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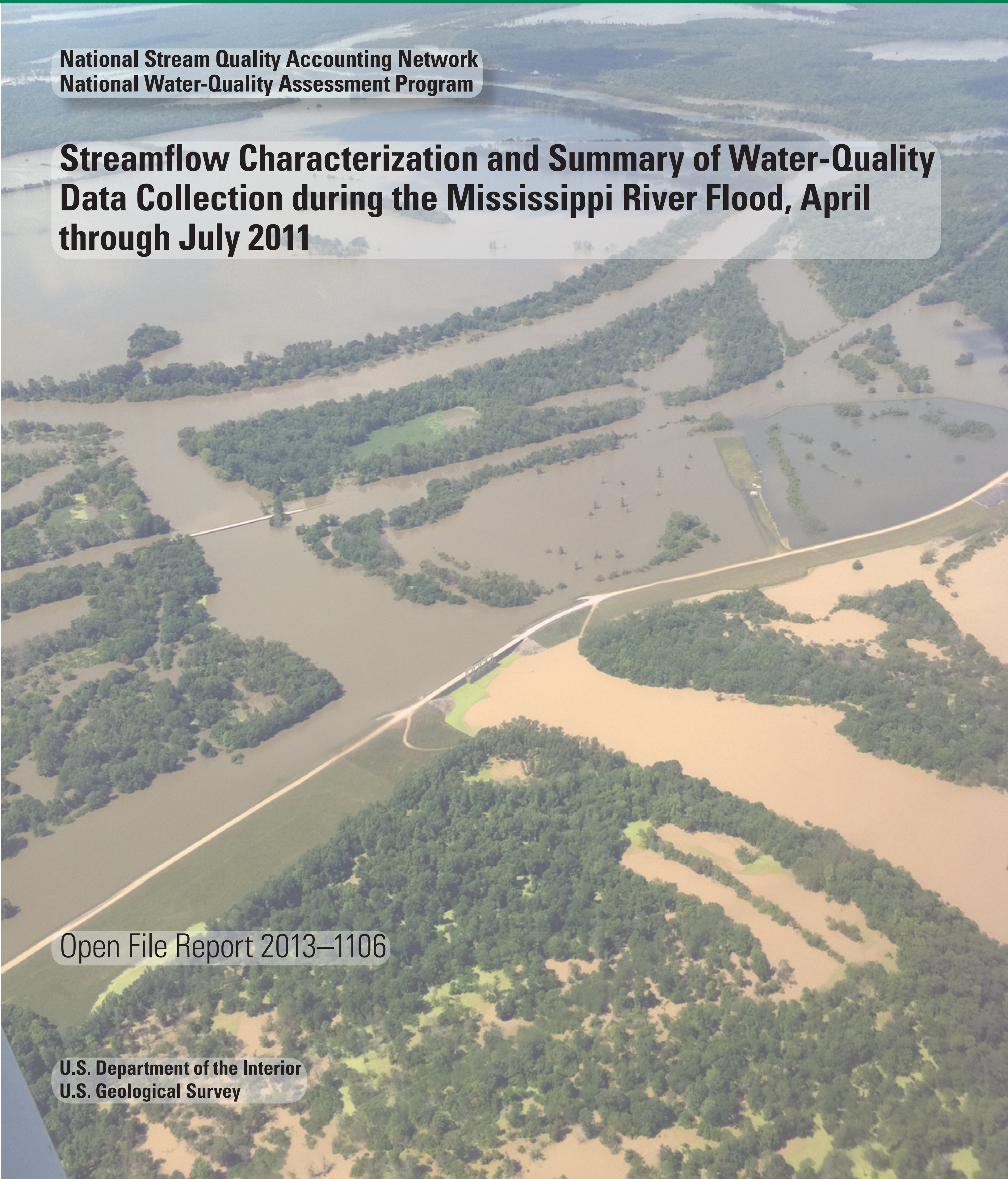
Streamflow Characterization and Summary of Water-Quality Data Collection during the Mississippi River Flood, April through July 2011



Open File Report 2013–1106

U.S. Department of the Interior
U.S. Geological Survey

Cover. Aerial view of the confluence of Steele Bayou with the Yazoo River looking southwest during the 2011 Mississippi River flood. The picture shows backwater flooding of the Yazoo River from the Mississippi River which is located in the upper foreground. Photo by Scott Koestler.

Streamflow Characterization and Summary of Water-Quality Data Collection during the Mississippi River Flood, April through July 2011

By Heather L. Welch and Kimberlee K. Barnes

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U.S. Department of the Interior
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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

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Suggested citation:
Welch, H.L., and Barnes, K.K., 2013, Streamflow characterization and summary of water-quality data collection during the Mississippi River flood, April through July 2011: U.S. Geological Survey Open-File Report 2013–1106, 29 p., http://pubs.usgs.gov/of/2013/1106/.

Contents

Abstract 1
Introduction....................1
  Purpose and Scope 3
Hydrologic Setting 3
  Upper Mississippi River Subbasin 3
  Missouri River Subbasin....................3
  Ohio River Subbasin 10
  Lower Mississippi-Atchafalaya River Subbasin....................10
  Flood-Control Structures 10
Methods....................10
  Streamflow Measurement 10
  Sample Collection, Processing, and Analysis....................10
  Quality-Control Data 14
Water-Quality Data Collected during the 2011 Flood 14
Streamflow Characterization....................14
  Comparison of Mean Daily and Instantaneous Streamflow during the 2011 Flood with Historical Streamflow 14
  Flood Period Hydrographs....................17
    Upper Mississippi River Subbasin 17
    Missouri River Subbasin....................17
    Ohio River Subbasin 19
Comparison of Peak Stage and Streamflow of the 2011 Flood to Those of Historic Floods............21
  Missouri River Subbasin....................21
  Ohio River Subbasin and the Lower Mississippi-Atchafalaya River Subbasin....................22
Concentrations of Selected Water-Quality Constituents in the Subbasins during the 2011 Flood 24
Summary and Conclusions....................24
References Cited....................26
Appendixes 29

Figures

1. Map showing the extent of the Mississippi River Basin and Subbasins 2
2. Map showing the upper Mississippi River Subbasin and sites sampled during the 2011 flood 8
3. Map showing the Missouri River Subbasin and sites sampled during the 2011 flood 9
4. Map showing the Ohio River Subbasin and sites sampled during the 2011 flood 11
5. Map showing the lower Mississippi-Atchafalaya River Subbasin and sites sampled during the 2011 flood 12
6. Map showing the location of water-quality samples collected in the Birds Point-New Madrid Floodway and the Morganza Floodway and the Bonnet Carré Spillway during the 2011 flood 13

7. Box plots comparing historical instantaneous streamflow with instantaneous streamflow measured during the 2011 flood at selected sites in the upper Mississippi River Subbasin, the Missouri River Subbasin, the Ohio River Subbasin, and the lower Mississippi-Atchafalaya River Subbasin 16
8. Hydrograph showing mean daily streamflow in the upper Mississippi River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection 18
9. Hydrograph showing mean daily streamflow in the Missouri River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection 18
10. Hydrograph showing mean daily streamflow in the Ohio River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection....19
11 Hydrograph showing the contribution of streamflow to the lower Mississippi-Atchafalaya River Subbasin from the upper Mississippi River and Ohio River Subbasins 20
12. Hydrograph showing mean daily streamflow at sites on the main stem in the lower Mississippi-Atchafalaya River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection....21
13. Hydrograph showing mean daily streamflow at sites on the Atchafalaya River in the lower Mississippi-Atchafalaya River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection....22
14. Photograph showing how U.S. Army Corps of Engineers documents the height of all major floods of the Mississippi River on the levee wall at Vicksburg, Mississippi 24

Tables

1. U.S. Geological Survey stations sampled for water-quality during the 2011 Mississippi River flood....4
2. U.S. Geological Survey streamflow station names, station numbers, drainage basin areas, and minimum, maximum, and median streamflow data for April through July 2011 at selected sites in the upper Mississippi River Subbasin, the Missouri River Subbasin, the Ohio River Subbasin, and the lower Mississippi-Atchafalaya River Subbasin....15
3. Maximum stages and streamflows for 2011 and selected largest-flood years at select U.S. Geological Survey streamflow stations in the Mississippi River Basin. 23
4. Concentrations of selected constituents measured in each of the four subbasins during the 2011 Mississippi River flood, April through July. 25

