GEOMORPHIC CHANGES ON THE MISSISSIPPI RIVER FLOOD PLAIN

AT MILLER CITY, ILLINOIS AS A RESULT OF THE FLOOD OF 1·9·9·3

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U.S. GEOLOGICAL SURVEY CIRCULAR 1120–J

Front Cover—View of Miller City, Illinois levee break, August 1993. (U.S. Geological Survey)

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

View of Spirt of St. Louis Airport, Chesterfield,Mo. (Srenco Photography, St. Louis, Mo.)

GEOMORPHIC CHANGES ON THE MISSISSIPPI RIVER FLOOD PLAIN AT MILLER CITY, ILLINOIS, AS A RESULT OF THE FLOOD OF 1993

By Robert B. Jacobson and Kevin A. Oberg

Floods in the Upper Mississippi River Basin, 1993

U.S. GEOLOGICAL SURVEY CIRCULAR 1120–J

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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
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
centimeter (cm)	0.3937	inch
square kilometer (km^2)	0.3861	square mile
cubic meter (m^3)	35.31	cubic foot
centimeter per second (cm/s)	0.0328	foot per second
cubic meter per second (m^3/s)	35.31	cubic foot per second
metric tons	1.102	short tons

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.

Geomorphic Changes on the Mississippi River Flood Plain at Miller City, Illinois, as a Result of the Flood of 1993

By Robert B. Jacobson *and* Kevin A. Oberg

Abstract

During the flood of 1993 on the upper Mississippi and Missouri Rivers, the most dramatic changes to flood plains resulted at levee-break complexes. At these sites, large discharges were concentrated through narrow levee breaks, which resulted in high water-surface slopes and intensely turbulent flow. These conditions created extensive, deep scours and permitted sediment-laden water to flow into areas behind the levees. As a result, large areas of formerly productive bottom land were eroded or covered by thick deposits of sand.

The levee break at Miller City, Illinois, created a typical large levee-break complex. As much as 28 percent of the Mississippi River discharge flowed through the break during the peak of the flood. With velocities as great as 300 centimeters per second, the flow through the levee break was able to scour an area 2,200 meters long to a maximum depth of more than 20 meters. Transport of sediment from the main channel, through the break, resulted in net deposition of at least 8.2 million cubic meters of sand.

Although the history of this part of the Mississippi River Valley indicates that channel changes have been extensive and frequent, the geomorphic changes that resulted from the 1993 flood seem to be unprecedented during the last 10,000 years or so. The large geomorphic changes at Miller City during the 1993 floods are attributable to the magnitude of the flood, the hydraulic head artificially increased by the levee, and the lack of energy dissipation on the agricultural flood plain relative to presettlement, forested conditions.

INTRODUCTION

Large amounts of rainfall in the upper Mississippi River Basin through winter, spring, and summer 1992–93 produced widespread and persistent flooding (Parrett and others, 1993; Wahl and others, 1993). The flood of 1993 on the upper Mississippi and Missouri Rivers set record discharges at many streamflow-gaging stations (Parrett and others, 1993). More than 26,000 km^2 of urban and agricultural land were inundated; total costs of the flood exceeded \$12 billion (Interagency Floodplain Management Review Committee, 1994).

More than \$1.2 billion in losses were attributed to actual flooding of agricultural bottomland (Interagency Floodplain Management Review Committee, 1994). Along the Missouri River, more than an estimated 1,800 km^2 of prime agricultural land was severely affected by erosion and deposition (Interagency Floodplain Management Review Committee, 1994). More than 300 km^2 of this prime agricultural land was covered with sand deposits that were more than 60 cm thick. The costs to remove this sand and return the soil to its former productivity levels have been estimated to be about \$1.2 million per square kilometer (Vance, 1994). The most severe erosion and sedimentation damages by far were associated with breaks of agricultural levees.

Purpose and Scope

This report documents the geomorphic changes associated with a levee break typical of those created by the 1993 flood. The geomorphic effects at levee breaks are of concern because erosion and sedimentation at levee-break complexes are substantial public safety and economic hazards. Furthermore, routing of sediment to and from storage in flood plains has the potential to redistribute sediment-borne contaminants. The levee-break complex chosen for documentation here occurred on the Mississippi River at river mile 34, which is near Miller City, Illinois (fig. 1). A chronology of events during the levee break, measurements of discharge and velocity in the main channel and the break, maps of erosion and deposition, descriptions of erosional features and sediments, and a comparison of the levee break to the Holocene history of the Mississippi channel are presented. Although it is one of the larger levee-break complexes created during the flood, the Miller City levee-break complex contains features typical of many of the levee-break complexes of the Mississippi and the Missouri Rivers.

