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SEDIMENT TRANSPORT

IN THE LOWER MISSOURI AND THE CENTRAL MISSISSIPPI RIVERS

JUNE 26 THROUGH SEPTEMBER 14

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U.S. GEOLOGICAL SURVEY CIRCULAR 1120-I

Front cover—View of Highway 67, West Alton, Missouri
(Srenco Photography, St. Louis, Mo.)

Back cover—View of Spirit of St. Louis Airport,
Chesterfield, Mo. (Srenco Photography,
St. Louis, Mo.)
Field Hydrologist making streamflow
measurements (U.S. Geological Survey)

SEDIMENT TRANSPORT IN THE LOWER MISSOURI AND THE CENTRAL MISSISSIPPI RIVERS, JUNE 26 THROUGH SEPTEMBER 14, 1993

By Robert R. Holmes, Jr.

Floods in the Upper Mississippi River Basin, 1993

U.S. GEOLOGICAL SURVEY CIRCULAR 1120–I

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

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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.

Director

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FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot
square meter (m^2)	10.76	square foot
kilometer (km)	0.6214	mile
metric ton (t)	1.102	short ton
metric ton per day (t/d)	1.102	short ton per day
meter per second (m/s)	3.281	foot per second
cubic meter per second (m^3/s)	35.31	cubic foot per second
hectare (ha)	2.471	acre
cubic hectometer (hm^3)	8.107	acre-foot

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.

Sediment Transport in the Lower Missouri and the Central Mississippi Rivers, June 26 through September 14, 1993

By Robert R. Holmes, Jr.

Abstract

Sediment data were collected at five sites in the lower Missouri and the central Mississippi Rivers during the 1993 flood. Bedloads were indirectly estimated to be generally less than 5 percent of the suspended-sediment load for this period. Suspended-sediment loads for the 1993 flood generally were less than during previous floods in 1951 and 1973, which is thought to be attributable to the trapping of sediment in the reservoirs in the Missouri River Basin that have been operational since 1953 and the depletion of sediment supply and dilution of sediment concentration by the large 1993 flood volumes.

Sediment apparently went into storage, either in the channel or the flood plain, upstream from St. Louis, Missouri, because the total suspended sediment transported by the Mississippi River past St. Louis was 22 million metric tons less than that transported past the two upstream sediment stations–below Grafton, Illinois, and at Hermann, Missouri. The storage of sediment was partly verified by the massive amounts of newly deposited sediments on the flood plains.

A nonhomogenous mixture of water is present at St. Louis, which is 24 kilometers downstream from the normal junction of the Missouri and the Mississippi Rivers. During the 1993 flood, the suspended-sediment concentration varied from one shoreline to the other by a factor of nearly five. Aerial photography taken on July 25 indicates the river became well mixed 88 kilometers downstream from the normal junction of the two rivers. Several days before and after July 25, the junction of the two rivers was 32 kilometers upstream from the normal junction.

The dynamics of sediment transport and movement were exemplified by 4 meters of channel-bed scour from July 12 through July 20 at the Mississippi River at Chester, Illinois. The channel-bed changes generally followed a pattern of scouring during the flood rise followed by channel-bed aggradation during the recession.

INTRODUCTION

Flooding in the upper Mississippi River Basin in 1993 will long be remembered for the magnitude and duration of the river stages and discharges and the sediment deposition in the flood plains. Record peak discharges were reported at 40 streamflow-gaging stations operated by the U.S. Geological Survey (USGS; Parrett and others, 1993) as the Mississippi River at St. Louis, Missouri, was continuously above flood stage for 81 days from June 26 through September 14.

The record flooding mobilized, transported, and deposited large quantities of sediment throughout the upper Mississippi River Basin. The Mississippi River system transports more sediment than any other river in North America (Meade and others, 1990). High quantities of sediment affect river navigation and operation of reservoirs and water-treatment plants. Sediments can adsorb and transport numerous contaminants, such as pesticides and toxic metals, that could be a problem for public health. To monitor the transport of sediment, the USGS operates data-collection stations for sediment transport at five sites on the lower Missouri and the central Mississippi Rivers.

Purpose and Scope

This report summarizes information on sediment concentrations, loads, and size distributions in the lower Missouri and the central Mississippi Rivers during the 81-day flood period from June 26 through

September 14, 1993. Data were collected at five existing USGS sediment data-collection stations (hereafter referred to as "sediment stations") during the flood (fig. 1; table 1). The data collected consist of water discharge, velocity, channel geometry, water-surface slope, detailed multivertical cross-section suspended-sediment concentrations, daily single-vertical suspended-sediment concentrations, and particle-size distributions of bed material and suspended sediment. Suspended-sediment concentrations and loads at the five sediment stations are analyzed in relation to temporal and spatial aspects of sediment transport. Bedload was estimated by applying theoretical equations to hydraulic and geometric data collected onsite during streamflow discharge measurements. In addition, sediment data from the 1993 flood are compared with those from the 1951 and the 1973 floods on the Mississippi River and from the period of record at each station.

Methods for Data Collection and Computation

Two types of sediment stations, daily and periodic, are operated by the USGS. The type of station is defined by the frequency and quantity of data collected. A daily sediment station has daily concentration and load published when, according to Porterfield (1972, p. 1), "sufficient determinations of sediment concentration and water discharge are obtained to justify computation of daily sediment discharge. The end product is a tabulation of daily mean concentration, suspended-sediment discharge (load), and periodic determinations of particle-size distribution of suspended sediment and bed material." The USGS oper-

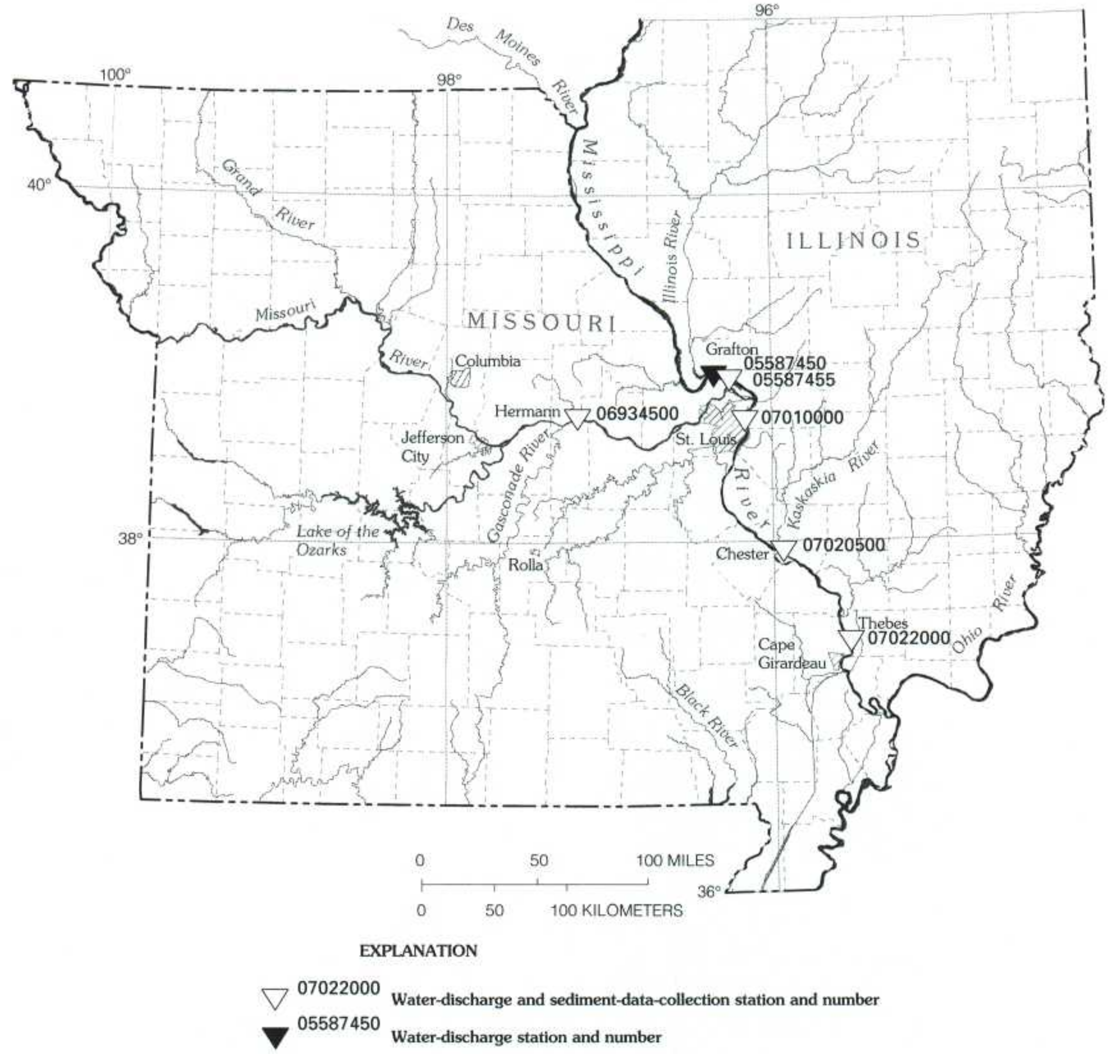


Figure 1. Location of water-discharge and sediment data-collection stations on the lower Missouri and the central Mississippi Rivers.

Table 1. U.S. Geological Survey sediment data-collection stations on the lower Missouri and the central Mississippi Rivers

[CY, current year]

Station number	Station (fig. 1)	River mile[1]	Period of record	Type of record published[2]
05587455	Mississippi River below Grafton, Ill[3]	214.6	March 1989 to CY	Daily.[4]
06934500	Missouri River at Hermann, Mo	97.9	April 1948 to CY	Periodic.
07010000	Mississippi River at St. Louis, Mo	180.0	.....do..........	Daily.
07020500	Mississippi River at Chester, Ill.	109.9	August 1980 to CY	Do.
07022000	Mississippi River at Thebes, Ill	43.7	October 1980 to CY	Do.

