotal for August levee breaks.			245	0.49	0.98	1.47

[1] Later breached deliberately at river kilometer 212.

the discharge graphs for St. Louis and Thebes (fig. 7). The levee breaks, therefore, probably do not account for all the water stored on the flood plain; additional water was stored by seepage through and under levees that did not fail.

Levee Seepage

Although the levee breaks made national news, the seepage of water through and under the levees also was important. Levee breaks happen suddenly and allow rapid inundation of the flood plain, whereas seepage continues steadily for as long as the river level is higher than that of the water in the adjacent flood plain protected by the levee. Seepage can continue long after the flood peak in the river has passed the levee (fig. 8). For example, although the flood peak passed Thebes on August 7, water continued to seep under the 51-km-long levee that protected the East Cape Girardeau (an area of 38 km^2) and the Clear Creek (an area of 73 km^2) Levee Districts, which are just upstream from Thebes, until September 25. The seepage slowly raised the water level an additional 0.6 m (B.G. Stout, Illinois Department of Transportation, written commun., 1993). The water level behind the levees rose even as the river level was falling and in spite of pumps that were operating to lower the water level. Homes and businesses behind the levees that

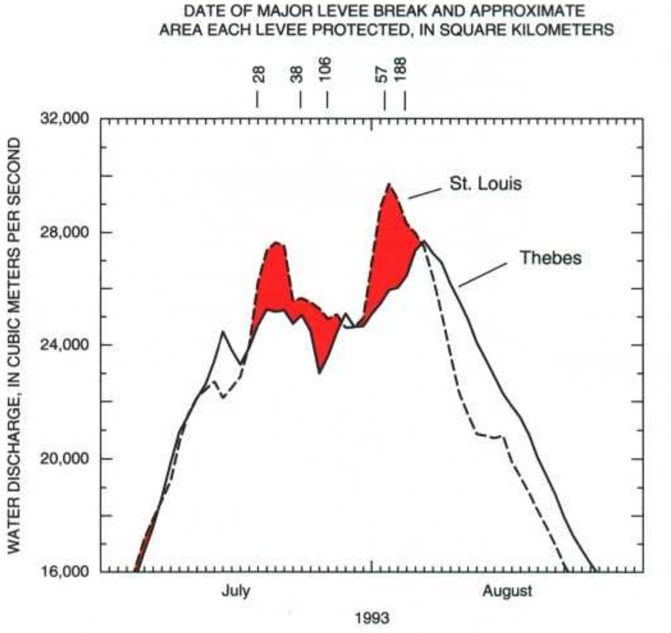


Figure 7. Daily mean discharge of the upper Mississippi River at St. Louis, Missouri, and at Thebes, Illinois. The discharge at St. Louis was plotted 2 days later to compensate for the travel time of water between the two stations. The red shaded area represents the volume of water lost between St. Louis and Thebes. For July, this volume was 1.36 x 10^9 cubic meters, and for August, it was 1.54 x 10^9 cubic meters.

were dry on August 7 were flooded on September 25. No measurements of the water level were made after September 25, but the water level probably rose a little higher when a minor flood peak passed Thebes on October 2. The river level did not drop sufficiently below the water level behind the levees until October 11, when the gates in the levees were opened, and the water began to drain back into the river (R.R. Colyer, East Cape Girardeau Levee District, oral commun., 1993). If a conservative mean water depth of about 1 m is assumed, then the volume of water stored on the flood plain in these levee districts must have been about 0.1 x 10^9 m^3. If seepage in other levee districts along the 217 km of river between St. Louis and Thebes is allowed for, then an additional 0.2 to 0.3 x 10^9 m^3 of water may have been stored on the flood plain. This volume, when added to the water stored from the levee breaks, may account for the difference in discharge between St. Louis and Thebes (fig. 7). The storage of water on the flood plain explains the observation that the wave-propagation speed between St. Louis and Thebes was slower than the predicted speeds or the measured speeds of previous high-water events that had no discharge losses caused by levee breaks or seepage (table 2).

FLOOD-WAVE COMPOSITION

A water budget was constructed by computing the discharge contribution from upstream tributaries to the flood wave and comparing it to the measured discharge at five primary stream-gaging stations on the upper Mississippi River—Prescott, Winona, Clinton, Keokuk, and St. Louis. For computations of tributary contributions during open-channel conditions from June through August discharges of tributaries and the discharges at stream-gaging stations on the upper Mississippi River upstream from the primary gaging station were lagged relative to the downstream primary gaging station (see travel times in table 1). The tributary and upstream contributions were computed as percentages of the reported daily mean discharge at the primary station (table 4) and not as percentages of the sum of all tributaries and the upstream lagged discharges. Therefore, if some of the water that passed an upstream tributary gaging station was later stored on the flood plain and did not reach the downstream primary station, then the sum of the percentages could be greater than 100, and the amount that is greater than 100 percent represents stored water (figs. 9–13).