Figure 1. Part of the upper Mississippi and Missouri Rivers.

Levee-Break Complexes

Levees may break as a result of a variety of mechanisms, which include overtopping by floodwater, liquefaction of the levee or foundation material, or mass failure. The term "levee break" in this report describes levee sections where the levee was completely removed or eroded at least to ground level, regardless of the erosion mechanism.

The 1993 flood resulted in breaks of 1,082 levees in the upper Mississippi and Missouri River Basins (Bhowmik and others, 1994). As many as 604 separate levee breaks were identified on the Missouri River between Kansas City and St. Louis, Missouri (J.C. Dohrenwend, U.S. Geological Survey, oral commun., 1994). Large hydraulic heads and flow constriction through narrow openings in the levee breaks created zones of intense scour downstream and upstream from typical breaks. Flow through the levee breaks also transported large quantities of sediment onto the flood plain.

A levee-break complex consists of the levee break and associated erosional and depositional features. Although erosion and deposition patterns in levee-break complexes can be quite complicated, they generally consist of scour, stripped, and depositional zones (fig. 2). The scour zone (locally called blue, blew, blow, or blown holes) is an area of deep erosion, usually more than 1 to 2 m deep, with steep sides. Detached blocks of cohesive sediment are common along the margins of the scours, which attest to erosion by gravitational slumping and toppling. The planform of scours ranges from circular to elongated; many scours extend upstream and downstream from the break to form elongated channels. In cases where the scour channels connect with the main channel upstream, the scours are efficient structures for funneling water and sediment onto the flood plain (fig. 2). Exit scours were formed when floodwater overtopped the levees or descended the banks as it reentered the main channel.

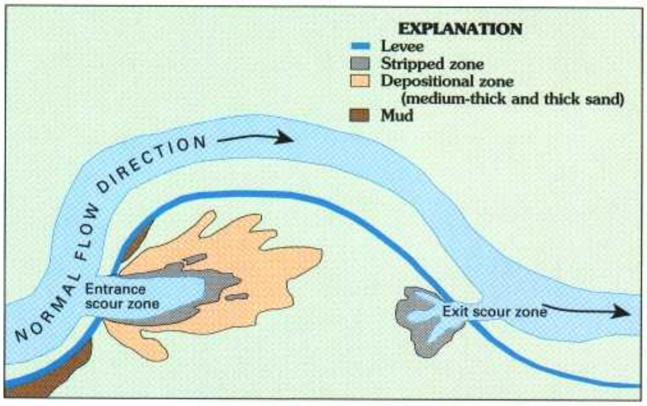

Figure 2. Definition of features in a typical levee-break complex.

Downstream from the levee break, the scour zone is skirted with a zone where erosion generally is less than 50 cm deep. This zone is referred to as the "stripped zone" (figs. 2, 3) because the plow horizons and rooted horizons of the soil are typically stripped, which leaves less erodible B-horizons and plow pans. Stripped zones commonly have shallow, rounded scours near their upstream margin and are characterized by abundant grooves (fig. 3). Some grooves are parallel to flow directions and seem to have been carved by debris carried by the floodwaters, whereas other grooves are evidently related to preexisting weaknesses in the soil, such as those caused by plowing (fig. 3).

A

B

Figure 3. Examples of stripped surfaces from the Miller City, Illinois, levee-break complex. *A*, Flow was toward the viewer; *B*, Flow was from left to right; with grooves.

Downstream from the stripped zone, there is a transition into the depositional zone that consists of sediment deposits of varying thicknesses. Because of the sequence of flooding at any particular site, sand and mud (silt- and clay-sized sediment) may have been deposited over stripped zones or may partially fill scours. Generally, sand deposits are thickest and coarsest closer to the scour. Sedimentary features include sand waves, dunes, and current ripples; commonly, areas of dunes and current ripples are draped with mud that was deposited during recession of the floodwaters or by subsequent floods (fig. 4). Extensive areas of the flood plain used for agriculture were covered with sand deposits, some of which were as much as 4 m thick; according to Vance (1994), some sand deposits were as much as 6 m thick on the Missouri River flood plain. Mud deposition seemed to be minor in extent. Mostly, mud was left as thin deposits in eddies or slackwater areas or was deposited during recession of the floodwaters in low areas that existed before the flood. The geomorphic effects of mud deposition were minor.