[1]River mile is measured from the junction of the Missouri and the Mississippi Rivers for the Missouri River stations and from the Ohio River inflow for the Mississippi River stations.

[2] Type of record published can be either daily or periodic. Daily stations have data collected frequently enough to define the daily sediment concentration and load, whereas periodic stations have data collected less frequently, and usually only load estimates are published for time spans of months or longer.

[3]Water discharge was measured at the Mississippi River at Grafton, station number 05587450.

[4]Although this is a daily record station, daily samples could not be collected at this station. Therefore, most of the 1993 flood period suspended-sediment loads was computed by transport relations.

ates four daily sediment stations on the central Mississippi River (table 1).

Data collected at a periodic sediment station are insufficient for daily load computation, but may be adequate to warrant estimation of sediment loads for months or longer periods. These estimates are made by the use of sediment-transport curves, which relate either suspended-sediment load or concentration to water discharge (Glysson, 1987). The USGS operates one periodic sediment station on the lower Missouri River at Hermann, Missouri (table 1).

All suspended-sediment data were collected according to methods described in Edwards and Glysson (1988). At a USGS daily sediment station, suspended-sediment samples generally are collected once daily (or more frequently) by a local contract observer (hereafter referred to as "observer") at a single location in the river. Multivertical cross-section samples (hereafter referred to as "cross-section sample") also are collected to "adjust" the single vertical observer samples. These cross-section samples are collected by using either an equal discharge increment method (EDI) or an equal width method (EWI; Edwards and Glysson, 1988) at 5 to 10 locations across the stream. From these data, the daily mean concentration and daily suspended-sediment load are computed by methods described in Porterfield (1972).

Conditions prevented the collection of daily samples at the Mississippi River below Grafton, Illinois, during the 1993 flood. Therefore, the EWI cross-section data, which were collected periodically, and the data from a few samples collected by the observer are the only sediment data available for this sediment station during the 1993 flood. A suspended-sediment transport relation (hereafter referred to as "curve") was developed by using the data from the cross-section samples collected during the flood and the sediment samples collected before the flood (fig. 2). These data, which are shown with the date of collection next to the sample point, indicate a looped curve (hereafter referred to as "hysteresis") (fig. 2). This hysteresis is more exaggerated than normal because of the depletion and dilution of sediment during the 1993 flood, which will be discussed in the section entitled "Sediment Loads." By using this curve, an estimate was made of the suspended-sediment concentration for each day during the flood period. The suspended-sediment load for the flood then was computed as the sum of all the daily loads that had been determined as the product of the estimated concentrations, water discharge, and a conversion factor for tons per day. The daily suspended-sediment loads before the flood period were determined by methods described in Porterfield (1972) for daily sediment stations.

Since 1948, monthly EDI cross-section samples have been collected at the Missouri River at Hermann by the USGS or the U.S. Army Corps of Engineers. During the 1993 flood, EDI samples were collected more frequently by the USGS. A curve was developed that related suspended-sediment concentration to water discharge. Because of depletion and dilution of sediment, the 1993 flood data plot below the straight line on the basis of previously collected data, and, therefore, a different line was drawn by visual fit (fig. 3). Daily suspended-sediment concentrations

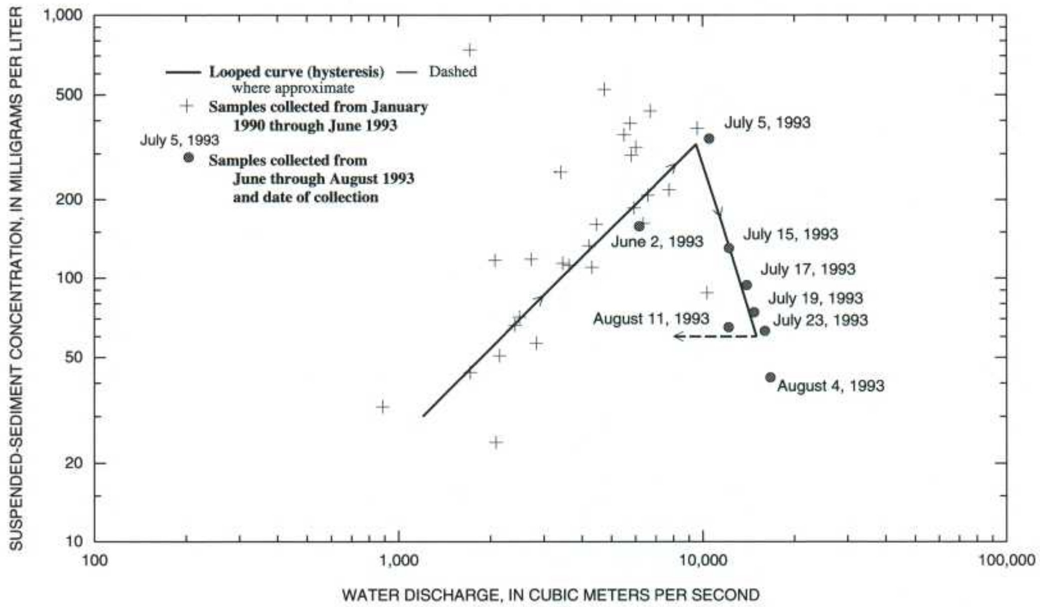


Figure 2. Relation between water discharge and suspended-sediment concentration for the Mississippi River below Grafton, Illinois.

were estimated from this curve. The suspended-sediment load for the flood period was determined to be the sum of all the daily loads that were computed as the product of the daily estimated mean suspended-sediment concentrations, the daily mean water discharge, and a conversion factor for tons per day.

During the flood, USGS personnel collected daily suspended-sediment samples from the Mississippi River at St. Louis[1] at two longitudinal locations (one each near the Missouri and the Illinois shorelines) to account for the incomplete mixing of the Missouri River inflow 24 km upstream. Cross-section samples usually consisted of 10 verticals collected by using the EDI method. However, during the flood, one cross-section sample was collected from the front of a barge tow as a nine-vertical EWI sample because the monorail system used to collect the samples was disabled.

The Mississippi River sediment stations at Chester and Thebes, Illinois, are daily sediment stations; suspended-sediment samples are collected at least daily by observers at a single location in the river. During the 1993 flood, samples were collected twice daily at Thebes and three times daily at Chester by the observers. Cross-section samples were collected by using the EDI method.

Bed-material samples were collected according to methods described in Edwards and Glysson (1988).

Suspended-sediment samples were collected from the Mississippi River at Chester, Illinois. by using a US P-63 sampler suspended from a specially designed boom-hoist car.

[1]During normal flow conditions, USGS personnel collect the two location samples weekly because use of contract observers at this station is not feasible. From a combination of the samples collected every 2 weeks, cross-section samples collected every 2 months, and the daily turbidity records from two nearby waterworks intakes (one on each side of the river), a daily record is computed.

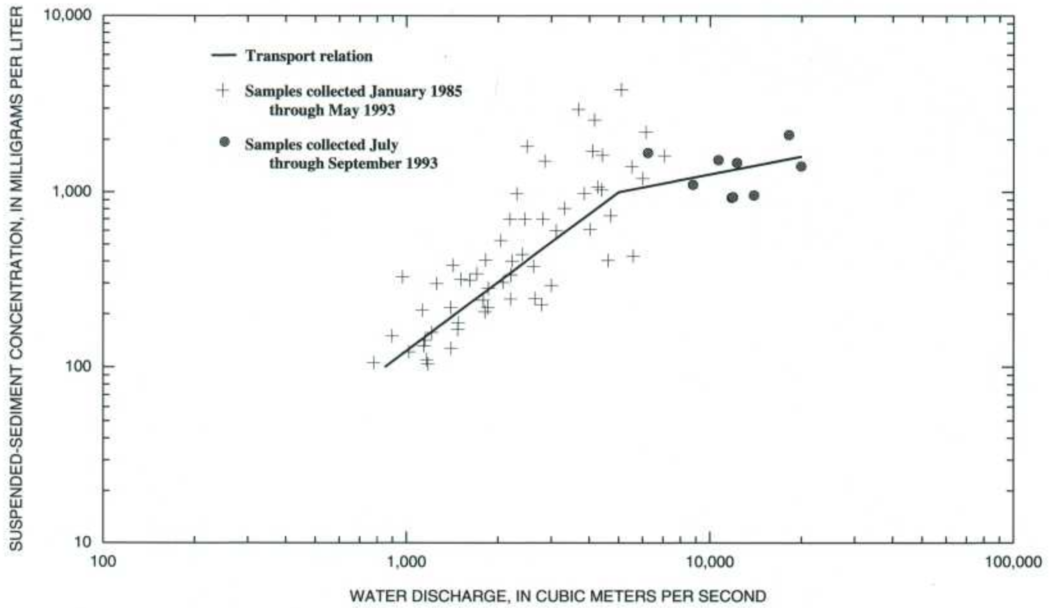


Figure 3. Relation between water discharge and suspended-sediment concentration for the Missouri River at Hermann, Missouri.

Most bed-material samples from the 1993 flood were collected from the bow of a boat because of the extreme depths and velocities.

Particle size was determined on all cross-section suspended-sediment and bed-material samples collected during the flood [tables 2 and 3]. For suspended-sediment cross sections collected by using the EDI method, concentration and size were analyzed for each vertical sampled. For those suspended-sediment and bed-material cross sections collected by using the EWI method, the samples from all the vertical sections were composited for a single analysis of size; the concentration of the composited suspended-sediment samples also was determined.

Bedload was not measured directly during this flood because accurate measurements in the Missouri and the Mississippi Rivers are not possible at this time under such conditions with existing bedload samplers. These inaccuracies are, for the most part, the result of the extreme temporal and spatial variability of bedload transport and the distortions of natural flow fields when the bedload sampler moves near the bed (Meade and others, 1990). The measurement inaccuracies are increased during the sampling conditions (high velocities and large depths) on the Missouri and the Mississippi Rivers during the flood.