The error in this percentage computation is a function of the error in estimating the lag time, the error in the rating curve for each stream-gaging station,

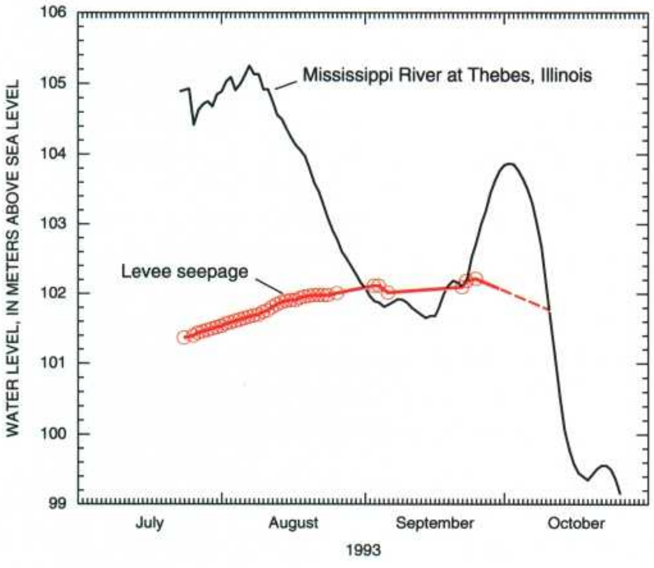
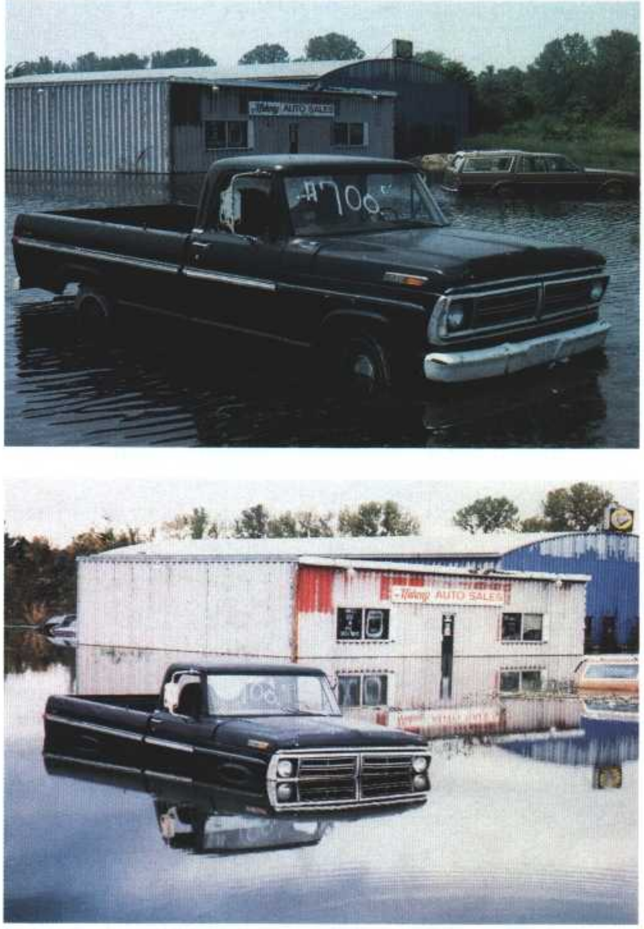


Figure 8. Water levels for the Mississippi River near Thebes, Illinois (black line), and for the adjacent East Cape Girardeau and Clear Creek Levee Districts (red line) from July through October 1993. The water level in the Levee Districts probably peaked between September 25 and October 11 (dashed extension of red line). Water levels inside the levee were supplied by B. G. Stout, Jr., of the Illinois Department of Transportation.



The photograph of the truck above was taken on August 16, 1993, and the one below was taken on October 11, 1993, within the East Cape Girardeau Levee District. See figure 8 for water levels inside the levee district. Photographs were supplied by R.H. Meade, U.S. Geological Survey.

and the number of tributaries. The error in estimating the lag time is proportional to the change in discharge with time (for a specific tributary or upstream gaging station) and weighted by the fraction of the total discharge contributed by the tributary or upstream gaging station. At most tributary and upstream gaging stations, the discharge changed slowly with time. However, for some tributary stations, the change in discharge with time was large, although the fraction of the total discharge contributed by these tributaries was often small and compensated for the large change in discharge with time. Assuming that the rating curve error was 5 percent, a few estimates of the error in the percentage computation were made for a range of discharges of the upper Mississippi River at Prescott and St. Louis. At Prescott these errors were slightly larger (7–15 percent) than those at St. Louis (7–10 percent).

Mississippi River at Prescott, Wisconsin

The daily mean discharge of two tributaries, the Minnesota and the St. Croix Rivers, accounted for 50 to 90 percent of the daily mean discharge at Prescott during June and July; the maximum daily mean discharge (3,680 m^3/s, or 7.5 times the mean discharge) at Prescott was measured on June 27 (fig. 9). The maximum daily mean discharge of the Minnesota River near Jordan, Minnesota, was 24 times the mean discharge, but the maximum daily mean discharge of the St. Croix River at St. Croix Falls, Wisconsin, was only 4.3 times the mean discharge. About 3 percent of the unaccounted discharge of the Mississippi River at Prescott is from ungaged tributaries (J.H. Hess, U.S. Geological Survey, oral commun., 1994).