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
ton per year (ton/yr)	0.9072	metric ton per year

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit ()F) may be converted to degrees Celsius (°C) as follows:
°C=(°F-32)/1.8

The distance above a vertical datum is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius

(µS/cm at 25 °C)

Abbreviations

GC-FID	gas chromatograph with a flame ionization detector
NASQAN	National Stream Quality Accounting Network
NAWQA	National Water Quality Assessment
USGS	U.S. Geological Survey

Streamflow Characterization and Summary of Water-Quality Data Collection during the Mississippi River Flood, April through July 2011

By Heather L. Welch and Kimberlee K. Barnes

Abstract

From April through July 2011, the U.S. Geological Survey collected surface-water samples from 69 water-quality stations and 3 flood-control structures in 4 major subbasins of the Mississippi River Basin to characterize the water quality during the 2011 Mississippi River flood. Most stations were sampled at least monthly for field parameters, suspended sediment, nutrients, and selected pesticides. Samples were collected at daily to biweekly frequencies at selected sites in the case of suspended sediment. Hydrocarbon analysis was performed on samples collected at two sites in the Atchafalaya River Basin to assess the water-quality implications of opening the Morganza Floodway. Water-quality samples obtained during the flood period were collected at flows well above normal streamflow conditions at the majority of the stations throughout the Mississippi River Basin and its subbasins.

Heavy rainfall and snowmelt resulted in high streamflow in the Mississippi River Basin from April through July 2011. The Ohio River Subbasin contributed to most of the flow in the lower Mississippi-Atchafalaya River Subbasin during the months of April and May because of widespread rainfall, whereas snowmelt and precipitation from the Missouri River Subbasin and the upper Mississippi River Subbasin contributed to most of the flow in the lower Mississippi-Atchafalaya River Subbasin during June and July. Peak streamflows from the 2011 flood were higher than peak streamflow during previous historic floods at most of the selected streamgages in the Mississippi River Basin. In the Missouri River Subbasin, the volume of water moved during the 1952 flood was greater than the amount moved during the 2011 flood.

Median concentrations of suspended sediment and total phosphorus were higher in the Missouri River Subbasin during the flood when compared to the other three subbasins. Surface water in the upper Mississippi River Subbasin contained higher median concentrations of total nitrogen, nitrate, orthophosphate, and atrazine during the flood period.

Introduction

The Mississippi River Basin drains about 41 percent of the conterminous United States including all or part of 31 states, as well as two Canadian provinces. The Mississippi River is the fourth longest river in the world and its river basin is the largest in North America (fig. 1). The four major Mississippi River subbasins are the upper Mississippi, the Missouri, the Ohio, and the lower Mississippi-Atchafalaya. The majority of corn, soybeans, wheat, cattle, hogs, and to a lesser extent, cotton and rice produced in the United States originates from agricultural regions within the Mississippi River Basin (Coupe and Goolsby, 1999). To optimize agricultural production, pesticides and fertilizers are applied to the land surface. These agricultural chemicals, along with sediment from agricultural fields, can be transported by local streams to the Mississippi River and eventually to the Gulf of Mexico.

From December 2010 through July 2011, the northern two-thirds of the United States experienced mostly wet conditions, while the southern United States experienced mostly dry conditions (Vining and others, 2013). Portions of the Ohio River Subbasin received nearly 20 inches of rain in April alone, which is about half of the annual average precipitation (Vining and others, 2013). The precipitation combined with melting of record snowfall in the Missouri River Subbasin resulted in extensive flooding of the Mississippi River Basin from April through July 2011, hereafter referred to as the "2011 flood" or simply "the flood" (Vining and others, 2013).

Because floods, by definition, affect lands not typically inundated by water, chemicals and sediment associated with the landscape can be carried by floodwater great distances from their source area. As a result, there is substantial deposition of sediment, sediment-associated constituents, and other chemicals on floodplains. In addition, soil saturation during periods of heavy precipitation leads to increased overland flow, limiting the processing of chemicals such as nutrients and pesticides in the soil profile. Therefore, the extensive flooding in the Mississippi River Basin from April through July 2011 likely resulted in large amounts of chemicals moving downstream to receiving surface-water bodies, such as the Gulf of Mexico.

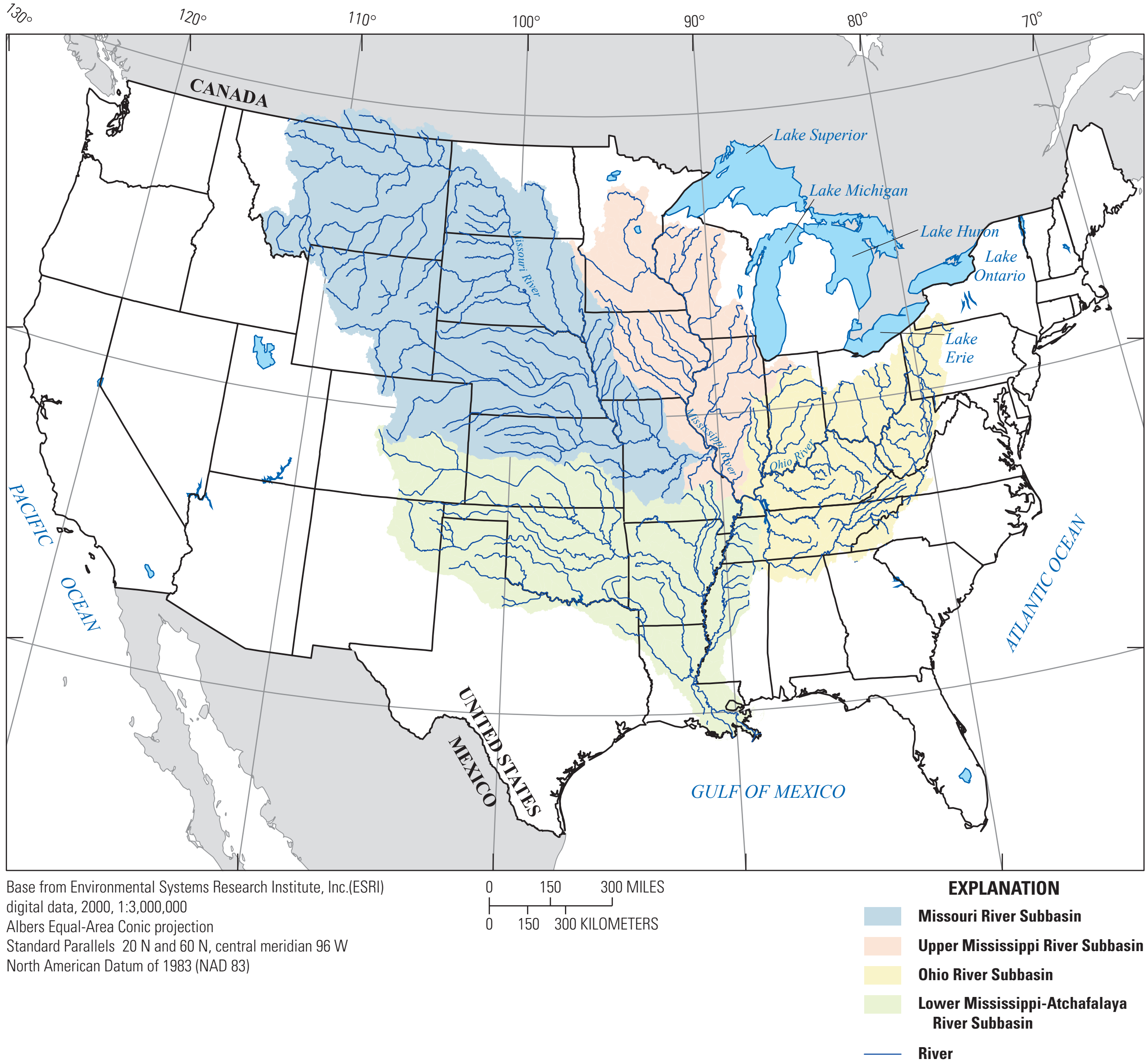

Figure 1. Extent of the Mississippi River Basin and Subbasins.