No direct determination of bedload could be made during the 1993 flood, but estimates of bedload were made for each of the five sediment stations. However, because of the lack of onsite verification data, no single equation could be used to make accurate estimates of the bedload for such a large river system. The following equations were used: Meyer-Peter and Muller (Meyer-Peter and Muller, 1948), Modified

An attempt was made to collect bedload samples for the Mississippi River at St. Louis, Missouri, by using an experimental sampler designed at the U.S. Geological Survey Cascades Volcano Observatory, Vancouver, Washington. The sampler was suspended from a crane on the U.S. Army Corps of Engineers, St. Louis District, barge *Pathfinder*.

Table 2. Concentration and particle-size distribution for multivertical suspended-sediment samples collected during the 1993 flood

[Q, water discharge; particle diameter, in millimeters; m^3/s, cubic meters per second; m, meters; mg/L, milligrams per liter; --, no data]

Date	Time	Q (m^3/s)	Distance from left shoreline (m)	Suspended sediment concentration (mg/L)	Percentage of sample smaller than particle diameter											
					2	1	0.5	0.25	0.125	0.062	0.031	0.016	0.008	0.004	0.002	0.001
				Mississippi River below Grafton, Illinois												
07–15–93	1514	12,100	Composite. . .	130	100	100	100	99	97	96	96	93	89	79	67	55
07–17–93	1120	13,900	. . . .do.	94	100	100	100	98	96	95	94	90	83	72	60	46
07–19–93	1228	14,700	. . . .do.	74	100	100	100	100	99	99	--	--	--	--	--	--
07–23–93	1045	16,200	. . . .do.	63	100	100	100	99	98	97	--	--	--	--	--	--
08–04–93	1640	16,600	. . . .do.	42	100	100	100	97	82	79	--	--	--	--	--	--
08–11–93	1235	11,500	. . . .do.	65	100	100	97	85	81	79	--	--	--	--	--	--
				Missouri River at Hermann, Missouri												
07–07–93	1430	11,400	239	1,430	100	100	95	89	64	62	60	51	45	39	32	25
			285	1,541	100	100	100	90	68	59	57	49	42	37	30	24
			338	1,630	100	100	95	83	60	57	55	47	41	35	29	23
			383	1,660	100	100	88	75	63	56	54	46	40	35	28	22
			444	1,400	100	100	97	94	74	66	64	55	48	41	34	27
07–13–93	1030	9,290	338	1,150	100	100	100	91	69	59	58	57	55	51	45	37
			392	1,150	100	100	97	90	65	58	58	56	54	50	44	36
			437	1,210	100	100	95	85	56	56	55	54	52	48	42	35
			498	1,080	100	100	95	86	64	62	61	59	57	53	47	38
07–16–93	1740	14,300	291	937	100	100	100	89	67	63	62	59	54	49	40	32
			390	971	100	100	100	84	66	64	63	60	55	50	41	32
			443	1,070	100	100	100	83	54	54	53	51	46	42	35	27
			504	856	100	100	100	89	68	68	67	64	58	53	44	34
07–17–93	1440	11,800	291	724	100	100	98	96	73	69	68	67	63	57	49	34
			337	874	100	100	95	84	63	57	56	55	52	47	40	28
			390	994	100	100	94	80	54	50	50	48	46	41	36	25
			443	1,180	100	100	95	83	60	52	51	50	47	43	37	26
			504	878	100	100	94	82	62	56	55	53	51	46	40	28

07–30–93	1325	18,200	297	1,980	100	100	100	100	88	88	86	74	63	54	46	40
			342	1,960	100	100	99	97	91	89	87	75	64	54	47	40
			396	2,250	100	100	95	91	82	78	76	66	56	48	41	35
			449	2,410	100	100	92	84	75	72	71	61	51	44	38	32
			502	2,030	100	100	97	94	87	86	84	73	61	52	45	39
08–01–93	1445	19,900	297	1,320	100	100	100	96	89	89	86	73	60	48	36	23
			342	1,340	100	100	98	95	88	87	84	71	59	47	35	23
			396	1,460	100	100	96	93	84	82	79	67	55	44	33	21
			449	1,600	100	100	93	88	76	74	71	60	50	40	30	19
			502	1,390	100	100	98	94	85	84	81	68	57	45	34	22
08–19–93	1230	6,230	134	631	--	--	--	--	--	81	--	--	--	--	--	--
			180	712	--	--	--	--	--	73	--	--	--	--	--	--
			233	805	--	--	--	--	--	59	--	--	--	--	--	--
			287	597	--	--	--	--	--	67	--	--	--	--	--	--
			400	610	--	--	--	--	--	72	--	--	--	--	--	--
Mississippi River at St. Louis, Missouri																
07–07–93	1200	19,100	97	195	100	100	100	96	93	90	89	84	77	68	57	44
			148	220	100	100	100	100	100	95	94	88	82	72	60	47
			187	228	100	100	100	100	100	97	96	90	83	74	61	48
			219	644	100	100	97	90	77	72	71	67	62	55	45	35
			277	836	100	100	97	89	79	75	74	70	64	57	47	37
			324	943	100	100	100	91	78	75	74	70	64	57	47	37
			372	908	100	100	98	94	86	84	83	78	72	64	53	41
			404	863	100	100	99	97	91	89	88	83	77	68	56	44
			477	1,010	100	100	99	94	88	87	86	81	75	66	55	43
			533	921	100	100	100	99	97	95	94	88	82	72	60	47
08–06–93	0930	26,200	Composite . . .	522	100	98	95	81	69	63	62	62	61	56	47	39
09–02–93	1310	12,900	94	121	--	--	--	--	--	86	--	--	--	--	--	--
			143	108	--	--	--	--	--	90	--	--	--	--	--	--
			180	125	--	--	--	--	--	81	--	--	--	--	--	--
			227	141	--	--	--	--	--	82	--	--	--	--	--	--
			256	155	--	--	--	--	--	82	--	--	--	--	--	--
			296	148	--	--	--	--	--	73	--	--	--	--	--	--
			344	255	--	--	--	--	--	74	--	--	--	--	--	--
			390	355	--	--	--	--	--	73	--	--	--	--	--	--

Table 2. Concentration and particle-size distribution for multivertical suspended-sediment samples collected during the 1993 flood—Continued

Date	Time	Q (m^3/s)	Distance from left shoreline (m)	Suspended sediment concentration (mg/L)	Percentage of sample smaller than particle diameter											
					2	1	0.5	0.25	0.125	0.062	0.031	0.016	0.008	0.004	0.002	0.001
Mississippi River at St. Louis, Missouri—Continued																
			454	530	--	--	--	--	--	69	--	--	--	--	--	--
			518	589	--	--	--	--	--	76	--	--	--	--	--	--
Mississippi River at Chester, Illinois																
07–21–93	1200	26,300	75	220	--	--	--	--	--	94	94	84	78	69	57	45
			130	247	100	100	100	98	90	87	87	77	72	64	53	41
			168	253	100	100	100	100	86	83	83	74	68	61	51	39
			200	302	100	100	100	93	78	71	71	63	59	52	43	34
			245	380	100	100	100	96	69	59	59	53	49	43	36	28
			270	319	100	100	100	88	73	68	68	61	56	50	41	32
			335	285	100	100	96	89	77	74	74	66	61	54	45	35
			392	240	100	100	100	96	90	88	88	78	73	65	54	42
			453	207	--	--	--	--	--	99	98	88	82	73	60	47
			532	216	--	--	--	--	--	96	96	85	79	71	59	46
07–30–93	1730	25,500	195	290	100	100	100	96	78	73	72	63	58	50	40	29
			265	396	100	100	100	87	60	56	55	49	45	39	31	22
			359	234	100	100	100	96	92	91	90	79	73	63	50	36
			495	209	--	--	--	--	--	98	97	85	78	68	53	39
08–05–93	1125	26,700	100	425	100	100	100	97	84	80	79	74	68	60	46	34
			219	352	100	100	100	98	96	95	94	88	81	71	55	40
			264	535	100	100	98	95	70	63	62	59	54	47	36	26
			365	364	100	100	99	97	93	91	90	85	78	68	52	38
			494	344	100	100	100	98	97	97	96	90	83	72	56	41
08–12–93	1606	24,000	98	115	--	--	--	--	--	98	98	93	84	73	59	44
			185	180	100	100	98	94	69	65	65	61	56	48	39	29
			263	236	100	100	100	92	57	50	50	47	43	37	30	22
			365	146	100	100	94	87	80	78	78	74	67	58	47	35
			539	122	--	--	--	--	--	94	94	89	80	70	57	42

Mississippi River at Thebes, Illinois																
07–18–93	1426	23,800	195	324	100	100	100	99	88	85	84	84	82	77	69	57
			277	352	100	100	100	98	82	78	77	77	75	71	63	52
			341	414	100	100	98	94	72	67	66	66	65	61	54	45
			446	408	100	100	100	92	72	67	66	66	65	61	54	45
			494	423	100	100	100	98	70	65	64	64	63	59	53	44
			533	540	100	100	100	94	55	51	50	50	49	46	41	34
			567	431	100	100	99	96	69	64	63	63	62	58	52	43
			610	476	100	100	99	97	63	58	57	57	56	53	47	39
			695	325	100	100	100	98	88	85	84	84	82	77	69	57
07–21–93	1920	25,300	195	288	100	100	98	96	88	85	83	76	69	63	54	43
			277	319	100	100	100	98	81	76	74	68	62	56	48	39
			341	394	100	100	97	90	66	62	61	55	51	46	39	32
			393	378	100	100	96	89	71	66	65	59	54	49	42	34
			446	550	100	100	99	85	49	44	43	39	36	33	28	22
			494	465	100	100	100	96	57	52	51	46	42	38	33	27
			533	1,060	100	100	98	82	58	23	23	20	18	17	15	12
			567	499	100	100	98	90	56	51	50	45	42	38	32	26
			610	429	100	100	98	97	62	56	55	50	46	41	36	29
			695	262	100	100	98	98	94	91	89	81	75	67	58	46
08–2–93	1610	25,100	247	437	100	100	98	94	91	90	90	84	76	65	50	35
			356	487	100	100	100	98	90	89	89	83	76	65	49	34
			469	514	100	100	99	96	79	76	76	71	65	55	42	29
			556	415	100	100	100	99	95	94	94	87	80	68	52	36
			665	495	100	100	100	98	82	79	79	73	67	57	43	30
08–06–93	1645	27,400	356	408	100	100	97	95	82	79	77	72	66	58	47	34
			469	423	100	100	100	92	80	78	76	71	65	57	46	34
			556	491	100	100	100	97	71	67	66	61	56	49	40	29
			665	416	100	100	100	97	82	78	76	71	65	57	46	34