Mississippi River at Winona, Minnesota

Many of the small tributaries of the upper Mississippi River between Prescott and Winona are ungaged; the percentage of the discharge contributed by these tributaries is unknown and probably explains why the total percentages at Winona usually are less than 95 percent (fig. 10). The Vermillion, the Cannon, the Zumbro, and the Whitewater Rivers, which have stream gages on either their main stems or some of their tributaries, accounted for 1 to 7 percent of the water that flowed past Winona. The major tributary that entered the upper Mississippi River between Prescott and Winona is the Chippewa River, which reached a maximum daily mean discharge (2,400 m^3/s, or 11 times the mean discharge) on June 23. This discharge flood peak arrived at Winona on June 24 and accounted for 56 percent of the water that passed Winona on that day. Discharge of the Mississippi River at Prescott accounted for 43 to 79 percent of the water that passed Winona in June and for 71 to 83 percent in July.

Mississippi River at Clinton, Iowa

The discharge from many small tributaries must be considered in an accounting of all the water that flowed past Clinton. The Black and the Wisconsin Rivers are the main tributaries between Winona and Clinton, but the combined discharge from the Trempealeau, the Root, the upper Iowa, the Turkey, the Grant, the Platte, and the Maquoketa Rivers accounted for 6 to 20 percent of the water that flowed past Clinton. Total discharge contributions were greater than 100 percent of

Table 4. Daily mean discharges for the Upper Mississippi River and some of its tributaries, June through August 1993

[Discharge values in cubic meters per second; station number is a unique U.S. Geological Survey identification number; some discharge values are provisional and may differ from later data published in the U.S. Geological Survey's Water-Data Reports; - - -, no data; ^{e}, estimate]

Day	Mississippi River near Anoka, Minnesota, station number 05288500			Minnesota River near Jordan, Minnesota, station number 05330000			St. Croix River at St. Croix Falls, Wisconsin, station number 05340500			Mississippi River at Prescott, Wisconsin, station number 05344500		
	June	July	August	June	July	August	June	July	August	June	July	August
1	564	750	518	467	1,590	736	368	266	91	1,400	3,140	1,570
2	600	753	493	476	1,450	739	388	294	85	1,450	2,970	1,540
3	623	759	484	498	1,330	742	365	261	84	1,520	2,920	1,510
4	623	790	450	527	1,300	736	331	286	78	1,540	2,800	1,490
5	606	801	442	555	1,310	725	292	331	75	1,550	2,780	1,470
6	583	833	419	581	1,340	716	255	351	85	1,530	2,780	1,440
7	558	872	408	598	1,390	705	230	348	82	1,510	2,780	1,420
8	535	929	394	603	1,460	694	219	320	65	1,490	2,800	1,400
9	507	946	419	598	1,470	683	231	306	99	1,470	2,860	1,380
10	479	966	396	592	1,440	654	277	382	79	1,470	2,890	1,500
11	450	974	374	592	1,390	626	334	419	73	1,480	3,030	1,400
12	425	952	362	603	1,310	603	317	413	76	1,500	3,090	1,210
13	422	920	348	626	1,240	583	271	354	76	1,460	3,030	1,160
14	405	920	354	657	1,170	572	255	292	73	1,400	2,890	1,130
15	394	898	377	663	1,100	572	262	264	92	1,400	2,760	1,090
16	385	878	365	649	1,050	583	254	240	81	1,420	2,660	1,100
17	445	861	343	705	1,000	657	273	223	79	1,420	2,570	1,120
18	445	835	365	884	980	782	232	200	86	1,420	2,470	1,120
19	459	793	399	1,070	957	915	219	184	95	1,550	2,380	1,180
20	470	750	388	1,290	935	1,020	233	170	93	1,680	2,310	1,340
21	493	716	382	1,680	906	1,040	239	167	78	1,870	2,230	1,520
22	515	685	391	2,150	869	1,000	271	140	80	2,070	2,160	1,600
23	544	663	402	2,430	847	932	278	121	100	2,380	2,080	1,620
24	620	649	399	2,570	824	861	374	130	86	2,730	1,990	1,610
25	694	640	396	2,570	804	801	459	121	94	3,140	1,940	1,530
26	739	612	399	2,440	787	748	558	123	89	3,430	1,900	1,460
27	762	586	422	2,290	762	700	558	110	91	3,680	1,840	1,390
28	770	572	436	2,120	745	646	464	105	86	3,620	1,760	1,330
29	762	549	433	1,950	731	609	396	97	99	3,480	1,700	1,300
30	762	530	433	1,770	722	586	328	91	98	3,310	1,640	1,270
31	---	521	436	---	725	569	---	98	103	---	1,580	1,230

Table 4. Daily mean discharges for the Upper Mississippi River and some of its tributaries, June through August 1993—Continued