The U.S. Geological Survey (USGS) has been monitoring streamflow and water quality in the Mississippi River Basin for decades as part of several national programs. The National Stream Quality Accounting Network (NASQAN) was established in 1973 to provide long-term water-quality monitoring for river systems throughout the United States. Since October 2007, the focus of NASQAN has been to document concentrations and loads of selected constituents delivered by major rivers to the coastal waters of the United States and selected inland subbasins to determine the sources and relative yields of those constituents within these subbasins. Twenty NASQAN sites and one National Monitoring Network site (operated by the USGS in partnership with the National Water Quality Monitoring Council) compose the water-quality and streamflow network in the Mississippi River Basin. Since the 1990s, the USGS National Water Quality Assessment (NAWQA) Program has been collecting samples to identify water-quality conditions in the Nation's major streams and rivers. Forty surface-water sites are sampled as part of the NAWQA Program in the Mississippi River Basin. Long-term water-quality and streamflow monitoring sites, such as those operated by the USGS within the NASQAN and NAWQA Programs, allows for comparing and contrasting chemical and sediment fluxes and concentrations at times of normal and unexpected stream conditions.

In 2011, the USGS utilized the existing NASQAN/NAWQA network and stations funded through various cooperative agreements to assess the effects of the 2011 flood on water quality in the Mississippi River Basin. Additional sites were added above and below the major flood-control structures to supplement the network and to help determine whether opening of the structures had any effect on water quality in the lower Mississippi-Atchafalaya River Subbasin. The information collected during the 2011 flood will allow the USGS to decide whether data collection methods during the flood allowed for adequate characterization of the water-quality effects and will also help in future planning of data collection during high-flow events.

Purpose and Scope

The purposes of this report are to (1) document data collection methods that were used during the 2011 flood, including an analysis of the quality assurance/quality control data that were collected, (2) compare streamflow measured during the 2011 flood to that of past historic floods within the upper Mississippi River Subbasin, the Missouri River Subbasin, the Ohio River Subbasin, and the lower Mississippi-Atchafalaya River Subbasin, (3) document sites that were sampled during the flood, and (4) document all water-quality data collected during the flood. Water-quality data were collected and streamflow was measured by the USGS at 69 sites and 3 flood-control structures during the 2011 flood. Water-quality collection methods and the data published in this report provide a basis for subsequent investigations of the 2011 flood.

In this report, the site numbers specified in table 1 (shown later) are cited in subsequent discussions to aid the reader in locating site-specific information presented in the figures and tables.

Hydrologic Setting

The Mississippi River originates in Lake Itasca, Minnesota and extends southward over 2,300 miles through the central part of the United States to the Gulf of Mexico. The river and its tributaries drain part or all of 31 different states within a basin area covering approximately 1.24 million square miles (mi^2) (fig. 1); the size of the basin is only exceeded by those of the Amazon and Congo Rivers. The drainage area of the river has been subdivided into four parts in this report for ease of discussion: (1) the upper Mississippi River Subbasin, which is the part upstream from the confluence with the Ohio River, excluding the Missouri River Subbasin; (2) the Missouri River Subbasin; (3) the Ohio River Subbasin; and (4) the lower Mississippi-Atchafalaya River Subbasin, located downstream from the confluence of the upper Mississippi and Ohio Rivers and draining into the Gulf of Mexico (fig. 1). Half of the water discharged to the Gulf of Mexico is contributed by the Ohio River and its tributaries, which represent approximately one-sixth of the total area drained by the Mississippi River. In contrast, the Missouri River drains 43 percent of the Mississippi River Basin, but contributes only about 12 percent of the total streamflow to the Gulf of Mexico (Meade, 1995).

Upper Mississippi River Subbasin

The upper Mississippi River Subbasin covers approximately 190,000 mi^2 across parts of seven states in the upper Midwest (fig. 2). The river flows about 1,300 miles from its headwaters at Lake Itasca in northern Minnesota to its confluence with the Missouri River at St. Louis, Missouri. The upper Mississippi River is divided into two sections: the reach from the headwaters at Lake Itasca to Saint Anthony Falls in Minneapolis, Minnesota, and the navigable channel formed by a series of man-made lakes between Minneapolis and St. Louis, Missouri. Authorized by Congress and built mostly in the 1930s, these artificial lakes were created using a system of 29 locks and dams constructed to regulate water levels in the channel for commercial navigation. Major tributaries of the upper Mississippi River include the Wisconsin, Illinois, Iowa, and Missouri Rivers. Land use in the subbasin is predominantly (1) corn and soybean cropland and pasture, covering about 60 percent of the area; and (2) forest land, covering about 20 percent of the area (Homer and others, 2007).

Missouri River Subbasin

The largest watershed within the Mississippi River Basin is the Missouri River Subbasin, which encompasses parts of 10 states and two Canadian provinces (fig. 3). This subbasin drains approximately 529,000 mi^2 of the north-central United States. Land use in the basin is predominately agricultural, covering about 95 percent of the total area, with more than half of the area in pasture and range grassland devoted to grazing (U.S. Army Corps of Engineers, 2006).

Beginning in the Rocky Mountains near Three Forks, Montana, three streams form the headwaters of the Missouri River, which flows more than 2,500 miles east and south through the central prairies joining the Mississippi River north of St. Louis, Missouri. The Missouri River valley consists of highly erodible soils, and the river itself is well known for having a shifting channel bottom, high turbidity, and typically, two periods of very high flows each year. The first high-flow event typically occurs in the spring and is caused by snowmelt on the plains, the second occurs in June from snowmelt and summer rainstorms in the Rocky Mountains. Prior to human modification, sediment loads averaged about 250 million tons per year (ton/yr) at Hermann, Missouri (U.S. Army Corps of Engineers, 2006). As part of the Flood Control Act of 1944, modification projects along the Missouri River began in the 1940s and 1950s, effectively dividing the river into three parts, approximately equal in length. The upper part contains six large dams creating the following reservoirs: Fort Peck Lake, Lake Sakakawea, Lake Oahe, Lake Sharpe, Lake Francis Case, and Lewis and Clark Lake. The middle part consists of free-flowing reaches, and the lower part, below Sioux City, Iowa, is channelized (Stone, date unknown).

Table 1. U.S. Geological Survey stations sampled for water-quality during the 2011 Mississippi River flood.

[Site locations are shown in figures 2-6. USGS, U.S. Geological Survey]

Site number	USGS station name	USGS station number	Station comments	Water-quality data collected
1	Ohio River at Cannelton Dam at Cannelton, Indiana	03303280		Field parameters, suspended sediment, nutrients, pesticides
2	White River at Hazelton, Indiana	03374100	Flow data collected from the White River at Petersburg, Indiana (03374000)	Field parameters, suspended sediment, nutrients, pesticides
3	Wabash River at New Harmony, Indiana	03378500	Flow data collected from the Wabash River at Mt. Carmel, Illinois (03377500)	Field parameters, suspended sediment, nutrients, pesticides
4	Tennessee River at Highway 60 near Paducah, Kentucky	03609750	Flow data collected from the Tennessee River near Paducah, Kentucky (Tennessee Valley Authority site 03609500)	Field parameters, suspended sediment, nutrients, pesticides
5	Ohio River at Dam 53 near Grand Chain, Illinois	03612500	Flow data collected from the Ohio River at Metropolis, Illinois (03611500)	Field parameters, suspended sediment, nutrients, pesticides
6	Mississippi River at Clinton, Iowa	05420500		Field parameters, suspended sediment, nutrients, pesticides
7	Iowa River at Wapello, Iowa	05465500		Field parameters, suspended sediment, nutrients, pesticides
8	Des Moines River at Keosauqua, Iowa	05490500		Field parameters, suspended sediment, nutrients, pesticides
9	Illinois River at Valley City, Illinois	05586100		Field parameters, suspended sediment, nutrients, pesticides
10	Mississippi River below Grafton, Illinois	05587455	Flow data collected from the Mississippi River at Grafton, Illinois (05587450)	Field parameters, suspended sediment, nutrients, pesticides
11	Tongue River at State Line near Decker, Montana	06306300		Field parameters, suspended sediment, nutrients
12	Powder River at Moorhead, Montana	06324500		Field parameters, suspended sediment, nutrients
13	Little Powder River near Broadus, Montana	06325500		Field parameters, suspended sediment, nutrients
14	Powder River near Locate, Montana	06326500		Field parameters, suspended sediment, nutrients
15	Yellowstone River near Sidney, Montana	06329500		Field parameters, suspended sediment, nutrients, pesticides
16	Belle Fourche River below Moorcroft Wyoming	06426500		Field parameters, suspended sediment, nutrients
17	Missouri River at Sioux City, Iowa	06486000		Suspended sediment
18	Little Sioux River near Turin, Iowa	06607500		Field parameters, suspended sediment, nutrients, pesticides
19	Boyer River at Logan, Iowa	06609500		Field parameters, suspended sediment, nutrients, pesticides