Table 3. Particle-size distribution for bed-material samples collected from July 7 through August 12, 1993, at selected sediment data-collection stations

[Q, water discharge; m^3/s, cubic meters per second; particle diameter, in millimeters]

Date	Time	Q (m^3/s)	Percentage of sample smaller than particle diameter								
			16	8	4	2	1	0.5	0.25	0.125	0.062
Missouri River at Hermann, Missouri											
07–07–93	1435	11,400	100	100	99	94	85	40	14	0	0
07–13–93	1030	9,290	100	100	93	92	86	38	12	0	0
07–30–93	1705	18,200	100	100	97	94	79	28	17	0	0
08–01–93	1445	19,900	100	100	92	79	59	35	13	0	0
Mississippi River at St. Louis, Missouri											
08–02–93	1330	28,700	100	100	94	83	66	25	15	14	14
08–04–93	1215	28,000	100	100	97	87	68	15	1	0	0
Mississippi River at Chester, Illinois											
08–12–93	1930	24,000	100	100	93	85	75	37	9	1	0
Mississippi River at Thebes, Illinois											
07–29–93	1030	25,400	100	100	95	90	80	54	22	8	6

Einstein (Colby and Hembree, 1955), and Schoklitsch (Shulits, 1935). The values from these equations give a range of bedload transport estimates for the 1993 flood. These three equations were selected on the basis of the onsite data required for computation, demonstrated use of the equations in a previous upper Mississippi River study (Jordan, 1965), grain size of material used to develop the equation, and the ability of the equation to estimate the bedload directly.

SEDIMENT TRANSPORT DURING THE 1993 FLOOD

The Mississippi River at St. Louis was continuously above flood stage from June 26 through September 14. From the sediment data collected during the flood at the five stations listed in table 1, suspended-sediment loads have been computed and bedload estimated for the flood period. The St. Louis sediment station was selected to define the flood period because data also had been collected there during the 1951 and the 1973 floods. The suspended-sediment loads and particle-size data allow examination of the spatial and temporal variation of sediment sizes at the five sediment stations, comparison of the 1993 flood with other floods and the period of record, and investigation of the storage and flux of sediment in the lower Missouri and the central Mississippi Rivers. The cross-section and single vertical suspended-sediment concentration data allow examination of the temporal distribution of concentration in a flood of this magnitude and the nonhomogenous mixture of sediment downstream of the junction of two large rivers.

Suspended-Sediment Concentrations and Loads and Bedload Estimates

Hydrographs of water discharge and suspended-sediment concentrations of samples collected during the flood of 1993 at the Mississippi River at St. Louis, Chester, and Thebes are shown in figure 4. No hydrographs of suspended-sediment concentration are shown for the Mississippi River below Grafton and the Missouri River at Hermann because daily samples were not collected as was explained in the "Methods for Data Collection and Computation" section. The water-discharge hydrographs of the flood (fig. 4) indicate that the significant rise was in early to mid-July and that the discharge peaked on August 1 at St. Louis and August 7 at Chester and Thebes. At the sediment station at St. Louis, the suspended-sediment concentration first peaked on July 4, and water-discharge first peaked on July 11. During the flood period, the suspended-sediment concentration peaked a second time within 1 day of the water-discharge peak on August 1. Similar characteristics of peak sequences between water discharge and suspended-sediment concentration can be seen at Chester and Thebes.

Suspended-sediment loads for the flood period were, in millions of metric tons, 7 at the Mississippi River below Grafton, 70 at the Missouri River at Hermann, 55 at the Mississippi River at St. Louis, 52 at the Mississippi River at Chester, and 51 at the Mississippi River at Thebes. The ranges in daily mean concentration and daily loads are listed in table 4.

Bedload was computed for the range of water discharges at each station during the 1993 flood. Average curves drawn through values of computed bedload values and corresponding water discharge (fig. 5) were used to estimate the daily bedload on the basis of the daily mean water discharge. The estimated bedloads for the flood period as calculated by use of each equation are listed in table 4. The three equations provide estimates that generally are within 11 percent of each other at each sediment station except for those below Grafton and at St. Louis, where the differences are 87 and 31 percent, respectively. The ranges of the measured variables used as input in the bedload equations are listed in table 5. The estimated bedloads generally are less than 5 percent of the measured suspended-sediment load for all sediment stations except for the station below Grafton where the bedload estimate made by using the Modified Einstein equation was 18 percent of the suspended-sediment load.

Accuracy of Suspended-Sediment Concentrations and Loads

The accuracy of suspended-sediment-concentration data is dependent on sampler error; measurement error, which includes spatial and temporal misrepresentations of the mean suspended-sediment concentration, as well as onsite personnel error; and laboratory analysis error. On the basis of reports by the Federal Interagency Sedimentation Project (1952) and Beverage and Futrell (1986), the sampler error was estimated to be less than 15 percent for the onsite conditions (velocity, depth, bed roughness) during the 1993 flood. By examining multivertical cross-section suspended-sediment data, measurement error was

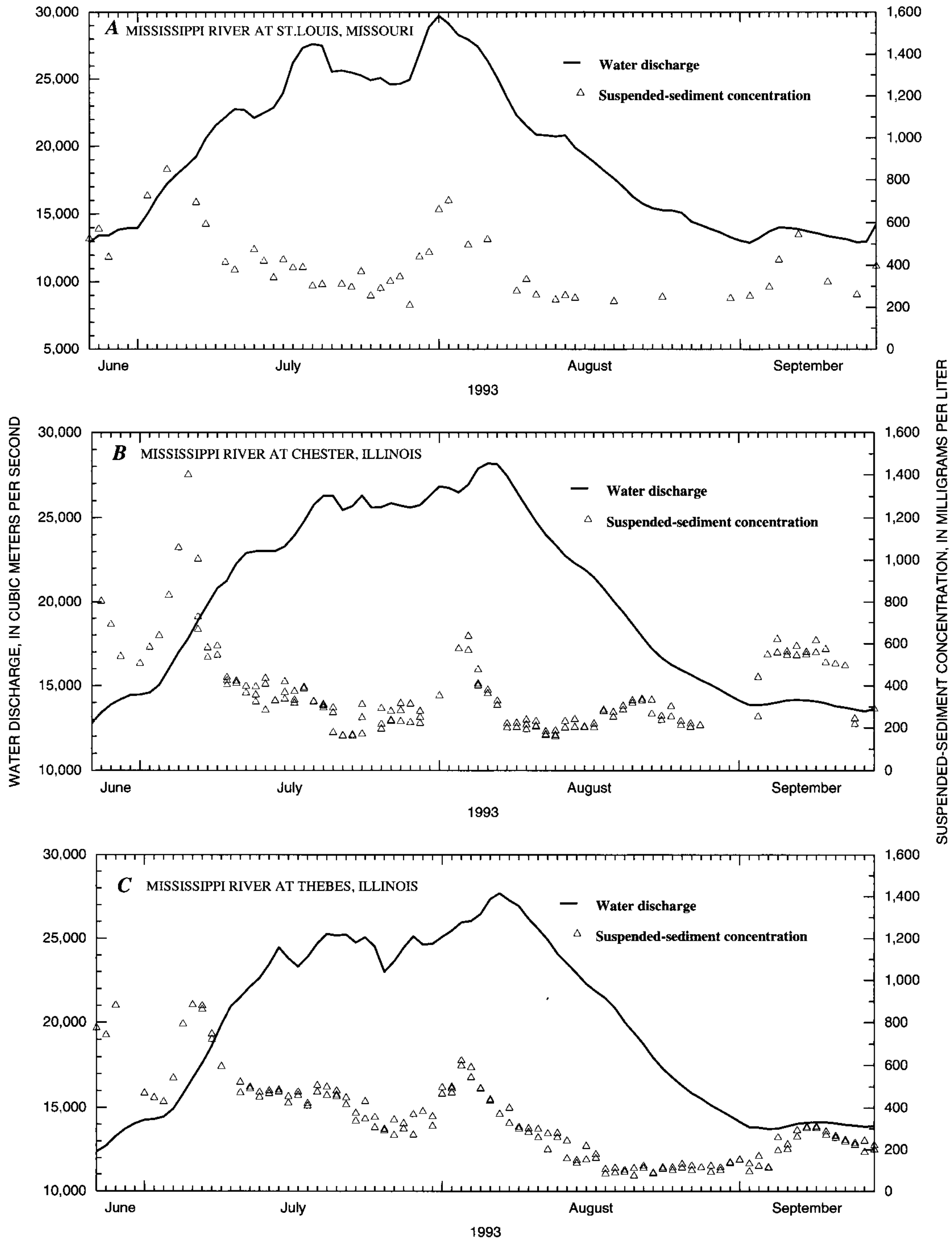


Figure 4. Water-discharge hydrographs and suspended-sediment-sample concentrations for the Mississippi River from June 26 through September 14, 1993. *A*, St. Louis, Missouri; *B*, Chester, Illinois; *C*, Thebes, Illinois.

thought to be less than 10 percent. From quality-assurance data collected as part of a study by the Branch of Quality Assurance, USGS (L.J. Schroder, USGS, written commun., 1993), and from replicates analyzed separately by the National Research Program, USGS, Denver, Colorado, the suspended-sediment concentrations analyzed in the laboratory for this study had an average error of 8 percent.