A

B

Figure 4. Sand dunes on the Missouri River flood plain between Kansas City and Hermann, Missouri, and in the Miller City, Illinois, levee-break complex. *A*, Missouri River Flood plain between Kansas City and Hermann, Missouri. View is to the north; flow was from left to right; *B*, Miller City, Illinois, levee-break complex. View is to the northwest; flow was from right to left.

Scour zones and sand deposits in levee-break complexes are by far the most dramatic geomorphic effects of the 1993 flood. In contrast, geomorphic changes in nonleveed areas consisted of minor bank erosion and sedimentation in natural levees and crevasse-splay features (fig. 5). Natural-levee sedimentation was prominent in nonleveed bank areas with dense woody vegetation. Crevasse-splay features, which consist of a scour (crevasse) and associated sand deposits (splay), are similar but much smaller natural analogs for levee-break complexes. Crevasse splays occur where a weakness in the natural levee, or flow concentration, results in erosion of a crevasse channel through which sediment is transported from the channel onto the flood plain (Collinson, 1978).

A

B

Figure 5. Natural levee and crevasse splays on the Missouri River flood plain between Kansas City and Hermann, Missouri. *A*, Natural levee; *B*, Crevasse splay.

Acknowledgments

The authors thank Ronald Eastwood, Illinois Department of Transportation (IDOT), for logistical support and access to video and photographic data. The U.S. Army Corps of Engineers (COE), St. Louis District, provided aerial photography, discharge-measurement data, and levee-break width data. Roger Edinson, IDOT, Department of Water Resources, provided postflood survey data of the extent of erosional scour at the Miller City, Illinois, levee-break complex.

THE FLOOD OF 1993 AND THE MILLER CITY, ILLINOIS, LEVEE-BREAK COMPLEX

The flood of 1993 on the upper Mississippi and Missouri Rivers was notable for the extreme discharge and long duration. Discharges in excess of the estimated 100-year flood were recorded on the Missouri River from Rulo, Nebraska, to Hermann, Missouri, and on the Mississippi River at Keokuk, Iowa, and St. Louis (Parrett and others, 1993; fig. 1). At Thebes, Illinois, the peak discharge was 28,200 m^3/s on August 7, 1993 (Reed and others, 1994); the estimated recurrence interval was from 10 to 50 years (Parrett and others, 1993). The daily mean discharge at Thebes is shown in figure 6.

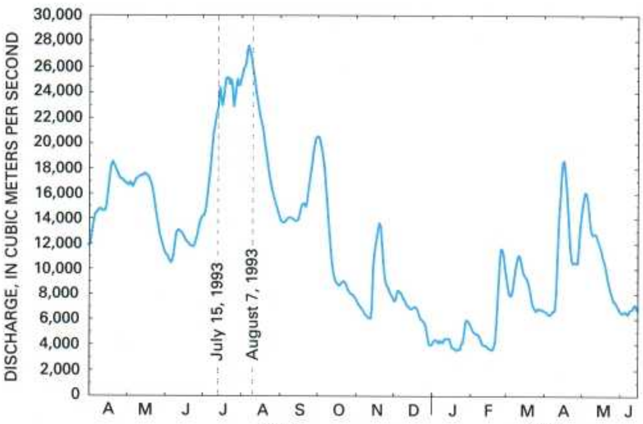

Figure 6. Daily mean discharge of the Mississippi River at Thebes, Illinois, April 1993–June 1994.

In addition to large discharges, the flood of 1993 was notable for its long duration. At St. Louis, the Mississippi River was above flood stage for more than 2 months. At Thebes, several smaller floods occurred from April 1993 through May 1994 in addition to the main flood of July through August 1993.

Downstream from the junction of the Ohio and the Mississippi Rivers (fig. 1), the magnitude of the flood was not severe because of low flows on the Ohio River in July and August 1993.