Day	Chippewa River at Durand, Wisconsin, station number 05369500			Mississippi River at Winona, Minnesota, station number 05378500			Black River near Galesville, Wisconsin, station number 05382000			Wisconsin River at Muscoda, Wisconsin, station number 05407000		
	June	July	August	June	July	August	June	July	August	June	July	August
1	467	374	158	1,990	4,500	2,060	166	94	52	309	600	289
2	589	365	197	2,010	4,470	2,040	311	128	87	354	555	279
3	552	348	252	2,070	4,390	1,940	245	154	112	530	473	270
4	385	402	211	2,140	4,250	1,840	150	197	104	623	433	270
5	328	371	174	2,160	4,130	1,820	96	203	80	629	450	279
6	274	374	143	2,140	4,020	1,830	68	196	67	566	518	276
7	245	354	163	2,110	3,940	1,830	62	152	59	445	580	264
8	311	328	116	2,060	3,790	1,860	63	119	54	456	597	245
9	289	345	186	2,040	3,710	1,900	79	106	54	436	634	218
10	382	337	368	2,020	3,650	1,890	162	99	61	425	682	235
11	436	345	365	2,040	3,620	1,930	408	96	101	538	660	246
12	413	343	309	2,050	3,650	2,000	462	88	107	677	597	240
13	385	326	232	2,060	3,710	2,020	340	84	90	773	547	237
14	345	273	189	2,070	3,710	1,950	215	80	72	827	532	238
15	323	283	138	2,080	3,710	1,890	134	78	64	850	481	289
16	314	262	176	2,050	3,620	1,790	108	75	63	827	439	323
17	328	231	184	2,040	3,540	1,720	106	68	62	759	436	340
18	558	226	179	2,130	3,460	1,740	145	66	61	716	442	311
19	847	184	163	2,360	3,310	1,770	331	64	58	682	510	283
20	1,040	232	161	2,800	3,200	1,820	801	64	54	722	462	273
21	1,350	187	135	3,140	3,060	1,870	1,540	58	50	838	430	261
22	2,150	176	120	3,460	2,920	1,880	1,350	56	47	971	411	246
23	2,400	160	126	3,770	2,800	1,880	869	54	44	1,190	382	249
24	1,800	159	136	4,250	2,680	1,910	572	51	43	1,420	354	220
25	1,190	117	148	4,640	2,590	1,990	422	51	40	1,600	351	225
26	833	110	140	4,760	2,480	2,030	300	56	39	1,670	354	236
27	733	185	132	4,760	2,410	2,050	208	57	38	1,650	334	237
28	586	154	126	4,700	2,340	2,050	146	72	38	1,410	348	227
29	541	140	96	4,640	2,280	2,020	116	57	38	943	343	227
30	530	148	117	4,590	2,190	2,000	104	51	45	665	320	229
31	---	167	190	---	2,110	1,990	---	48	53	---	289	220

Table 4. Daily mean discharges for the Upper Mississippi River and some of its tributaries, June through August 1993—Continued

Day	Mississippi River at McGregor, Iowa, station number 05389500			Mississippi River at Clinton, Iowa, station number 05420500			Rock River near Joslin, Illinois, station number 05446500			Wapsipinicon River near De Witt, Iowa, station number 05422000		
	June	July	August	June	July	August	June	July	August	June	July	August
1	2,300	5,300	2,700	2,890	6,570	3,770	337	685	464	78	253	196
2	2,320	5,210	2,620	2,920	6,630	3,710	331	776	456	75	250	177
3	2,350	5,070	2,530	2,920	6,630	3,620	331	858	445	72	236	159
4	2,420	4,960	2,460	2,920	6,570	3,430	326	901	428	72	237	136
5	2,530	4,900	2,390	2,940	6,430	3,260	343	886	411	90	269	124
6	2,610	4,810	2,340	3,000	6,540	3,170	377	799	399	91	348	118
7	2,650	4,700	2,280	3,200	6,740	2,890	382	705	385	95	422	111
8	2,660	4,560	2,220	3,480	6,710	2,920	436	657	385	165	541	105
9	2,670	4,450	2,190	3,820	6,480	2,940	668	637	374	214	586	112
10	2,630	4,330	2,170	3,880	6,370	3,000	923	643	388	214	467	188
11	2,580	4,220	2,170	3,820	6,310	2,970	986	646	374	182	391	190
12	2,550	4,130	2,210	3,740	6,230	2,920	929	640	377	168	365	194
13	2,560	4,110	2,250	3,620	6,170	2,920	821	637	385	168	391	199
14	2,690	4,110	2,280	3,620	6,090	2,860	733	643	360	168	513	195
15	2,710	4,080	2,390	3,710	5,920	2,890	683	666	351	157	609	208
16	2,640	4,050	2,500	3,710	5,690	2,890	680	677	346	162	575	233
17	2,630	4,050	2,570	3,740	5,520	2,970	651	677	348	162	510	266
18	2,620	4,020	2,590	3,910	5,440	3,260	612	677	337	159	532	264
19	2,680	3,990	2,550	4,020	5,350	3,510	615	716	329	177	538	274
20	2,830	3,940	2,480	4,130	5,350	3,740	680	753	317	200	544	314
21	3,090	3,820	2,430	4,190	5,240	3,680	773	762	314	207	572	323
22	3,430	3,710	2,400	4,220	5,130	3,540	793	750	314	203	507	314
23	3,940	3,600	2,410	4,220	5,010	3,370	753	742	306	209	464	300
24	4,280	3,450	2,400	4,300	4,900	3,230	719	700	303	217	433	289
25	4,450	3,370	2,370	4,670	4,760	3,260	685	643	286	212	394	320
26	4,640	3,260	2,340	5,010	4,640	3,260	649	595	292	198	337	371
27	4,810	3,110	2,330	5,350	4,530	3,170	612	564	286	227	289	377
28	4,980	3,030	2,350	5,660	4,390	3,090	600	535	276	286	274	365
29	5,130	2,920	2,370	5,920	4,220	3,000	634	518	273	273	241	354
30	5,270	2,830	2,400	6,290	4,080	3,140	649	498	292	281	225	354
31	---	2,760	2,430	---	3,940	3,200	---	481	303	---	219	374

Table 4. Daily mean discharges for the Upper Mississippi River and some of its tributaries, June through August 1993—Continued