For daily record sediment stations, Colby (1956, p. 137) indicated the accuracy of sediment loads computed for a large river, such as the Mississippi, "in which flow is comparatively constant, sediments are

Table 4. Suspended-sediment loads and estimated bedloads at sediment data-collection stations from June 26 through September 14, 1993

[mg/L, milligrams per liter; t/d, metric tons per day; t metric tons; Min, minimum; Max, maximum; --, not determined]

Station (fig. 1)	Range of daily mean concentration (mg/L)		Range of daily mean load (million t/d)		Suspended-sediment load (million t)	Bedload estimated using indicated equation (million t)		
	Min	Max	Min	Max		Meyer-Peter and Muller	Modified Einstein	Schoklitsch
Mississippi River below Grafton, Ill.	--	--	0.02	0.27	7.0	0.45	1.25	0.16
Missouri River at Hermann, Mo.	--	--	--	--	70	.96	1.00	.95
Mississippi River at St. Louis, Mo.	222	850	.28	1.77	55	1.82	2.25	1.55
Mississippi River at Chester, Ill.	164	1,270	.28	1.96	52	1.56	1.61	1.47
Mississippi River at Thebes, Ill.	89	878	.14	1.35	51	2.50	2.32	2.60

fine, and concentrations are high enough to sample accurately" to be about 10 percent. The annual suspended-sediment load for these stations generally has been thought to be within 10 percent of the true value on the basis of multiple computations of the same record by using variations in the suspended-sediment concentration hydrographs. These variations were shifted within the estimated range of errors associated with suspended-sediment concentration. These errors are evident when the data are plotted as shown in figure 4. By interpolating the suspended-sediment-concentration hydrographs through the middle of the "noise pattern" in these data, some of the error can be dampened out.

Table 5. Minimum and maximum values of miscellaneous sediment, hydraulic, and slope data collected during multivertical sediment sampling and water-discharge measurements, June 26 through September 14, 1993

[m^3/s, cubic meters per second; m/s, meters per second; m, meters; m^2, square meters; m/km, meters per kilometer]

Station (fig. 1)	Percent silt of samples	Water-discharge measurements						Water-surface slope (m/km)
		Water discharge (m^3/s)	Mean stream velocity (m/s)	Maximum stream velocity (m/s)	Mean depth (m)	Maximum depth (m)	Cross-section area (m^2)	
Mississippi River below Grafton, Il.								
Minimum	79	8,670	1.42	2.25	9.05	12.8	6,080	0.035
Maximum	99	16,200	1.78	3.04	10.6	18.6	9,130	.048
Missouri River at Hermann, Mo.								
Minimum	56.8	4,790	1.34	2.17	6.73	11.4	2,970	.148
Maximum	83.2	21,200	2.40	3.43	10.8	15.9	6,480	.172
Mississippi River at St. Louis, Mo.								
Minimum	63	12,900	1.62	2.21	12.9	17.7	7,750	.072
Maximum	85.9	29,200	2.54	4.14	16.99	26.8	12,100	.15
Mississippi River at Chester, Ill.								
Minimum	77	13,400	1.49	2.32	9.81	19.3	8,649	.109
Maximum	85.2	26,800	2.26	4.27	17.9	27.4	13,400	.123
Mississippi River at Thebes, Ill.								
Minimum	60.6	13,800	1.66	2.65	10.6	18.0	8,110	.130
Maximum	85.6	27,600	2.45	3.86	11.3	22.9	11,300	.164

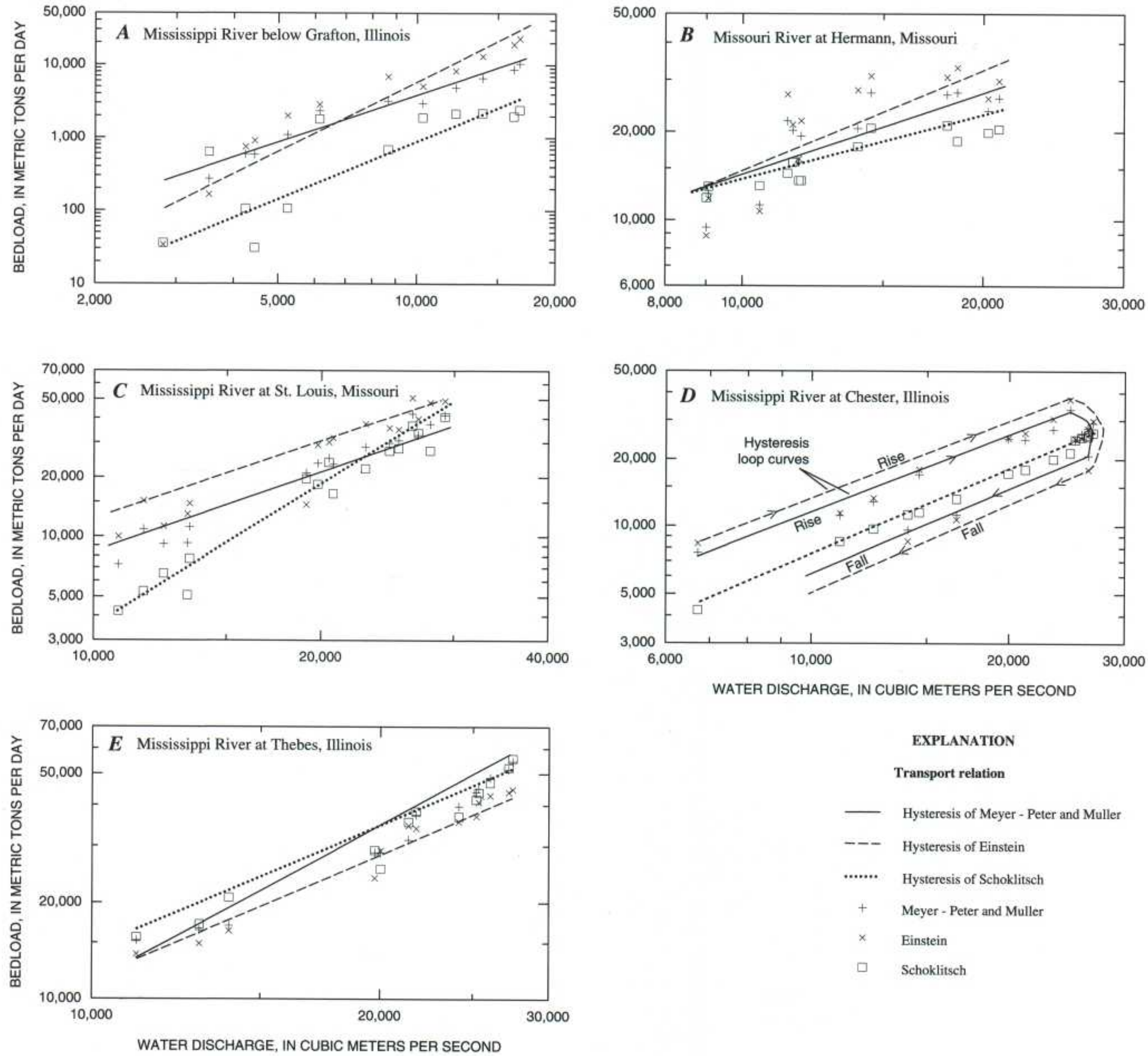


Figure 5. Relation between water discharge and bedload by using the Meyer-Peter and Muller, the Modified Einstein, and the Schoklitsch bedload equations for selected data-collection stations. *A*, Mississippi River below Grafton, Illinois; *B*, Missouri River at Hermann, Missouri; *C*, Mississippi River at St. Louis, Missouri; *D*, Mississippi River at Chester, Illinois; *E*, Mississippi River at Thebes, Illinois.

For suspended-sediment loads estimated from transport relations, accuracy varies with the type of stream and density of data collection. In general, the accuracy of the estimate increases with a longer period of record estimated (for example, 3-month period load in comparison with a daily load) because "some of the inaccuracies in measured daily sediment loads will inevitably cancel each other when summed over long periods" (Walling, 1977, p. 531). Because the curves used in this report were developed by "visual fit" instead of by regression analysis, a statistical measure of error is unavailable. However, the probable accuracy of the load estimates for the flood period was determined by a curve that was developed for the Mississippi River at Thebes by using data from four multivertical cross sections and four of the samples collected by observers during the flood period. Because a daily record exists for this station, the suspended-sediment load estimated by the transport relation for the flood period was compared with the daily computed load for the flood period with the result that the daily record computed load had been overestimated by 14 percent. This error is a combination of all data collection and laboratory errors previously discussed plus any error inherent in the transport relation.

Bed-material samples often were collected from a boat by using a US BM–54 sampler.

Particle Size of Suspended-Sediment and Bed-Material Samples

The mean suspended-sediment particle-size distributions for cross-section samples collected during the 1993 flood are shown in figure 6. For these samples, the farther downstream, the coarser sediment particular constitute a larger percentage of the particle-size distribution. The contributions of all major tributaries in the upper Mississippi River system flowed past the sediment station at Thebes; suspended-sediment particle-size distributions at Thebes for multivertical samples collected before and during the 1993 flood period are shown in figure 7. No definite trend of coarsening or fining is noted as the water discharge changes.