History of the Miller City Levee-Break Complex

The levee near Miller City, which is locally called the Len Small levee, was designed and constructed by local landowners to protect agricultural land in Dogtooth Island bend of the Mississippi River (fig. 7). The levee is continuous along the left bank (facing downstream) of the Mississippi River from Fayville, Illinois, to past the apex of Dogtooth Island bend. The levee was designed to deflect high-velocity floodwaters of the Mississippi River away from agricultural land at the upstream part of the bend. The downstream part of Dogtooth Island bend is not protected by a levee, so low-velocity back-flooding has occurred in the area south of the Miller City Road during many floods. The Len Small levee

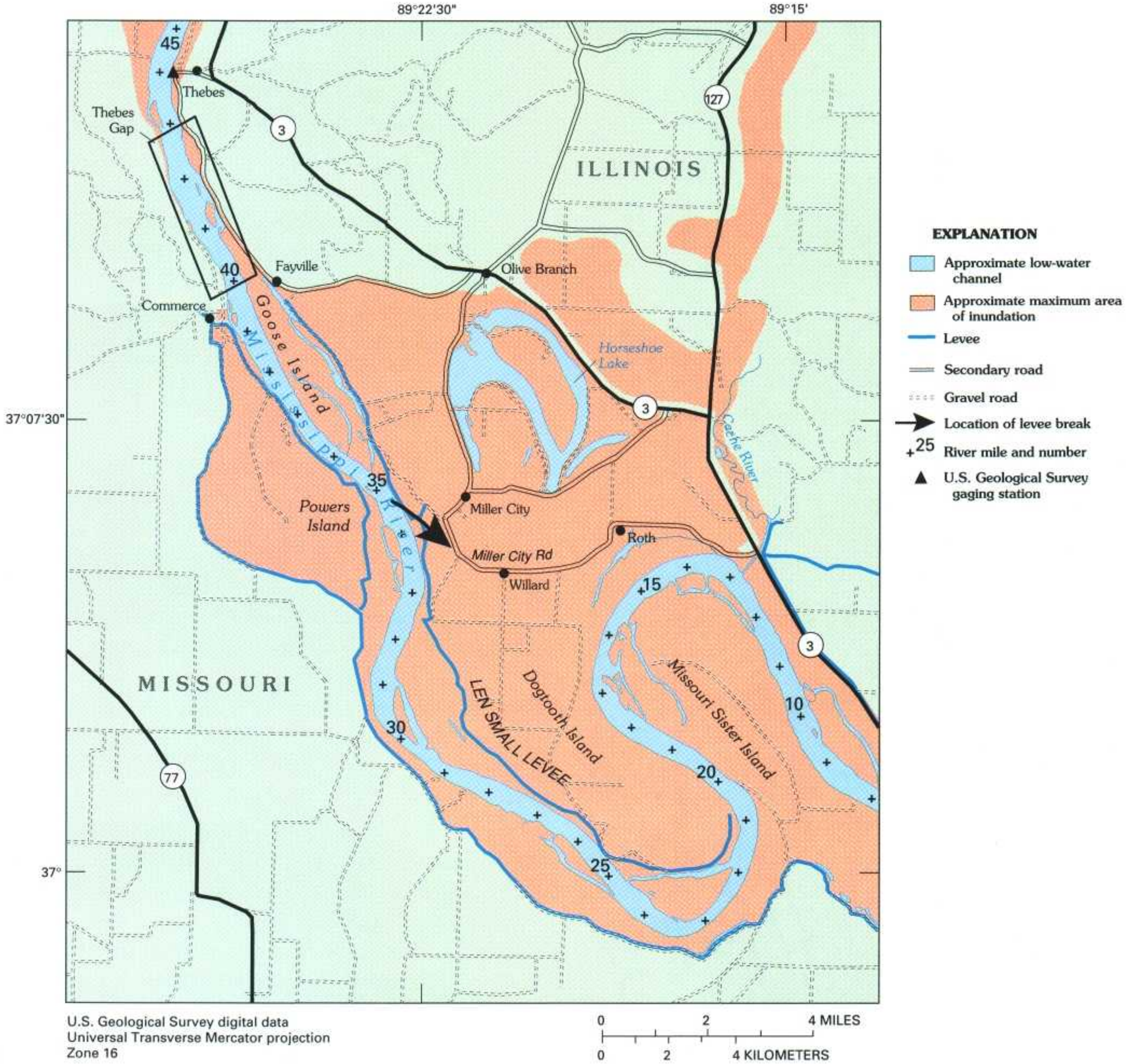

Figure 7. Features of the Miller City, Illinois, levee-break complex area.

was constructed from locally available materials by using draglines and scrapers. Most of the levee material is uncompacted top soil. Internal stratigraphy of levee remnants showed that black top soil was interbedded with clean, white sand units. The river side of the levee was protected with riprap at the site of the break and for some distance upstream and downstream. The riprap and numerous wingdams located in this reach of the Mississippi River are maintained by the COE to improve navigation.