Table 1. U.S. Geological Survey stations sampled for water-quality during the 2011 Mississippi River flood.—Continued

[Site locations are shown in figures 2-6. USGS, U.S. Geological Survey]

Site number	USGS station name	USGS station number	Station comments	Water-quality data collected
20	Missouri River at Omaha, Nebraska	06610000		Field parameters, suspended sediment, nutrients, pesticides
21	Cherry Creek at Denver, Colorado (urban Denver)	06713500		Field parameters, suspended sediment, nutrients, pesticides
22	South Platte River at Denver, Colorado (urban Denver)	06714000		Field parameters, nutrients
23	Big Thompson River at I-25 near Loveland, Colorado (urban influence)	06741530		Field parameters, suspended sediment, nutrients
24	Elkhorn River at Waterloo, Nebraska	06800500		Field parameters, suspended sediment, nutrients, pesticides
25	Salt Creek below Stevens Creek near Waverly, Nebraska (downstream of Lincoln, Nebraska)	06803525		Field parameters, suspended sediment, nutrients
26	Salt Creek near Ashland, Nebraska (downstream of Lincoln, Nebraska)	06805000		Field parameters, suspended sediment, nutrients
27	Platte River at Louisville, Nebraska	06805500		Field parameters, suspended sediment, nutrients, pesticides
28	Nishnabotna River above Hamburg, Iowa	06810000		Field parameters, suspended sediment, nutrients, pesticides
29	Missouri River at St. Joseph, Missouri	06818000		Field parameters, suspended sediment, nutrients
30	Kansas River at Desoto, Kansas	06892350		Field parameters, suspended sediment
31	Missouri River at Kansas City, Missouri	06893000		Field parameters, suspended sediment
32	Indian Creek at State Line Road Leawood, Kansas (urban Kansas City)	06893390		Field parameters, suspended sediment, nutrients, pesticides
33	Rock Creek at Kentucky Road in Independence, Missouri	06893620		Field parameters, suspended sediment, nutrients
34	Little Blue River at Lees Summit Road in Independence, Missouri	06893820		Field parameters, suspended sediment, nutrients
35	Adair Creek at Independence, Missouri	06893830		Field parameters, suspended sediment, nutrients
36	East Fork Little Blue River near Blue Springs, Missouri	06893890		Field parameters, suspended sediment, nutrients
37	Spring Branch Creek at Holke Road in Independence, Missouri	06893970		Field parameters, suspended sediment, nutrients

Table 1. U.S. Geological Survey stations sampled for water-quality during the 2011 Mississippi River flood.—Continued

[Site locations are shown in figures 2-6. USGS, U.S. Geological Survey]

Site number	USGS station name	USGS station number	Station comments	Water-quality data collected
38	Little Blue River near Lake City, Missouri	06894000		Field parameters, suspended sediment, nutrients
39	Missouri River at Sibley, Missouri	06894100		Field parameters, suspended sediment, nutrients
40	North Creek near Dunlap, Missouri	06899580		Field parameters, suspended sediment, nutrients
41	Medicine Creek near Laredo, Missouri	06900050		Field parameters, suspended sediment, nutrients
42	Little Medicine Creek near Harris, Missouri	06900100		Field parameters, suspended sediment, nutrients
43	Muddy Creek near Chula, Missouri	06900640		Field parameters, suspended sediment, nutrients
44	Locust Creek near Unionville, Missouri	06900900		Field parameters, suspended sediment, nutrients
45	Little East Locust Creek near Browning, Missouri	06901250		Field parameters, suspended sediment, nutrients
46	Locust Creek near Linneus, Missouri	06901500		Field parameters, suspended sediment, nutrients
47	Grand River near Sumner, Missouri	06902000		Field parameters, suspended sediment, nutrients
48	Hickory Branch near Mendon, Missouri	06902995		Field parameters, suspended sediment, nutrients
49	Mussel Fork near Mystic, Missouri	06905725		Field parameters, suspended sediment, nutrients
50	Lamine River near Pilot Grove, Missouri	06907300		Field parameters, suspended sediment, nutrients
51	Little Sac River near Walnut Grove, Missouri	06918600		Field parameters, suspended sediment, nutrients
52	Cedar Creek near Pleasant View, Missouri	06919500		Field parameters, suspended sediment, nutrients
53	Pomme de Terre River near Polk, Missouri	06921070		Field parameters, suspended sediment, nutrients
54	Big Creek near Blairstown, Missouri	06921720		Field parameters, suspended sediment, nutrients
55	Big Piney River at Devil's Elbow, Missouri	06930450		Field parameters, suspended sediment, nutrients

Table 1. U.S. Geological Survey stations sampled for water-quality during the 2011 Mississippi River flood.—Continued

[Site locations are shown in figures 2-6. USGS, U.S. Geological Survey]

Site number	USGS station name	USGS station number	Station comments	Water-quality data collected
56	Gasconade River above Jerome, Missouri	06930800		Field parameters, suspended sediment, nutrients
57	Missouri River at Hermann, Missouri	06934500		Field parameters, suspended sediment, nutrients, pesticides
58	Mississippi River at Thebes, Illinois	07022000		Field parameters, suspended sediment, nutrients, pesticides
59	New Madrid Floodway upper inflow breach at BirdsPoint	365659089073101		Field parameters, suspended sediment, nutrients, pesticides
60	New Madrid Floodway combined outflow	363618089251701		Field parameters, suspended sediment, nutrients, pesticides
61	Mississippi River at Tiptonville, Tennessee	362146089301901		Field parameters, suspended sediment, nutrients, pesticides
62	Mississippi River at Memphis, Tennessee	07032000		Field parameters, suspended sediment, nutrients, pesticides
63	Arkansas River at David D Terry Lock and Dam below Little Rock, Arkansas	07263620	Flow data collected from the Arkansas River at Murray Dam near Little Rock, Arkansas (07263450)	Field parameters, suspended sediment, nutrients, pesticides
64	Mississippi River above Vicksburg at mile 438, Mississippi	322023090544500	Flow data collected from the Mississippi River at Vicksburg (07289000)	Field parameters, suspended sediment, nutrients, pesticides
65	Yazoo River below Steele Bayou near Long Lake, Mississippi	07288955		Field parameters, suspended sediment, nutrients, pesticides
66	Mississippi River near St. Francisville, Louisiana	07373420	Flow data collected from the Mississippi River at Tarbert Landing, Mississippi (US Army Corps of Engineers site 01100)	Field parameters, suspended sediment, nutrients, pesticides
67	Atchafalaya River at Melville, Louisiana	07381495	Flow data collected from the Atchafalaya River at Simmesport, Louisiana (U.S. Army Corps of Engineers site 03045)	Field parameters, suspended sediment, nutrients, pesticides, oil and gas
68	Atchafalaya Floodway near Ramah, Louisiana north of I-10	302410091305201	Flow and daily suspended sediment data collected from the Morganza Spillway at Hwy 190 near Lottie, Louisiana (07381530)	Field parameters, suspended sediment, nutrients, pesticides
69	Mississippi River at Baton Rouge, Louisiana	07374000		Field parameters, suspended sediment, nutrients, pesticides
70	Lower Atchafalaya River at Morgan City, Louisiana	07381600		Field parameters, suspended sediment, nutrients, pesticides, oil and gas
71	Wax Lake Outlet at Calumet, Louisiana	07381590		Field parameters, suspended sediment, nutrients, pesticides
72	Bonnet Carré Spillway at U.S. Highway #61 near Norco, Louisiana	300115090245000		Field parameters, suspended sediment, nutrients, pesticides
73	Mississippi River at Belle Chasse, Louisiana	07374525		Field parameters, suspended sediment, nutrients, pesticides

Base from Environmental Systems Research Institute, Inc.(ESRI) digital data, 2000, 1:3,000,000
Albers Equal-Area Conic projection
Standard Parallels 20 N and 60 N, central meridian 96 W
North American Datum of 1983 (NAD 83)

0 50 100 MILES
0 50 100 KILOMETERS

EXPLANATION

Upper Mississippi River Subbasin

6 USGS water-quality sampling site and identifier shown in table 1

Figure 2. Upper Mississippi River Subbasin and sites sampled during the 2011 flood.