Day	Iowa River at Wapello, Iowa, station number 05465500			Skunk River at Augusta, Iowa, station number 05474000			Mississippi River at Keokuk, Iowa, station number 05474500			Des Moines River at Keosauqua, Iowa, station number 05490500		
	June	July	August	June	July	August	June	July	August	June	July	August
1	592	1,220	1,810	152	564	442	4,300	9,320	7,960	895	1,130	1,920
2	578	1,350	1,730	151	561	419	4,250	9,460	7,110	920	1,030	1,780
3	575	1,270	1,770	176	439	360	3,960	9,660	5,890	937	1,130	1,670
4	600	1,160	1,680	272	343	328	4,250	9,850	6,850	963	1,240	1,570
5	682	1,190	1,560	396	416	306	4,560	10,100	5,970	1,060	1,650	1,490
6	708	1,630	1,400	354	600	283	4,560	10,500	5,780	917	2,240	1,420
7	699	2,700	1,380	253	728	269	4,500	11,200	5,440	883	2,710	1,350
8	864	3,000	1,380	527	903	255	4,640	11,100	5,070	1,420	2,680	1,290
9	1,040	2,780	1,350	748	1,180	241	5,240	11,800	4,730	1,110	2,680	1,220
10	1,070	2,340	1,420	691	1,300	413	5,800	12,300	5,130	881	2,680	1,320
11	943	2,340	1,760	603	1,250	507	6,140	11,900	5,380	770	2,810	1,230
12	892	2,490	2,050	320	1,120	674	6,230	11,900	6,170	716	2,920	1,340
13	898	2,700	1,780	212	847	677	6,260	11,900	6,230	691	3,060	1,460
14	960	2,890	1,480	197	654	572	5,780	11,700	6,340	674	3,030	1,350
15	1,040	2,560	1,370	178	648	496	5,890	11,500	6,120	634	3,030	1,350
16	1,070	2,230	1,590	165	583	725	5,780	11,400	6,090	606	3,000	1,320
17	1,030	2,150	2,040	167	634	835	5,690	11,400	6,570	623	2,970	1,250
18	932	2,170	2,200	163	617	835	5,660	11,200	6,680	637	2,890	1,180
19	934	2,210	2,050	175	694	875	5,690	11,000	6,940	719	2,890	1,190
20	1,060	2,420	1,980	275	731	855	5,780	10,900	6,940	779	2,860	1,480
21	1,130	2,540	1,910	348	702	762	6,030	10,900	7,080	793	2,800	1,510
22	1,190	2,320	1,990	320	671	702	6,200	11,000	7,050	872	2,690	1,360
23	1,260	2,090	2,210	331	694	629	6,430	11,000	6,970	878	2,690	1,280
24	1,200	2,580	2,200	425	787	566	6,570	11,200	6,940	883	2,680	1,230
25	1,480	2,920	2,020	906	1,010	527	7,650	11,300	6,940	895	2,710	1,180
26	1,750	2,780	1,830	722	1,110	456	7,870	11,400	6,680	883	2,640	1,140
27	1,680	2,320	1,740	445	1,070	430	7,820	11,200	6,400	883	2,460	1,110
28	1,620	2,070	1,630	371	946	470	8,100	10,900	6,230	883	2,270	1,080
29	1,420	1,900	1,590	300	750	476	8,160	10,300	6,120	889	2,120	1,080
30	1,220	1,810	1,600	354	566	430	8,550	10,300	5,950	1,010	2,010	1,160
31	---	1,770	1,700	---	462	470	---	9,090	6,060	---	1,940	1,210

Table 4. Daily mean discharges for the Upper Mississippi River and some of its tributaries, June through August 1993—Continued