The levee broke on July 15, 1993, at about 1:00 p.m. local time. According to anecdotal evidence from several witnesses, the levee was inspected 15 minutes before the break. At the time of the break, the water level on the channel side of the levee was estimated to be as much as 2 m below the levee crest. [For comparison, at the U.S. Geological Survey (USGS) streamflow-g.aging station at Thebes, which is about 16 km upstream, the daily mean stage was 104.68 m on July 15; on July 20 and August 7, the daily mean stage at Thebes peaked at 105.24 m (table 1)]. An eyewitness related that a loud noise drew his attention at 12:50 p.m. When he looked at the levee from a distance of about 500 m, he saw a near-horizontal, 15- to 30-cm-diameter fountain of water gushing out of the side of the levee. The hole quickly enlarged, and a section of the levee failed. As the levee eroded and widened, water began to fill the area between the main levee and a cross levee (fig. 8*A*). During the first few days after the break, flow through the break was extremely turbulent (fig. 9) with standing waves[1] that were about 1 m high.

The area between the main levee and the cross levee is the upstream end of a channel that the Mississippi River occupied during 1820 (fig. 10). The extension of the 1820 channel formed an arcuate trough to the east and south with about 1.5 m of relief before the 1993 flood. The 1820 channel was bounded to the north and east by a terrace scarp that cut laterally into alluvial deposit of late Wisconsin and presumed early Holocene age (Fisk, 1944). The scarp ranged from about 2 to 3 m high. As the low area between the two levees filled, water flowed northward and eastward over the scarp, and followed low areas of former channels that extended toward Horseshoe Lake (figs. 8*A*, 10). As water levels rose in the Horseshoe Lake area, flow began to move southward along former channels, descended the scarp, and reentered the 1820 channel to the east and downstream of the cross levee (fig. 8*A*). By July 17, water that reentered the 1820 channel had eroded a secondary scour at least 400 m long by upstream (northward) migration of a steep head cut (location A, fig. 8*A*). Most of the area of Dogtooth Island bend south of the Miller City Road was inundated by backflooding or seepage by this time.

Much of the early floodwater followed low areas directly to Horseshoe Lake. Subsequent overflow of Horseshoe Lake to the south and east caused water to flow across the Miller City Road between Willard and Roth, Illinois (fig. 7), and down 0.5- to 1-m-high scarps that separate paleochannels of the Mississippi River, notably the scarp between deposits of Holocene channel-position stage 2 and those of channel-position stages 5 and 9 (fig. 10). Observations during the flood indicated that flow over the road and down the terrace scarps typically was fast, highly turbulent, and characterized by standing waves.

Aerial videotape from July 17 indicated small areas of flow over the cross levee at the extreme northern and southern ends. Larger quantities of overflow were noted on July 19. Because the area had been evacuated, the precise time and mechanism of failure of the cross levee are not known. However, by July 20, a substantial part of the cross levee had broken, and by July 31, the entire 400 m of the cross levee was removed.

After the cross levee was breached, flow through the main levee was concentrated in the 1820 channel, and floodwater that moved through the secondary scour immediately downstream of the cross levee (location A, fig. 8*A*) reversed direction and flowed northeastward. By July 26, flow was 5,570 m^3/s from the Mississippi River main channel into the break, and 8,000 m^3/s of flow was measured near the peak discharge on August 7. From July 17 through August 10, the northern (left) bank of the main scour eroded laterally more than 60 m (location B, fig. 8*A*). In the process, more than 680 m of a county road was removed, as well as a house, a machine shed, and the front yard and front porch of another house (fig. 9).

[1]Standing waves are stationary wave forms indicative of critical flow, which occurs in flows with large ratios of velocity to depth.

Table 1. Daily mean discharge and stage of the Mississippi River at Thebes, Illinois, upstream from the Miller City, Illinois, levee-break complex, discharge upstream from and at the levee-break complex, and width of the levee break, July 15 to August 25, 1993

[m^3/s, cubic meters per second; m, meters; --, not measured]