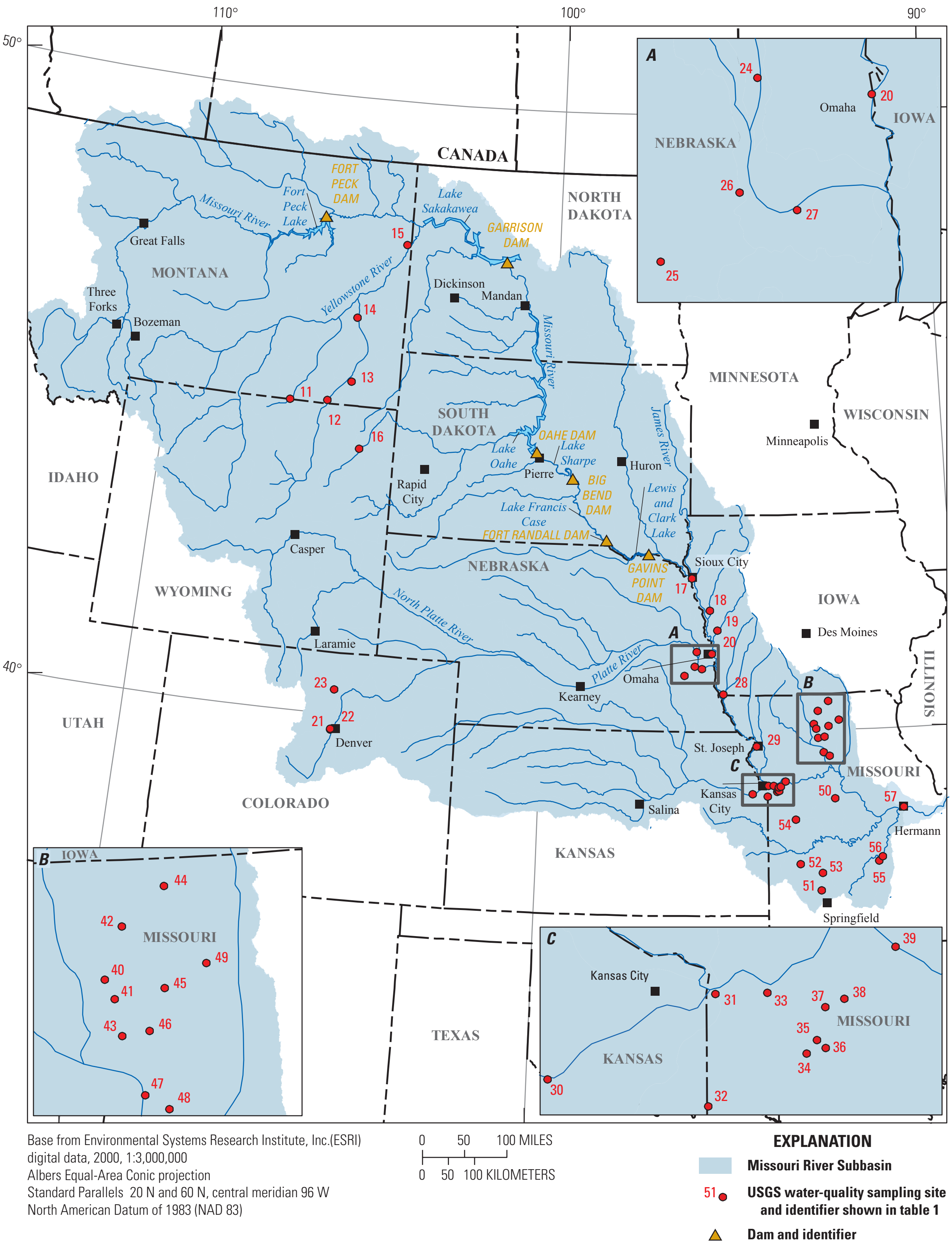

Figure 3. Missouri River Subbasin and sites sampled during the 2011 flood.

Ohio River Subbasin

The Ohio River is located in the Eastern United States and is approximately 981 miles long. The river is formed by the confluence of the Allegheny and Monongahela Rivers in Pittsburgh, Pennsylvania, and joins the Mississippi River near the city of Cairo, Illinois (fig. 4). The Ohio River Subbasin encompasses about 190,000 mi^2 across 15 states and is the largest tributary, by volume, of the Mississippi River. A series of 60 active navigation locks and dams have deepened the naturally shallow river for commercial navigation. Major tributaries include the Tennessee, Cumberland, Wabash, and Kanawha Rivers. Although almost 10 percent of the U.S. population lives within the basin, land use in the basin is predominately forest land, covering about 51 percent of the area and agriculture covering about 35 percent of the area (U.S. Army Corps of Engineers, 2009).

Lower Mississippi-Atchafalaya River Subbasin

The lower Mississippi-Atchafalaya River Subbasin drains all or part of 11 different states downstream from the confluence of the upper Mississippi and the Ohio Rivers (fig. 5). Parts of the lower Mississippi-Atchafalaya River Subbasin drain streams located in the Mississippi Alluvial Plain, which is relatively flat and contains rich, productive soils used extensively for agriculture. The lower Mississippi-Atchafalaya River Subbasin also receives inflow from streams located in rangeland, urban areas, and mountainous regions. Several tributaries, such as the White River, Arkansas River, Yazoo River, and Big Black River, contribute to streamflow in this part of the Mississippi River Basin; however, only 75 percent of that streamflow enters the northern Gulf of Mexico through the river's delta (Horowitz, 2010). The remaining streamflow is diverted at the Old River Control Structure downstream from Vicksburg, Mississippi. The diverted flow then merges with the Red River to form the Atchafalaya River about 25 miles upstream from Melville, Louisiana (Meade, 1995; Mossa, 1996). Sites sampled during the 2011 flood in the lower Mississippi-Atchafalaya River Subbasin are shown in figure 5.

Flood-Control Structures

Three major flood-control structures are located in the lower Mississippi River Basin: the Birds Point-New Madrid Floodway in Missouri, and the Morganza Floodway and the Bonnet Carré Spillway in Louisiana (fig. 6). The 2011 flood marked the first time in history that the three major flood-control structures of the Mississippi River and Tributaries Project were operated simultaneously (Anderson, 2011; Schneider, 2011). Prior to 2011, the Birds Point-New Madrid Floodway had been operated once during the 1937 flood, the Morganza Floodway had been operated once during the 1973 flood, and the Bonnet Carré Spillway had been operated nine times (Schneider, 2011). Initial preparation of the Birds Point-New Madrid Floodway is required when the stage at Cairo, Illinois (located at the confluence of the upper Mississippi and Ohio Rivers), is approximately 59 feet (U.S. Army Corps of Engineers, 2012a). On May 2, 2011, the Birds Point-New Madrid Floodway was operated, followed by the opening of the Bonnet Carré Spillway on May 9, 2011, to keep streamflow near New Orleans, Louisiana, at approximately 1.25 million cubic feet per second (ft^3/s) (Anderson, 2011). Approximately 210 mi^2 of agricultural lands were inundated by floodwater through the Birds Point-New Madrid Floodway through June 3, 2011 (fig. 6*A*). All gates on the Bonnet Carré Spillway were closed by June 20, 2011. The Morganza Floodway was opened on May 14, 2011, when streamflow in the Mississippi River reached approximately 1.5 million ft^3/s (Anderson, 2011), and remained open through July 7, 2011 (fig. 6*B*).

Methods

Streamflow Measurement

The acoustic Doppler current profiler method described by Olson and Norris (2007) was used by the USGS to measure instantaneous streamflow at the sampled stations, where streamflow is the volume of water moving down a stream or river per unit of time, measured in cubic feet per second. At 10 stations (site numbers 2 through 5, 10, 63, 64, and 66 through 68; figs. 4 and 5; table 1), instantaneous streamflow was measured at a separate location from where the water-quality sample was collected. The mean daily streamflow (Q) was calculated and reported by the USGS according to standard procedures (Rantz, 1982). The U.S. Army Corps of Engineers monitored daily streamflow at the Mississippi River at Tarbert Landing, Mississippi (associated with water-quality site number 66; fig. 5; table 1), total outflow at the Old River outflow channel near Knox Landing, Louisiana, and streamflow at the Atchafalaya River at Simmesport, Louisiana (associated with water-quality site number 67; fig. 5; table 1).