Day	Illinois River at Valley City, Illinois, station number 05586100			Missouri River at Hermann, Missouri, station number 06934500			Mississippi River at St. Louis, Missouri, station number 07010000			Mississippi River at Thebes, Illinois, station number 07022000		
	June	July	August	June	July	August	June	July	August	June	July	August
1	646	1,470	2,250	4,360	5,300	20,300	10,800	14,000	29,700	11,400	14,200	25,100
2	612	1,640	1,880	4,280	6,660	18,500	10,600	14,600	29,200	11,200	14,300	25,500
3	600	1,700	1,530	4,390	7,650	16,500	10,500	16,000	28,600	11,100	14,400	25,900
4	657	1,710	1,510	4,360	8,210	14,500	10,200	17,100	28,000	10,900	14,900	26,000
5	677	1,760	1,420	4,420	8,270	12,900	10,200	17,900	27,400	10,700	15,800	26,500
6	711	1,800	1,520	4,810	8,330	11,800	10,300	18,600	26,400	10,600	16,700	27,400
7	708	1,730	1,590	6,630	11,400	10,800	11,200	19,300	25,100	10,700	17,600	27,700
8	660	1,720	1,580	6,740	11,800	10,300	12,400	20,600	23,700	11,100	18,700	27,300
9	663	1,690	1,540	6,680	11,600	9,910	12,900	21,600	22,300	12,000	19,900	26,900
10	694	1,610	1,530	6,320	10,300	9,540	13,000	22,200	21,600	12,800	21,000	26,200
11	750	1,590[e]	1,480	5,920	9,710	9,290	12,800	22,800	20,900	13,100	21,500	25,600
12	801	1,560[e]	1,460	5,580	9,370	9,290	12,700	22,800	20,800	13,200	22,100	24,900
13	847	1,590[e]	1,480	5,130	9,400	10,500	12,600	22,100	20,700	13,100	22,600	24,100
14	889	1,620	1,460	4,640	9,830	9,010	12,300	22,500	20,700	13,000	23,400	23,500
15	935	1,640[e]	1,420	4,450	12,300	8,500	12,100	22,900	19,900	12,900	24,500	22,900
16	986	1,670[e]	1,370	4,450	13,900	8,210	11,800	24,000	19,200	12,700	23,800	22,300
17	1,030	1,640[e]	1,350	4,620	11,800	7,790	11,700	26,200	18,500	12,500	23,300	21,800
18	1,070	1,590[e]	1,370	4,560	10,600	7,080	11,800	27,400	17,900	12,300	23,900	21,400
19	1,110	1,540	1,420	4,280	10,100	6,230	11,700	27,600	17,300	12,200	24,700	20,800
20	1,140	1,500[e]	1,460	4,250	9,830	5,580	11,500	27,500	16,600	12,100	25,300	20,000
21	1,180	1,470[e]	1,420	4,250	9,540	5,270	11,600	25,600	15,900	12,000	25,200	19,400
22	1,210	1,440[e]	1,380	4,360	9,290	5,130	11,500	25,700	15,300	11,900	25,200	18,700
23	1,250	1,490[e]	1,320	4,810	9,120	5,210	11,600	25,500	15,000	11,900	24,800	18,000
24	1,280	1,640	1,290	4,450	9,060	5,470	11,800	25,300	14,900	11,800	25,100	17,300
25	1,340	1,770	1,250	5,270	9,830	5,240	12,000	24,900	14,900	12,000	24,500	16,800
26	1,380	2,000	1,210	5,720	10,600	4,900	12,900	25,100	14,700	12,400	23,000	16,300
27	1,370	2,090	1,170	4,900	10,900	4,670	13,400	24,700	14,400	12,700	23,600	15,900
28	1,350	2,180	1,120	4,870	12,100	4,500	13,400	24,700	14,200	13,300	24,400	15,500
29	1,280	2,250	1,060	5,100	14,500	4,280	13,800	25,000	13,900	13,700	25,100	15,200
30	1,290	2,100	1,010	4,960	18,000	3,910	14,000	26,900	13,700	14,000	24,600	14,800
31	---	2,200	971	---	20,900	3,910	---	28,900	13,300	---	24,700	14,500

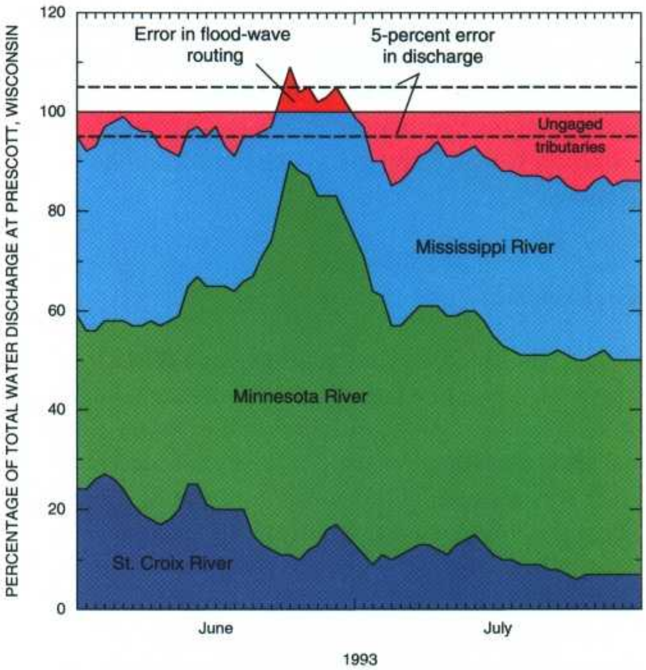


Figure 9. Flood-wave composition of the Mississippi River at Prescott, Wisconsin. The amount of water is proportional to the vertical distance between successive curves. Pink represents discharge from ungaged smaller tributaries and any flood-wave routing errors of less than 100 percent. Red represents any flood-wave routing errors of more than 100 percent.

the actual discharge at Clinton between June 26 and July 2 (fig. 11). The sharp daily mean discharge peak of the Black River for June 21 (1,540 m^3/s, or 31 times the mean discharge) was expected to reach Clinton about June 27; however, much of the peak discharge may have been stored on the flood-plain delta near the mouth of the Black River (J.F. Sullivan, Wisconsin Department of Natural Resources, oral commun., 1993) and did not reach Clinton until after July 2 (fig. 11). The Wisconsin River had a broad daily mean discharge peak (1,670 m^3/s, or 6.8 times the mean discharge), which accounted for 16 to 28 percent of the daily mean discharge at Clinton between June 16 and July 2. The Mississippi River at Winona contributed from 49 to 80 percent of the daily mean discharge at Clinton during June and July.