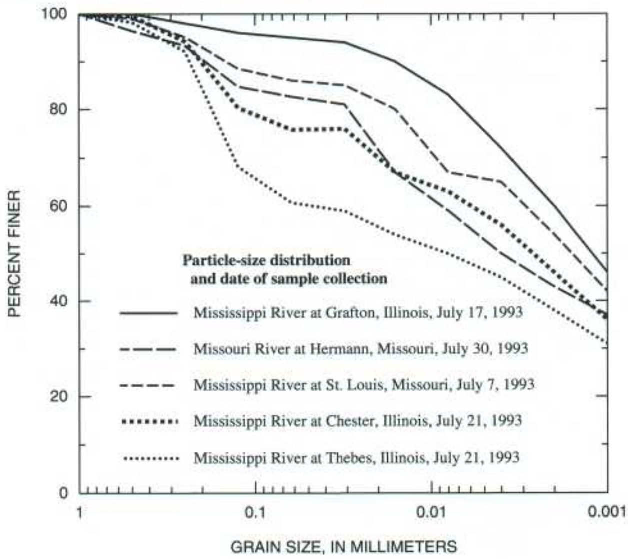


Figure 6. Mean particle-size distributions for multivertical suspended-sediment cross-section samples collected during the 1993 flood rise at the sediment data-collection stations.

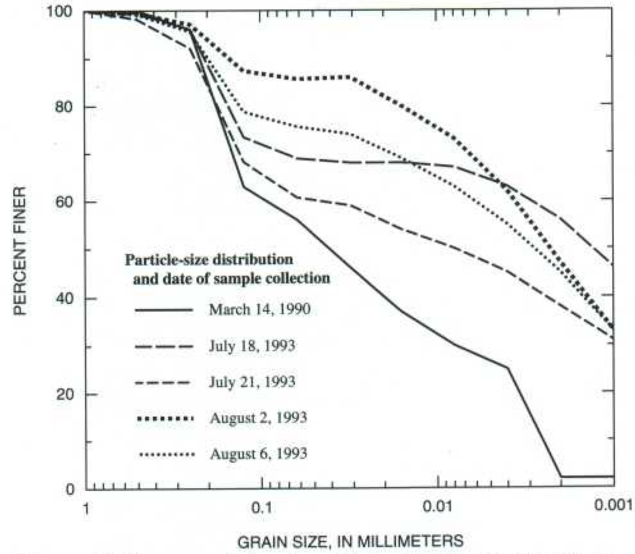


Figure 7. Mean particle-size distribution for multivertical suspended-sediment cross-section samples collected from the Mississippi River at Thebes, Illinois.

The size distribution of bed material during the flood period is shown in figure 8. The bed material coarsened upstream.

Sediment Loads

Major floods occurred in the upper Mississippi River system in 1951 and 1973. Suspended-sediment loads from these two floods were determined only for the Missouri River at Hermann and the Mississippi River at St. Louis (U.S. Army Corps of Engineers, 1957; Chin and others, 1975). In 1951, the Mississippi

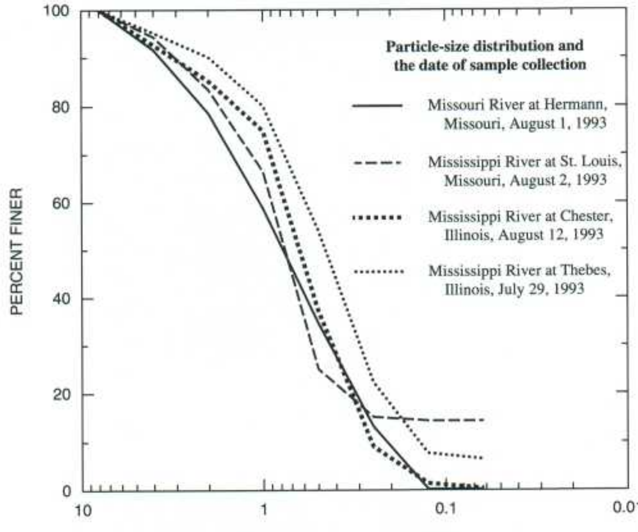


Figure 8. Bed-material particle-size distribution for selected sediment data-collection stations

River at St. Louis was above flood stage for 31 days from June 29 through July 29, whereas in 1973, the river was above flood stage from March 9 through May 20 for a total of 73 days. The water-discharge volumes and suspended-sediment loads for all flood periods are listed in table 6.

During the 1993 flood, less sediment was transported on a per-day basis than during the 1951 and the 1973 floods. One explanation for this difference could be the effect of anthropogenic basin changes from 1951 to 1993. Since 1953, reservoirs upstream on the Missouri River have substantially decreased the sediment transported to the lower Missouri River (Meade and Parker, 1985). Holmes (1993) reported a significant downward trend in suspended-sediment concentration from 1948 through 1979 for the Mississippi River at St. Louis, whereas no trend was detected from 1980 through 1991. In addition, a large number of levee breaches occurred during the 1993 flood on the Missouri River. These breaches provided numerous potential sinks for sediment.

For the Mississippi River sediment stations at St. Louis, Chester, and Thebes, the median daily suspended-sediment concentration and load for the 1993 flood and the period of record are listed in table 7. The median daily loads during the flood were more than five times the median load for the period of record, whereas the median concentrations for the 1993 flood period are extremely low and almost equal to the median concentration for the period of record. Furthermore, the suspended-sediment concentrations during the flood are low when compared with concentrations from previous rises in streamflow during the 1993 water year. The hydrographs of water discharges and suspended-sediment concentrations on the Mississippi River at Thebes for increases in discharge during November 1992 and during the 1993 flood are shown in figure 9. The peak suspended-sediment concentration for the first peak in the 1993 flood rise is about one-third of that for the November rise, whereas the peak water discharge for the 1993 flood is about twice that for the November 1992 rise. The large differences in suspended-sediment concentrations possibly are caused by the seasonal differences of the two rises; for example, late fall and mid- to late summer. However, the differences are more likely attributable to the depletion of the sediment supply and dilution of the sediment concentration that could be caused by any combination of the following: the unusually wet spring and early summer in 1993 prevented many farmers from plowing and planting, which reduced the amount of fine sediment available to be transported to the rivers; greater-than-normal flow for much of the spring and early summer on the Missouri and the Mississippi Rivers had already purged the system of much of the fine sediment available for resuspension; extremely high-water discharges diluted the sediment concentration; or the impact of raindrops, which detach sediment particles, was decreased on native soil by water in many fields.

Between 21 and 29 percent of the 1993 annual suspended-sediment load was transported during the flood period at the sediment stations on the lower Missouri and the central Mississippi Rivers (table 8). These percentages of annual load transported are less than those transported by smaller rivers (Meade and others, 1990) where between 52 and 98 percent of the sediment load was transported in 10 percent of the

Table 6. Suspended-sediment loads and volumes of water discharge for the 1951, 1973, and 1993 flood periods on the Missouri River at Hermann, Missouri, and the Mississippi River at St. Louis, Missouri

[hm, hectare-meters; t, metric tons]

Station (fig. 1)	1951 flood period[1]		1973 flood period[2]		1993 flood period[3]	
	Volume of water discharge (million hm)	Suspended-sediment load (million t)	Volume of water discharge (million hm)	Suspended-sediment load (million t)	Volume of water discharge (million hm)	Suspended-sediment load (million t)
Missouri River at Hermann, Mo.	3.5	[4]57	5.2	[5]75	5.9	70
Mississippi River at St. Louis, Mo.	5	55	12	58	13.7	55

[1]Flood period is defined as the 31-day period, June 29 through July 29, 1951.
[2]Flood period is defined as the 73-day period, March 9 through May 20, 1973.
[3]Flood period is defined as the 81-day period, June 26 through September 14, 1993.
[4]Data from U.S. Army Corps of Engineers (1957).
[5]Data from Chin and others (1975).

Table 7. Median daily suspended-sediment concentrations and loads for the 1993 flood and the period of record at the daily sediment data-collection stations

[mg/L, milligrams per liter; t/d, metric tons per day; --, no data]

Station (fig. 1)	1993 flood		Period of record	
	Median daily concentration (mg/L)	Median daily load (t/d)	Median daily concentration (mg/L)	Median daily load (t/d)
Mississippi River below Grafton, Ill.	--	62,700	125	41,300
Mississippi River at St. Louis, Mo	340	694,000	326	128,000
Mississippi River at Chester, Ill.	326	682,000	304	127,000
Mississippi River at Thebes, Ill	317	717,000	302	139,000

time. The larger the river system, the less effect suspended-sediment load transported during lower frequency floods have on the annual sediment delivery. However, regardless of the size of a river system, major channel and bed changes are the result of the dynamics of sediment transport during these low-frequency floods.

The mean annual suspended-sediment loads also are listed in table 8. The 1993 water year annual load exceeded the mean annual load by 52 to 75 percent for all stations except the Missouri River at Hermann where the 1993 load exceeded the mean annual load by 128 percent.

Mixing of Sediment From the Missouri and the Mississippi Rivers

The Missouri River flows into the Mississippi River 24 km upstream from the sediment station at St. Louis (fig. 1). At St. Louis, the water from the Missouri River, which routinely carries a larger sediment concentration, is not completely mixed with the water from the central Mississippi River. The sediment contributions for each river are evident in figure 10. The more sediment-laden Missouri River water flows along the Missouri shoreline (in the background) and the clearer Mississippi River water flows along the Illinois shoreline. The lateral distribution of suspended-sediment concentrations determined from cross-section samples collected during the flood period is shown in figure 11. The concentration of suspended sediment near the Missouri shoreline was about five times greater than that near the Illinois shoreline.