Date	Daily mean discharge at Thebes, Illinois (m^3/s)	Daily mean stage at Thebes, Illinois (meters above sea level)	Discharge at river mile 35, immediately upstream of the Miller City levee break (m^3/s)[1]	Discharge measured in the levee break at river mile 34 (m^3/s)	Surveyed width of the levee break (m)
07-15	24,451	104.68	--	--	--
07-16	23,687	104.81	--	--	--
07-17	23,065	104.88	--	--	--
07-18	23,659	105.01	--	--	113
07-19	24,508	105.15	--	--	120
07-20	25,159	105.24	--	--	--
07-21	25,159	105.15	--	--	--
07-22	25,215	105.09	--	--	--
07-23	24,734	104.93	--	--	--
07-24	25,046	104.92	--	--	--
07-25	24,480	104.78	--	--	--
07-26	22,980	104.53	--	5,570	472
07-27	23,602	104.67	--	4,920	478
07-28	24,423	104.74	--	5,480	484
07-29	25,102	104.79	--	--	--
07-30	24,621	104.75	--	5,580	532
07-31	24,649	104.83	24,000	5,550	--
08-01	25,074	104.95	--	6,720	539
08-02	25,442	105.00	--	--	--
08-03	25,923	105.03	--	6,930	558
08-04	26,008	104.97	--	--	--
08-05	26,432	105.04	--	--	--
08-06	27,338	105.18	--	7,100	587
08-07	27,677	105.24	--	8,000	--
08-08	27,253	105.14	--	--	--
08-09	26,913	105.09	--	6,600	--
08-10	26,149	104.95	22,900	7,560	--
08-11	25,555	104.85	--	6,090	618
08-12	24,904	104.71	--	--	--
08-13	24,083	104.58	--	--	--
08-14	23,489	104.45	--	--	--
08-15	22,895	104.34	--	--	--
08-16	22,272	104.23	--	--	--
08-17	21,819	104.12	--	--	--
08-18	21,423	104.04	19,500	5,130	--
08-19	20,829	103.91	18,200	4,730	--
08-20	20,008	103.75	--	--	--
08-21	19,386	103.60	--	--	--
08-22	18,735	103.41	--	--	--
08-23	17,942	103.22	--	--	--
08-24	17,291	103.03	--	--	--
08-25	16,782	102.87	--	2,890	625

[1]Discharges measured in main channel upstream from the levee break are somewhat lower than those measured at the U.S. Geological Survey gage at Thebes, Illinois, possibly because of unmeasured flow to the west of Powers Island (fig. 7).