Mississippi River at Keokuk, Iowa

The Rock River reached a maximum earlier (June 11) than did most tributaries of the upper Mississippi River. The maximum daily mean discharge (986 m^3/s, or 5.7 times the mean discharge) of the Rock River represented 17 percent of the daily mean discharge at Keokuk (fig. 12). The combined discharge of the Iowa, the Skunk, and the Wapsipinicon Rivers in Iowa accounted for 17 to 48 percent of the daily mean discharge at Keokuk from June through August. The individual maximum daily mean discharges of these three tributaries arrived at Keokuk on or about July 10, July 11, and July 19. The discharge of the Mississippi River at Clinton accounted for less than 50 percent of the discharge at Keokuk after July 19, and the combined discharges of the Iowa, the Skunk, and the Wapsipinicon Rivers accounted for slowly increasing percentages of the discharge at Keokuk through August.

Mississippi River at St. Louis, Missouri

The discharges of the Des Moines and the Illinois Rivers each accounted for 5 to 12 percent of the daily mean discharge at St. Louis from June through August. The Mississippi River at Keokuk accounted for about 50 percent of the discharge at St. Louis with a maximum of 54 percent on July 13 and 14. In early August, the Mississippi River at Keokuk accounted

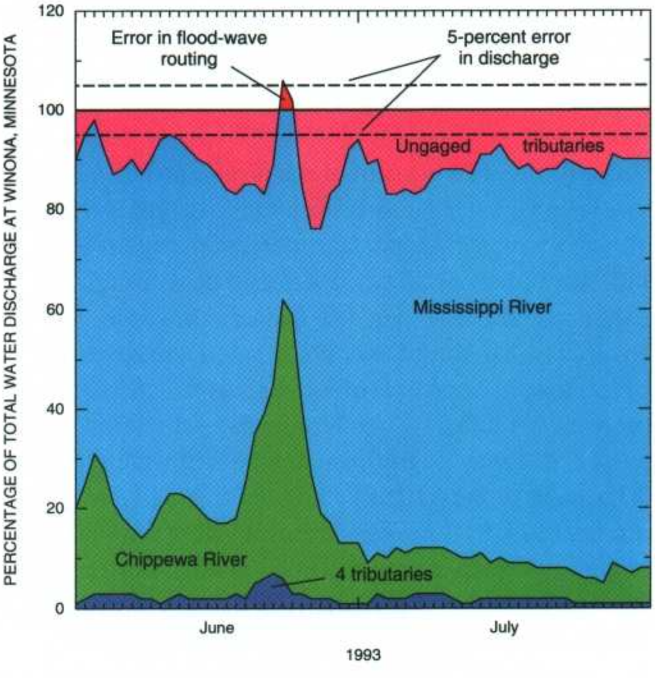


Figure 10. Flood-wave composition of the Mississippi River at Winona, Minnesota. The amount of water is proportional to the vertical distance between successive curves. Pink represents discharge from ungaged smaller tributaries and any flood-wave routing errors of less than 100 percent. Red represents any flood-wave routing errors of more than 100 percent. The four tributaries are the Vermillion, the Cannon, the Zumbro, and the White Water.

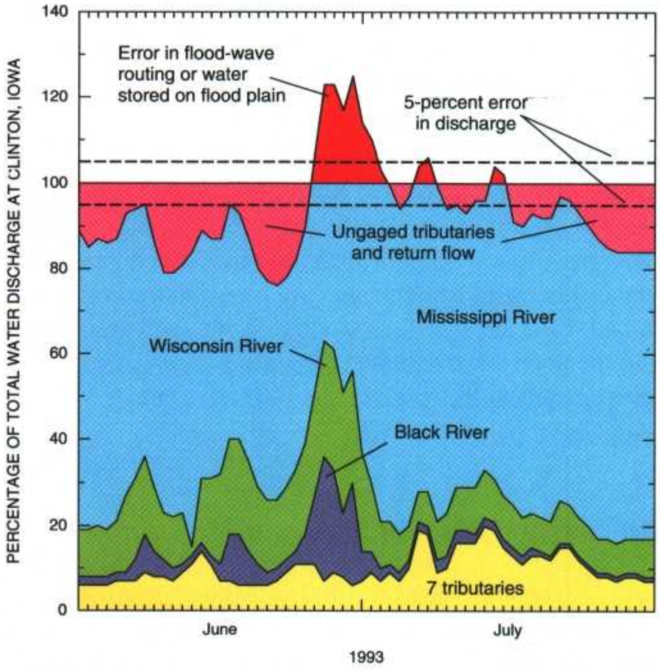


Figure 11. Flood-wave composition of the Mississippi River at Clinton, Iowa. The amount of water is proportional to the vertical distance between successive curves. Pink represents discharge from ungaged smaller tributaries, any flood-wave routing errors of less than 100 percent, or return flow to the upper Mississippi River. Red represents flood-wave routing errors of more than 100 percent or water that did not arrive at Clinton because of flood-plain storage. The seven tributaries are the Trempealeau, the Grant, and the Platte in Wisconsin, the Root in Minnesota, and the upper Iowa, the Turkey, and the Maquoketa in Iowa.

for only about 21 percent of the discharge at St. Louis due to large contributions from the Missouri River. However, in late August, this percentage again increased to about 50 percent due to decreasing contributions (about 30 percent) from the Missouri River. The Missouri River contributed a maximum percentage (70 percent) of the discharge at St. Louis on August 1 and 2, which are the dates the flood peak passed St. Louis. Significant amounts of water (10–20 percent of the discharge measured at St. Louis) did not reach St. Louis as a result of flow through major levee breaks onto the flood plain at upstream sites (table 3). The Meyer and the Indian Grave South and North levees were breached on July 9 and July 13, respectively, and flow through these breaks probably accounted for some of the water that did not reach St. Louis between July 10 and July 17 (fig. 13). The Sny levee was breached on July 25 after a long battle to save it (Stewart, 1993). Flow through this breach probably accounted for the additional water that was stored and did not reach St. Louis between July 28 and August 4. Some of the water stored on the flood plain drained back to the river (fig. 13) and represented the "missing" water that could not be accounted for by the Illinois, the Des Moines, and the Missouri Rivers or by the Mississippi River at Keokuk.