Sample Collection, Processing, and Analysis

Water-quality samples are typically collected 12 to 14 times per year at NASQAN and NAWQA sites. From April to July 2011, the frequency of sample collection was increased at some sites to monitor the effects of the 2011 flood. Periodic water-quality samples were collected while the Birds Point-New Madrid Floodway was in operation during the flood (fig. 6*A*). Samples were collected on May 5, 2011, at site numbers 59 and 60 in the floodway and downstream at site numbers 61 and 62 (figs. 5 and 6*A*). A sample was also collected at site number 62 on May 18, 2011. Streamflow was measured and sediment samples were collected from the Morganza Floodway at a location different from the

Base from Environmental Systems Research Institute, Inc.(ESRI) digital data, 2000, 1:3,000,000
Albers Equal-Area Conic projection
Standard Parallels 20 N and 60 N, central meridian 96 W
North American Datum of 1983 (NAD 83)

Figure 4. Ohio River Subbasin and sites sampled during the 2011 flood.

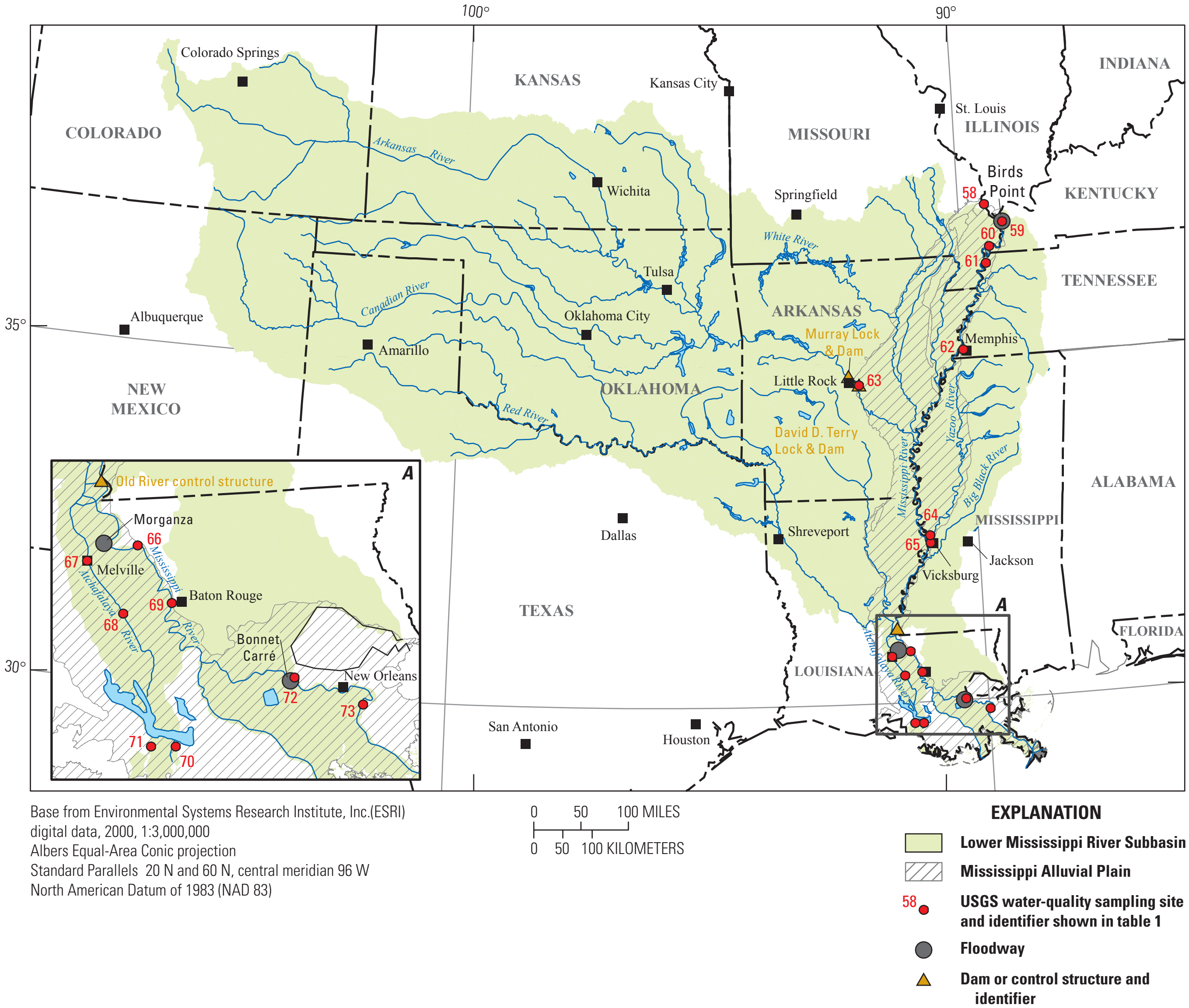

Figure 5. Lower Mississippi-Atchafalaya River Subbasin and sites sampled during the 2011 flood.

water-quality sampling station (site number 68; table 1). At this separate location, streamflow was measured daily from May 14 through June 27, and sediment samples were collected from May 18 through June 10 (fig. 6*B*). The Bonnet Carré Spillway was sampled seven times in May and June, and 28 sediment samples were collected at site number 72 during the same time period. Samples for oil and gasoline analysis were collected from the Atchafalaya River at site numbers 70 and 71 (fig. 5; table 1).

Sediment and water-quality samples were collected using isokinetic depth-integrated samplers according to protocols detailed in the USGS National Field Manual for the Collection of Water Quality Data (U.S. Geological Survey, variously dated). The equal-discharge increment sampling method was used to collect a streamflow-weighted sample, representing the entire flow passing through a cross section. The equal-width increment sampling method was used to collect samples at sites 66 through 73 (fig. 5; table 1). Suspended-sediment concentration samples were analyzed at either the USGS sedimentation laboratory in Baton Rouge, Louisiana, or the sedimentation laboratory in Iowa City, Iowa, according to the method described by Guy (1969). Particle-size was analyzed by the USGS sedimentation laboratory in Iowa City, Iowa.

All samples collected for analysis of major ions and nutrients were preserved according to standard USGS protocols and (along with samples analyzed for pesticides) were shipped overnight on ice for analysis at the USGS National Water-Quality Laboratory in Denver, Colorado. Major ions were measured using atomic absorption spectrometry, and nutrient concentrations were quantified using colorimetry (Fishman and Friedman, 1989). Pesticides analyzed at the laboratory were quantified using gas chromatography-mass spectrometry.