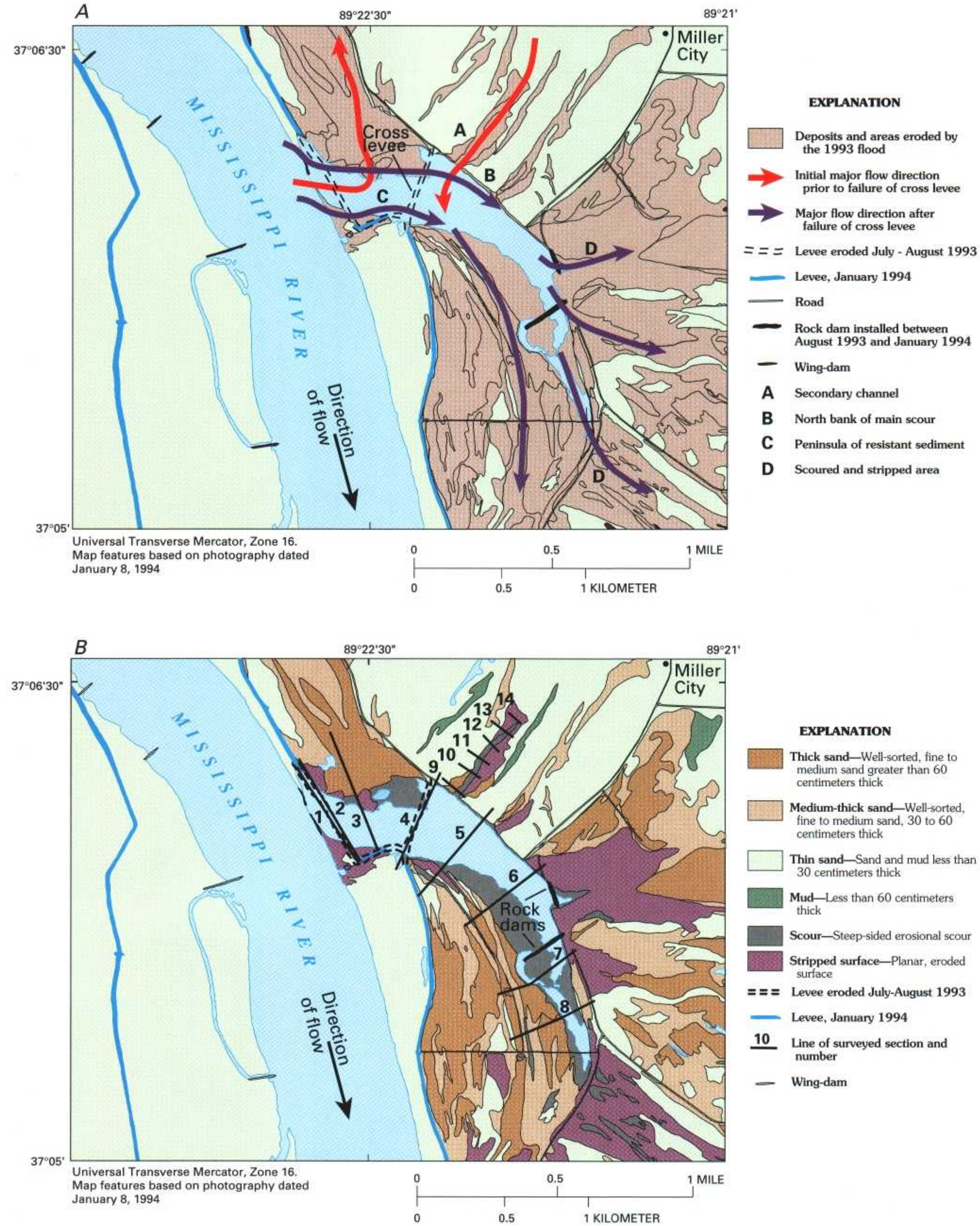

Figure 8. Upstream end of the Miller City, Illinois, levee-break complex. *A*, Flow directions and locations; *B*, Erosional and depositional features.

A

B

C

Figure 9. Miller City, Illinois, levee-break complex. *A*, Turbulence at northern end (Illinois Department of Transportation); *B*, Turbulence and vortices in center (Illinois Department of Transportation), and; *C*, Northern margin of main scour, October 1993.

Observations from water and aerial reconnaissance from July 26 through August 8 indicated that the main-flow vectors were oriented along the 1820 channel with divergence to the northeast and southeast (fig. 8*A*). To the north of the Miller City Road, in the area between Willard and Roth, flow vectors were to the east and northeast; secondary flow diverged southward across the Miller City Road (fig. 7). All the Dogtooth Island bend area south of the Miller City Road was inundated at this time, although water that flowed at higher velocities seemed to be confined to the northern one-half of the area. Floodwater diverged to the south and followed the 1820 channel until it encountered the levee. Then it concentrated in a low area defined by channel-position stage 12 (Fisk, 1944) and flowed to the southeast until ponded water forced the flow to the east and back into the main channel near river mile 16 (fig. 7).

Because of the wide angle of divergence of flow, it is impossible to define the degree to which flow around Dogtooth Island bend was cut off as a result of flow through the levee break. The location of flow back into the Mississippi River channel ranged from about river mile 20 as determined by the downstream extent of the Len Small levee, to about river mile 13.3, which is immediately upstream from the Cache River cutoff (fig. 7).

Floodwaters slowly receded after the peak on August 7 (table 1). As higher areas became dry, flow concentrated in the 1820 channel and the newly scoured areas. Flow in secondary scours oriented to the north and northeast once again reversed and moved into the 1820 channel. Probably the most dramatic change during this time was about 3 km east of Roth where large volumes of water were continuing to drain from Horseshoe Lake (fig. 7). As the water level dropped in the main channel of the Mississippi River, a reentry scour was created by upstream migration of the headcut (fig. 11). Erosion processes were still continuing during the last week of August 1993.

Subsequent to the summer flooding during 1993, the Miller City area was affected substantially by three additional floods (fig. 6). During late September and early October 1993, intense rainfall in Missouri resulted in another rise on the Mississippi River; the peak discharge of 20,600 m^3/s was at Thebes. In mid-November 1993, intense rain in Missouri and southern Illinois created a flood with a peak discharge of about 13,500 m^3/s at the streamflow-gaging station at Thebes. Both floods were sufficient to create a high volume of flow through the levee break with subsequent inundation of most of Dogtooth Island bend south of the Miller City Road. Before the November flood, construction had begun on a new levee alignment, and rock dams had been built across the main scour and one of the secondary scours (fig. 8*B*). The November flood caused increased erosion around the southwestern corner of the dam that had been constructed across the main scour. Another flood in April 1994 had a peak discharge of 18,500 m^3/s at Thebes. This flood created extensive changes, which included erosion of as much as 100 m of the southern margin of the main scour and extensive reworking of sand deposits in the area of the 1820 channel. The April 1994 flood also destroyed about 1,000 m of newly reconstructed levee.