SUMMARY

The flood wave that propagated down the upper Mississippi River from June through August 1993 was a composite of individual tributary flood waves. The average wave-propagation speed in the river was about 0.58 m/s upstream from St. Louis and about 0.42 m/s downstream from St. Louis.

The wave-propagation speed was determined primarily by hydrologic factors, such as tributary inflow and flood-plain storage, rather than by hydraulic factors, such as water depth, channel width, and channel roughness. Flow through levee breaks accounted for most of the flood-plain storage on the upper Mississippi River, but levee seepage also was significant, especially in its impact on human activi-

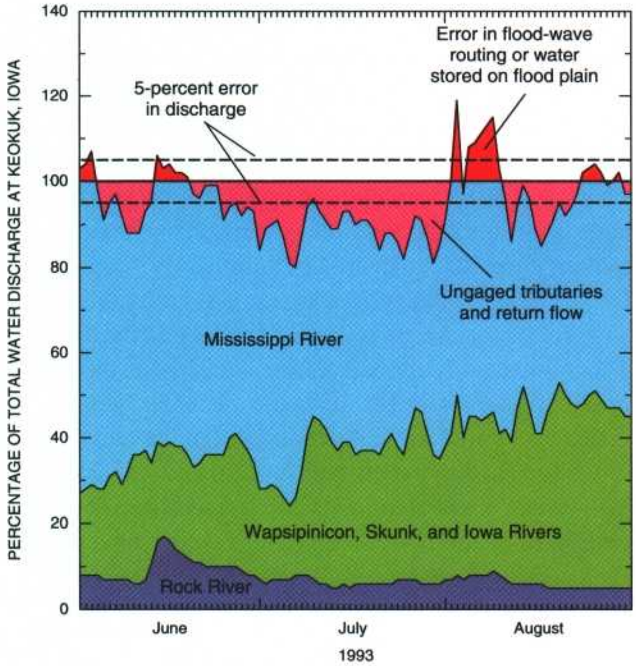


Figure 12. Flood-wave composition of Mississippi River at Keokuk, Iowa. The amount of water is proportional to the vertical distance between successive curves. Pink represents discharge from ungaged smaller tributaries, any flood-wave routing errors of less than 100 percent, or return flow to the upper Mississippi River. Red represents flood-wave routing errors of more than 100 percent or water that did not arrive at Keokuk because of flood-plain storage.

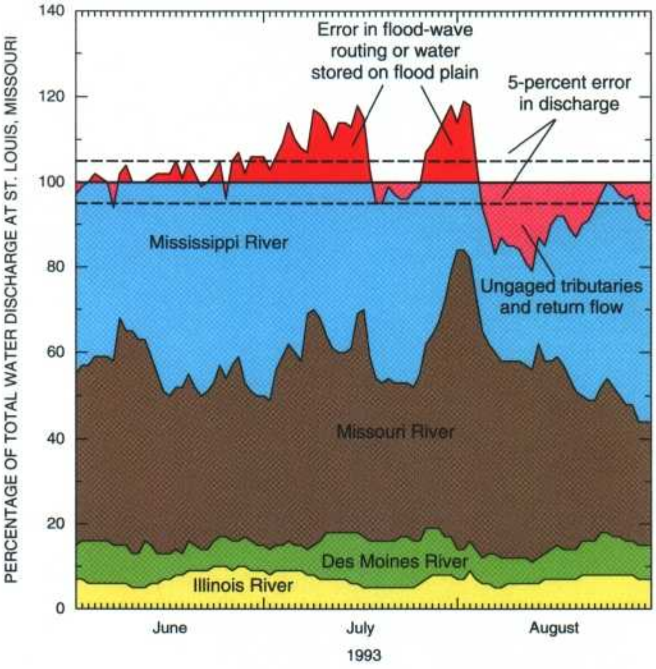


Figure 13. Flood-wave composition of Mississippi River at St. Louis, Missouri. The amount of water is proportional to the vertical distance between successive curves. Pink represents discharge from ungaged smaller tributaries, any flood-wave routing errors of less than 100 percent, or return flow to the upper Mississippi River. Red represents flood-wave routing errors of more than 100 percent or water that did not arrive at Keokuk because of flood-plain storage.

ties. Seepage through and under levees continued long after the peak of the composite flood wave in the river had passed, which caused extended periods of inundation.

The flood wave peaked twice as it passed St. Louis during July and August. The first discharge peak of 27,600 m^3/s on July 19 comprised about equal amounts (40 percent) of upper Mississippi and Missouri River water. A second and larger discharge of 29,700 m^3/s peaked on August 1; the Missouri River accounted for about 70 percent of the total discharge, or about twice the discharge contributed by the Mississippi River at Keokuk.

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