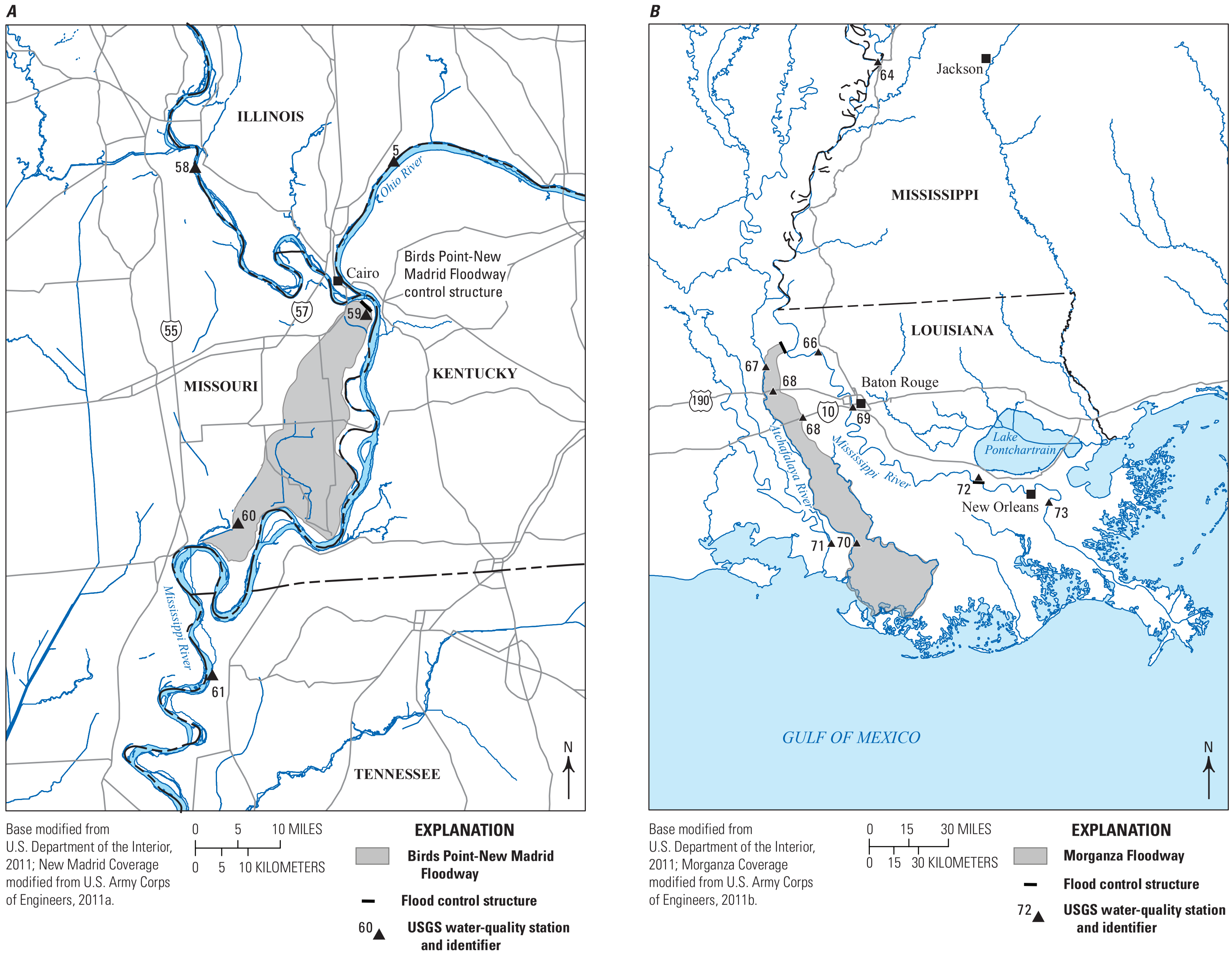

Figure 6. Location of water-quality samples collected in the *A*, Birds Point-New Madrid Floodway and *B*, the Morganza Floodway and the Bonnet Carré Spillway during the 2011 flood.

Samples collected for hydrocarbon analysis were chilled to 4°C and shipped overnight for analysis at TestAmerica Laboratories, Inc., in Arvada, Colorado. Gasoline-range organics were separated using a purge and trap method and then analyzed using a gas chromatograph with a flame ionization detector (GC-FID), as outlined by the U.S. Environmental Protection Agency (1986). Diesel- range organics were extracted using a separatory funnel liquid-liquid extraction method and analyzed using the GC-FID (U.S. Environmental Protection Agency, 1986). Hexane extractable compounds were separated using solid-phase extraction and analyzed using a gravimetric method (U.S. Environmental Protection Agency, 1999).

Quality-Control Data

Quality-control data were collected at selected sites from April through July 2011 and included field equipment blanks to measure contamination, replicate samples to estimate variability, and field-spike samples to measure recovery of analytes. Seventeen field equipment blanks were collected at 13 sites within the Mississippi River Basin during the flood period. There were no detections of analyzed pesticides in the field equipment blanks. Data from blanks and spikes are not shown in appendix 1.

Variability in the sample dataset was quantified by collecting 5 to 12 replicates at 10 sites within the Mississippi River Basin during the flood period (appendix 1). The relative percent difference for nutrients ranged from 0.00 to 58 percent, with a median of 3.7 percent. The relative percent difference is computed as

$$|A-B|/[[A+B]/2\times100 \quad (1)$$

where A and B represent the environmental sample concentration and the replicate sample concentration, respectively.

Large percent differences generally were observed between pairs when the nutrient of interest was not filtered or was associated with suspended sediment. Variability in the results between the pairs can be introduced during sample collection, as well as during the processing of the samples in the churn splitter (U.S. Geological Survey, variously dated). In one pair of samples for nutrient analysis, a compound was detected in the environmental sample but was not detected in the replicate sample. The relative percent difference for pesticides ranged from 0.00 to 13.3 percent, with a median of 3.02 percent. In one instance, a pesticide was detected in one sample but not the other. The relative percent difference for major ions ranged from 0.0 to 7.8 percent with a median of 1.42 percent. The relative percent difference for total dissolved solids and suspended sediment ranged from 1.8 to 70.3 percent with a median of 5.61 percent.

Water-Quality Data Collected during the 2011 Flood

Data collected at the 69 water-quality stations and the 3 flood-control structures is summarized in table 1, and the locations of the water-quality stations are shown in figs. 2 through 6. Results of the water-quality analysis samples are provided in appendixes 1–8.

Streamflow Characterization

Comparison of Mean Daily and Instantaneous Streamflow during the 2011 Flood with Historical Streamflow

Maximum mean daily streamflows measured during the 2011 flood in the upper Mississippi River Subbasin were 228,000 ft^3/s in the Mississippi River at Clinton, Iowa (site number 6); 34,100 ft^3/s in the Iowa River at Wapello, Iowa (site number 7); 65,500 ft^3/s in the Des Moines River at Keosaqua, Iowa (site number 8); 75,400 ft^3/s in the Illinois River at Valley City, Illinois (site number 9); 361,000 ft^3/s in the Mississippi River at Grafton, Illinois (site number 10); and 853,000 ft^3/s in the Mississippi River at Thebes, Illinois (site number 58; table 2). Median instantaneous streamflows at site numbers 6, 10, and 58 during the flood period were 2 to 3 times higher than historical median streamflows (fig. 7*A*). The lowest instantaneous streamflows measured in the upper Mississippi River Subbasin during the 2011 flood were at site numbers 7, 8, and 9; yet, the median instantaneous streamflow at each of these sites during the 2011 flood was still higher than the historical median instantaneous streamflow.

Maximum mean daily streamflows measured during the 2011 flood in the Missouri River Subbasin was 37,000 ft^3/s in the Yellowstone River near Sidney, Montana (site number 15); 46,500 ft^3/s in the Missouri River at Omaha, Nebraska (site number 20); 15,500 ft^3/s in the Platte River at Louisville, Nebraska (site number 27); 16,300 ft^3/s in the Kansas River at Desoto, Kansas (site number 30); 88,400 ft^3/s in the Missouri River at Kansas City, Missouri (site number 31); and 274,000 ft^3/s in the Missouri River at Hermann, Missouri (site number 57; table 2). The median instantaneous streamflow measured at the time of water-quality sampling during the flood period was higher than median instantaneous streamflows measured at times of water-quality sampling historically at site numbers 20, 27, and 57 (fig. 7*B*). Median instantaneous streamflow at site numbers 20 and 57 during the flood was about 2.5 times as high as the historical median instantaneous streamflow.

Table 2. U.S. Geological Survey streamflow station names, station numbers, drainage basin areas, and minimum, maximum, and median streamflow data for April through July 2011 at selected sites in the upper Mississippi River Subbasin, the Missouri River Subbasin, the Ohio River Subbasin, and the lower Mississippi-Atchafalaya River Subbasin.

[The complete list of water-quality stations are shown in table 1 and site locations are shown in figures 2–6. USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; mi^2, square mile; --, data not available]