Waters from two major rivers sometimes can flow for tens of kilometers before they become visually mixed. The mixing distance depends on the river conditions, such as water discharge, season, temperature, and relative water discharge and sediment inputs from the two rivers. Aerial photographs taken on July

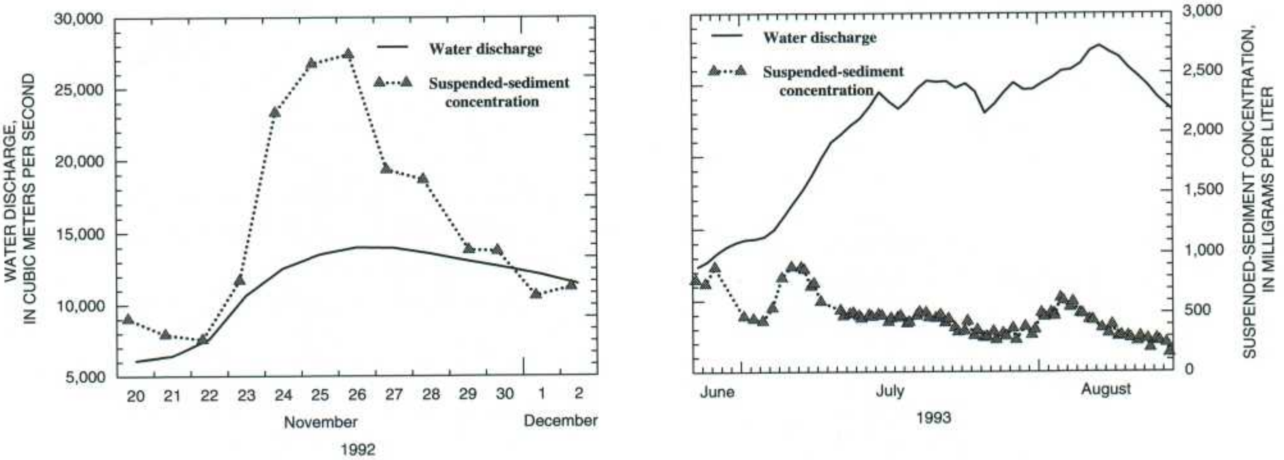


Figure 9. Water-discharge and suspended-sediment-concentration hydrographs for two floods on the Mississippi River at Thebes, Illinois.

Table 8. 1993 flood and annual suspended-sediment loads at the sediment data-collection stations

[t, metric tons]

Station (fig. 1)	Flood of 1993 sediment load (million t)	1993 water year annual sediment load[1] (million t)	Percentage of annual load transported during 1993 flood	Mean annual load for period of record (million t)
Mississippi River below Grafton, Ill[1]	[2]7	33	21	[3]21.3
Missouri River at Hermann, Mo	[2]70	[2]265	26	[4]116
Mississippi River at St. Louis, Mo	55	187	29	[5]119
Mississippi River at Chester, Ill	52	192	27	[6]126
Mississippi River at Thebes, Ill.	51	203	25	[7]116

[1]1993 water year is from October 1, 1992, through September 30, 1993.
[2]Load computed by using transport relations.
[3]Record used to compute mean annual load—1987 to 1993, includes data collected from 1987 to 1989 at Alton, Illinois, 25 miles downstream.
[4]Record used to compute mean annual load—1949 to 1981, annual load estimates provided by U.S. Army Corps of Engineers, Kansas City District.
[5]Record used to compute mean annual load—1980 to 1993; does not include record from 1949 to 1979 because of anthropogenic changes documented in Holmes (1993).
[6]Record used to compute mean annual load—1983, 1988 to 1993; does not include record from 1980 to 1982 and from 1984 to 1987 because of missing records during those years.
[7]Record used to compute mean annual load—1983, 1985, 1987, 1989 to 1993; does not include record from 1980 to 1982, 1984, and 1986 to 1988 because of missing records during those years

25, 1993, show that the Mississippi River became well mixed 88 km downstream from its normal junction with the Missouri River. In addition, for a large part of the 1993 flood period, the two rivers began flowing together 32 km upstream from where they normally meet. Inspection of aerial photography taken on August 3, 1993, after major levees failed downstream from St. Louis on August 1 and 3 indicates that the rivers became mixed 43 km downstream from the normal junction of the two rivers. Aerial photographs taken on June 22, 1988, during a major drought shows that the rivers were mixed within 8 km of their junction. Knowledge of how this mixing takes place is important for the management of water-treatment plants that are supplied by the Mississippi River.

Storage and Flux of Sediment in the Lower Missouri and the Central Mississippi River Basins

Large quantities of sediment were transported past the five sediment stations on the lower Missouri and the central Mississippi Rivers during the 1993 flood (table 8). The suspended-sediment load of the Missouri River at Hermann was 10 times greater than that of the Mississippi River below Grafton. The suspended-sediment load transported by the Mississippi River past St. Louis was 22 million metric tons less than the sum of the 77 million metric tons of suspended-sediment load transported past the two upstream sediment stations below Grafton and at Hermann during the flood period. The smaller load at St. Louis implies that sediment went into storage between the upstream stations and St. Louis. This implication is partly verified by the presence of massive quantities of newly deposited sand on river-bend flood plains (fig. 12). Most of the sand seems to be associated with major levee breaks where high hydraulic heads built up before the levee broke. These high hydraulic heads in conjunction with the levee break resulted in high-energy flows that transported tremendous quantities of sand onto the flood plains. Recent surveys (G.K. Schalk, USGS, written commun., 1994) from selected Missouri River bend flood plains indicate more material was deposited on the flood plain than was scoured from the levees and flood plains, which indicates that much of the sand came from the river. Deposition of as much as 0.14 m of silt and clay and 4 m of sand

Figure 10. The Mississippi River at St. Louis, Missouri, July 30, 1993, looking west, showing the lateral variability in sediment concentration. Lighter areas are higher in suspended sediment, (Photograph from Srenco Photography, St. Louis, Missouri, 1993, and published with permission.)

over more than 20,000 hectare has been observed on the river-bend flood plains downstream from Hermann. Preliminary estimates from the surveys indicate that more than 35 million metric tons of sediment were deposited on the flood plain between Hermann and the mouth of the Missouri River.

More sediment was transported by the Missouri River at Hermann than by the Mississippi River at St. Louis because the water-surface slope of the Missouri River at Hermann was about 30 percent greater than that of the Mississippi River at St. Louis (table 5). This smaller slope decreases the transport power of the river and, in turn, decreases the ability of the river to suspend and transport sediment.

The total sediment loads at the Mississippi River sediment stations at St. Louis, Chester, and Thebes for the flood period were within 7 percent of each other [within the accuracy of suspended-sediment-data collection (Meade and others, 1990)]. Therefore, on a macroscale, sediment was neither being stored nor added to the system between St. Louis and Thebes, which implies that the system as a whole was in equilibrium because the load at St. Louis virtually equalled that at Chester and Thebes. Potential major sinks for sediment were created by levee breaks on the Mississippi River below St. Louis; however, aerial and ground reconnaissance revealed noticeably less associated sand deposition than was evident at the Missouri River levee breaks. The smaller sand deposits on the Mississippi River could be related to stream pattern differences (abundant, wooded midchannel islands on the Mississippi River compared with much fewer midchannel islands in the Missouri River), differences in width of riparian zones, timing of major levee breaks, and differences in energy slope.

On a microscale, there were dynamic changes in the reach from St. Louis to Thebes. Channel-bed changes for the Mississippi River at Chester are shown

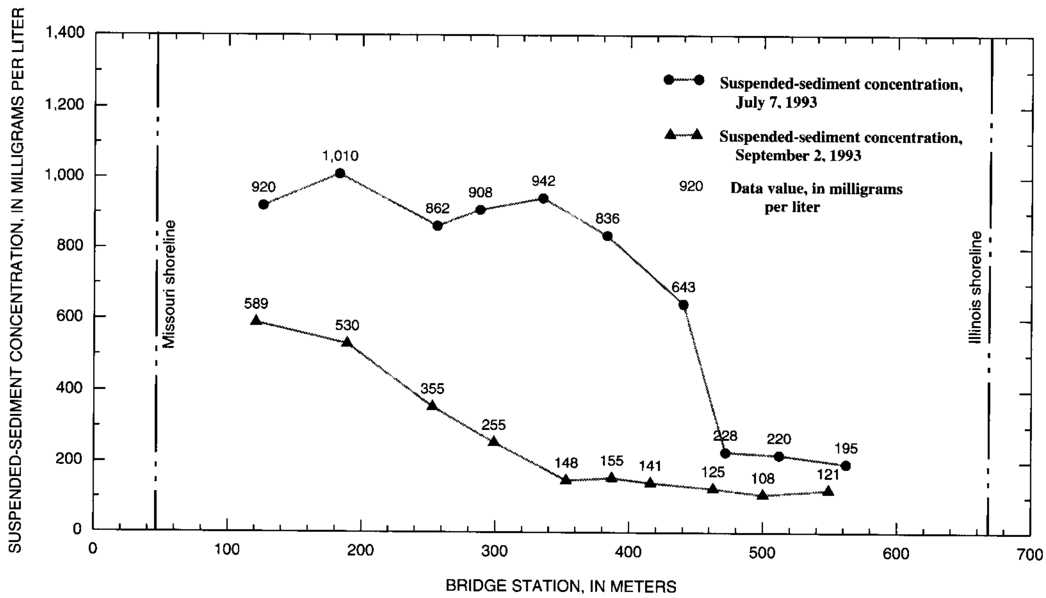


Figure 11. Lateral distribution of suspended-sediment concentrations for the Mississippi River at St. Louis, Missouri.

in figure 13. Scour in the channel bed was as great as 4 m from July 12 through July 20, 1993 (fig. 13*A*). Such scouring adds to the sediment in transport. A general pattern of scour during the flood rise was followed by aggradation during the recession (fig. 13*B*). However, as of February 3, 1994, the channel bed still had not aggraded to the previous bed level of November 17, 1992 (fig. 13*C*).

SUMMARY

Sediment data were collected at five sediment stations on the lower Missouri and the central Mississippi Rivers during the 1993 flood. The suspended-sediment loads transported past these sites for the 81-day flood period from June 26 through September 14, 1993, were, in millions of metric tons, 7 at the Mississippi River below Grafton, 70 at the Missouri River at Hermann, 55 at the Mississippi River at St. Louis, 52 at the Mississippi River at Chester, and 51 at the Mississippi River at Thebes. By using the Meyer-Peter and Muller, the Modified Einstein, and the Schoklitsch equations, bedload was estimated for these sites to be generally less than 5 percent of the suspended-sediment load, except for the station below Grafton.