Measurements

Measurements of discharge, velocity, and bathymetry in the levee break were made by the U.S. Army Corp of Engineers (COE) and the USGS from July 26 through September 9, 1993. The USGS measurements were made in cooperation with the Illinois Department of Transportation (IDOT). Discharge and velocity were measured in the Mississippi River upstream from the levee break and in the levee break. The COE measured discharge by the moving-boat technique (Smoot and Novak, 1969) and bathymetry by use of a digital echo-sounder and range–range positioning system. The range of the COE boat was limited by its draft;

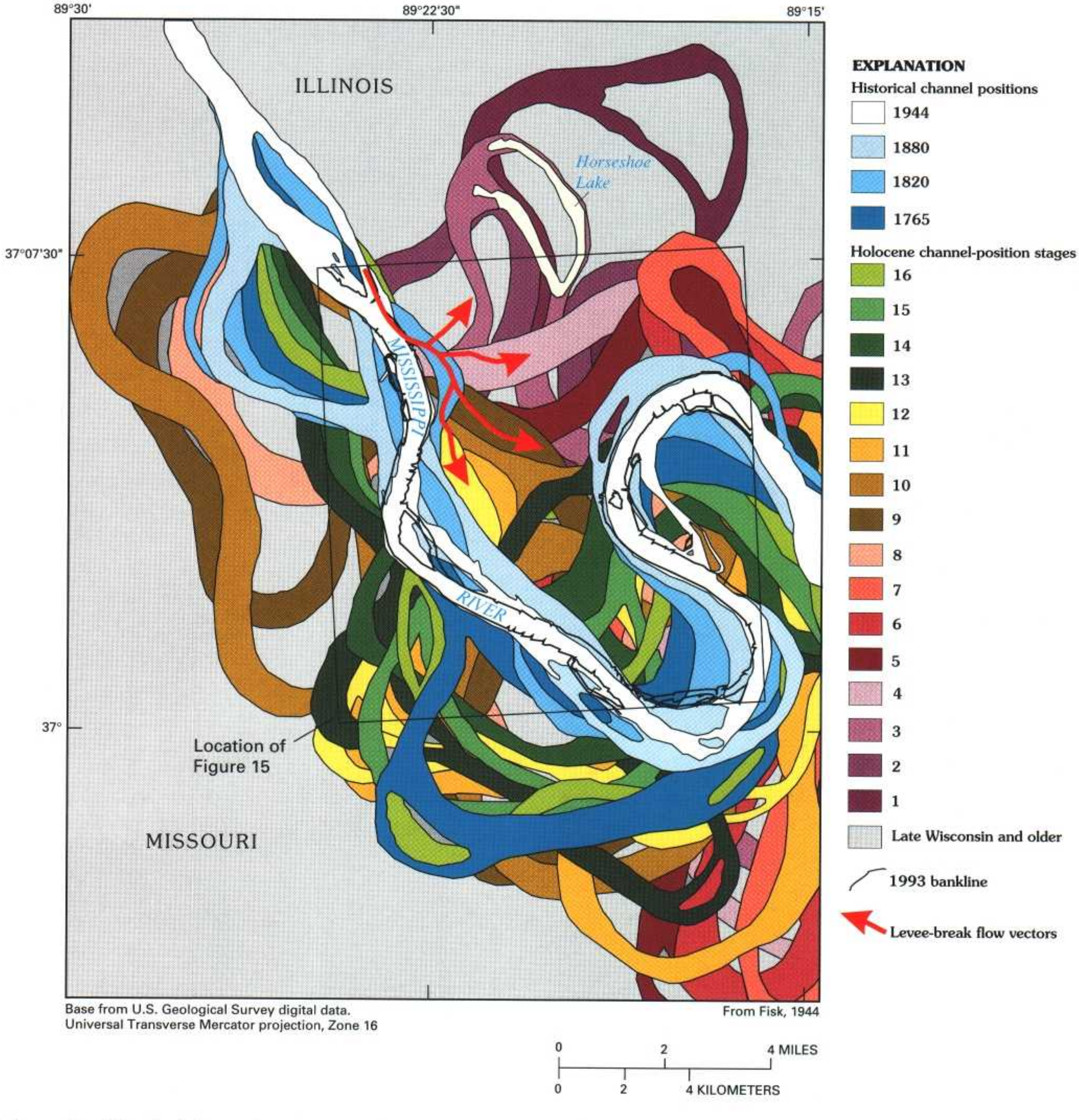

Figure 10. Historical channel positions and Holocene channel-position stages in the Miller City, Illinois, area.