The 1993 flood generally transported less sediment per volume of water discharge than did other floods on the Mississippi River. This decrease in transported sediment probably is attributable to the construction and operation of reservoirs in the upper Missouri River since 1953 that greatly decreased the supply of sediment, as well as the depletion and dilution of sediment that was evident during the 1993 flood. Possible causes of these phenomena are the unusually wet spring and early summer that prevented many farmers from plowing and planting, which made less fine sediment available to be transported to the rivers; greater-than-normal flow for much of the spring and early summer, so that the Missouri and the Mississippi Rivers had already purged the system of much of the fine sediment available for resuspension; extremely high water discharges diluted the sediment concentration; and the decrease in raindrop impact on native soil because of the water in many fields.

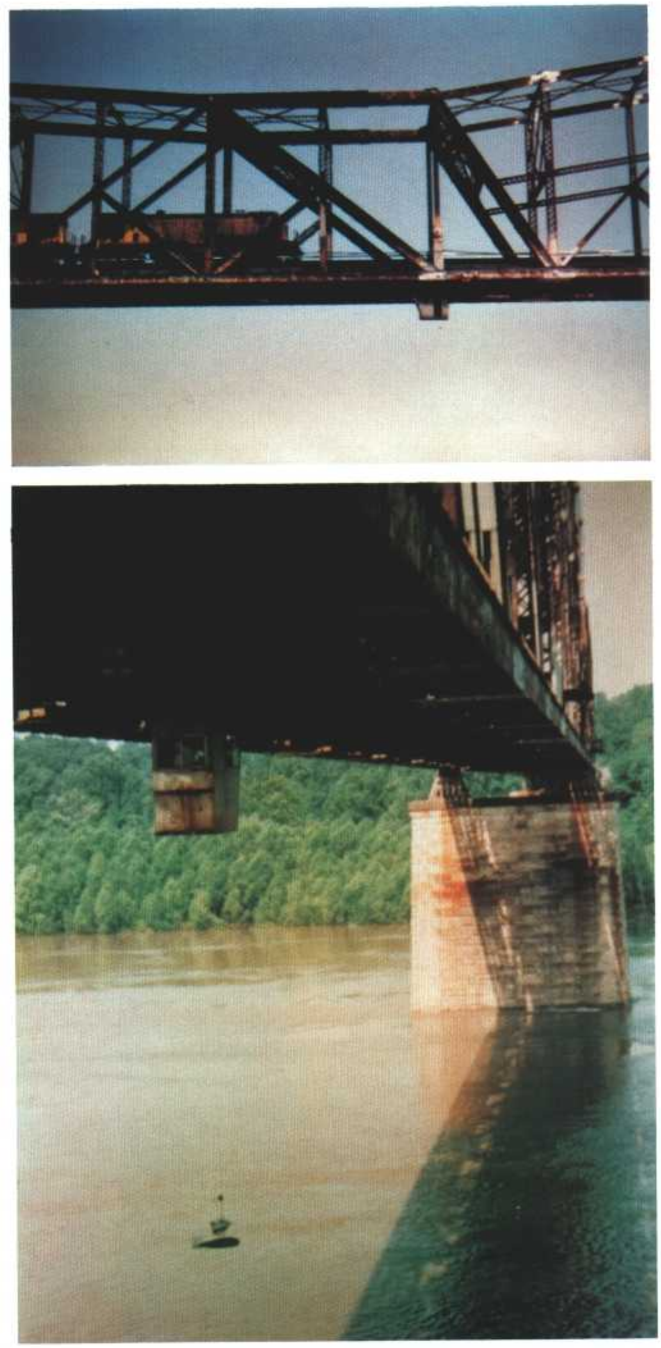
The suspended-sediment load transported by the Mississippi River past St. Louis was 22 million t less than the total of the suspended-sediment loads transported past the two upstream sediment stations below Grafton and at Hermann (77 million t). This loss of sediment implies that sediment was being stored between the upstream stations and St. Louis and is partly verified by the massive amount of newly deposited sediments on more than 20,000 ha of the flood plain downstream from Hermann. New sediment deposits as thick as 4 m were observed. The ability of the Mississippi River near St. Louis to transport sediment generally was less than the Missouri River at Hermann because the water-surface slopes at St. Louis were about 30 percent less than those at Hermann.

The Missouri River at Hermann contributed 10 times as much sediment as the Mississippi River contributed below Grafton, which is upstream from the

Figure 12. View of the sand deposited on the Missouri River flood plain near the junction of the Missouri and the Mississippi Rivers, November 8, 1993. (Photograph from U.S. Army Corps of Engineers, 1993, and published with permission.)

junction of the two rivers. The inflow of the Missouri River causes a nonhomogenous mixture of water in the Mississippi River past St. Louis 24 km downstream from the inflow. The suspended-sediment concentration near the Missouri shoreline is almost five times that near the Illinois shoreline. Aerial photographs taken on July 25, 1993, show that the Mississippi River became well mixed 88 km downstream from its normal junction with the Missouri River.

In the Mississippi River reach between St. Louis and Thebes, the suspended-sediment loads are fairly constant, which implies equilibrium; however, many dynamic changes occurred within this reach. For example, at Chester, as much as 4 m of scour was measured between July 12 and July 20, 1993. The channel-bed changes generally followed a pattern of



Collection of data on large rivers, such as the Missouri and the Mississippi, often requires specialized equipment, such as this monorail system built underneath the Thebes, Illinois, railroad bridge.

scouring during the flood rise followed by aggradation during the recession.

The particles of the suspended sediment transported in the Mississippi River between Grafton, Ill. and Thebes, Ill. are larger in size in the downstream direction, whereas no change in particle size is seen with variation of discharge. Bed material coarsens in the upstream direction.

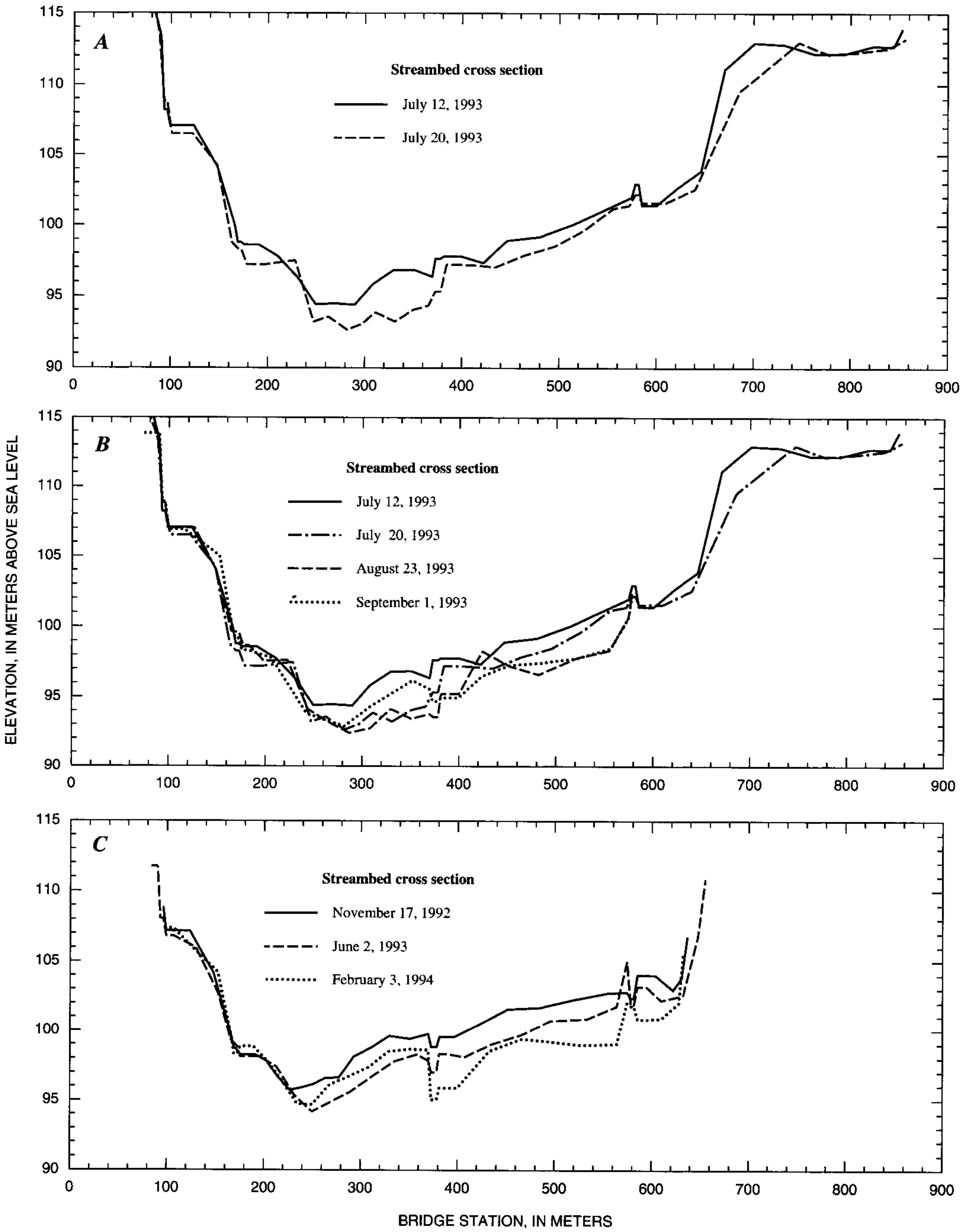


Figure 13. Streambed cross sections for the Mississippi River at Chester, Illinois. *A*, Streambed scouring prior to flood peak; *B*, Streambed aggradation following the flood peak; *C*, Streambed levels 6 months after flood peak.

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