Water-quality station number	USGS station name	USGS station number	Basin area (mi^2)	Mean daily streamflow, ft^3/s (April through July 2011)		
				Minimum	Maximum	Median
	Upper Mississippi River Subbasin					
6	Mississippi River at Clinton, Iowa	05420500	85,600	73,600	228,000	112,500
7	Iowa River at Wapello, Iowa	05465500	12,500	7,540	34,100	16,750
8	Des Moines River at Keosaqua, Iowa	05490500	14,083	6,900	65,500	24,000
9	Illinois River at Valley City, Illinois	05586100	26,743	11,300	75,400	52,300
10	Mississippi River at Grafton, Illinois	05587450	171,300	141,000	361,000	285,000
58	Mississippi River at Thebes, Illinois	07022000	713,200	383,000	853,000	544,000
	Missouri River Subbasin					
15	Yellowstone River near Sidney, Montana	06329500	[1]69,083	8,380	37,000	17,770
20	Missouri River at Omaha, Nebraska	06610000	322,800	37,200	46,500	39,750
27	Platte River at Louisville, Nebraska	06805500	[2]85,370	4,680	15,500	9,555
30	Kansas River at Desoto, Kansas	06892350	[3]59,756	7,990	16,300	11,100
31	Missouri River at Kansas City, Missouri	06893000	[4]484,100	64,300	88,400	72,950
57	Missouri River at Hermann, Missouri	06934500	[4]522,500	96,300	274,000	210,000
	Ohio River Subbasin					
1	Ohio River at Cannelton Dam at Cannelton, Indiana	03303280	97,000	20,900	647,000	157,000
3	Wabash River at Mount Carmel, Illinois	03377500	28,635	11,100	268,000	59,400
4	Tennessee River near Paducah, Kentucky[5]	03609500	40,200	20,700	199,000	54,900
5	Ohio River at Metropolis, Illinois	03611500	203,000	84,000	1,260,000	391,500
	Lower Mississippi-Atchafalaya River Subbasin					
64	Mississippi River at Vicksburg, Mississippi	07289000	1,144,500	603,000	2,310,000	1,150,000
65	Yazoo River below Steele Bayou near Long Lake, Mississippi	07288955	13,355	-49,400	52,900	15,350
66	Mississippi River at Tarbert Landing, Mississippi[6]	01100	1,124,900	443,000	1,619,000	888,500
67	Atchafalaya River at Simmesport, Louisiana[6]	03045	--	189,000	692,000	383,000
69	Mississippi River at Baton Rouge, Louisiana	07374000	1,125,800	497,700	1,429,000	920,400
70	Lower Atchafalaya River at Morgan City, Louisiana	07381600	--	114,000	487,000	224,000
71	Wax Lake Outlet at Calumet, Louisiana	07381590	--	96,000	313,000	177,000
73	Mississippi River at Belle Chasse, Louisiana	07374525	1,130,000	496,000	1,230,000	862,000

[1]691 mi^2 is probably noncontributing.

[2]14,370 mi^2 is probably noncontributing.

[3]A large area is noncontributing.

[4]The 3,959 mi^2 in the Great Divide Basin are not included.

[5]Streamflow data collected by the Tennessee Valley Authority.

[6]Streamflow data collected by the U.S. Army Corps of Engineers.

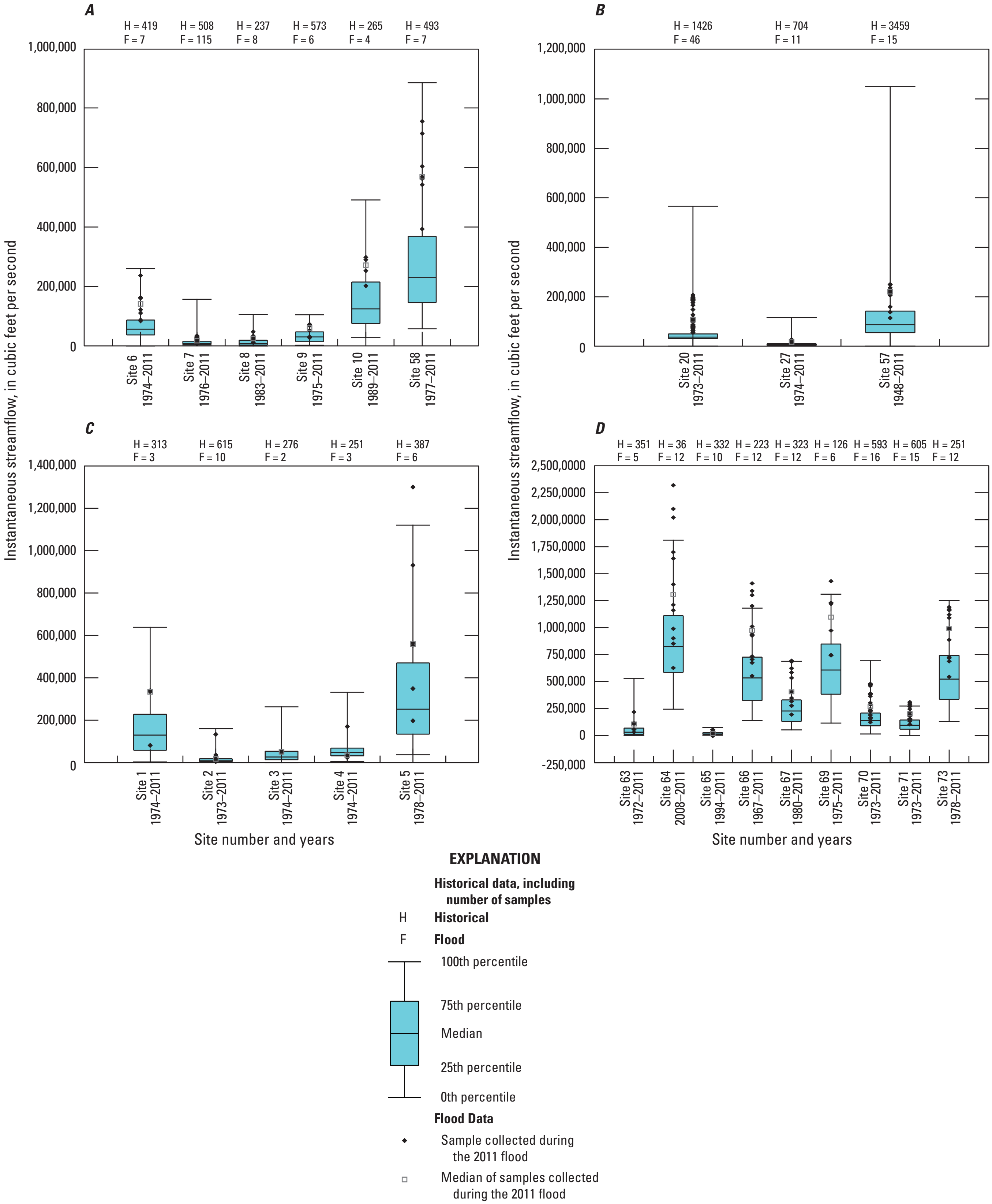

Figure 7. Box plots comparing historical instantaneous streamflow with instantaneous streamflow measured during the 2011 flood at selected sites in *A*, the upper Mississippi River Subbasin, *B*, the Missouri River Subbasin, *C*, the Ohio River Subbasin, and *D*, the lower Mississippi-Atchafalaya River Subbasin. [Hist., historical; Fld., flood]. The date ranges shown indicate the period of record for instantaneous streamflow data.

Maximum mean daily streamflows measured during the 2011 flood in the Ohio River Subbasin were 647,000 ft^3/s in the Ohio River at Cannelton Dam (site number 1); 268,000 ft^3/s in the Wabash River (site number 3); 199,000 ft^3/s in the Tennessee River (site number 4); and 1.26 million ft^3/s in the Ohio River at Metropolis (site number 5; table 2). In general, instantaneous streamflows measured at the time of water-quality sampling during the flood were within the range of instantaneous streamflows measured historically at site numbers 1 to 5 located within the subbasin (fig. 7*C*). Median instantaneous streamflows during the flood period were higher than historical observations at site numbers 1, 3, and 5. At site number 5, the median instantaneous streamflow during the flood period was more than twice the historical median streamflow, and the highest instantaneous streamflow measured at this site for the period of record (1.3 million ft^3/s) occurred during the 2011 flood. Instantaneous median streamflow at site number 2 during the flood was approximately the same as the historical median; whereas at site number 4, the median instantaneous streamflow during the flood was lower than the historical median. The lower streamflow at site number 4 was most likely a consequence of upstream dams being used in the basin to dampen the effects of floodwaters that would have increased streamflow and stage at Cairo, Illinois (Camillo, 2012), the city located at the confluence of the upper Mississippi and Ohio Rivers.

Maximum mean daily streamflows measured during the 2011 flood in the lower Mississippi-Atchafalaya River Subbasin were 2,310,000 ft^3/s for the Mississippi River at Vicksburg, Mississippi (site number 64); 1,619,000 ft^3/s for the Mississippi River at Tarbert Landing, Mississippi (site number 66); 1,429,000 ft^3/s for the Mississippi River at Baton Rouge, Louisiana (site number 69); 1,230,000 ft^3/s for the Mississippi River at Belle Chasse, Louisiana (site number 73); 692,000 ft^3/s for the Atchafalaya River at Simmesport, Louisiana (site number 67); 313,000 ft^3/s at Wax Lake Outlet at Calumet, Louisiana (site number 71); and 487,000 ft^3/s for the Lower Atchafalaya River at Morgan City, Louisiana (site number 70; table 2). Median instantaneous streamflow during the flood period was higher than the historical median at all stations in the lower Mississippi-Atchafalaya River Subbasin except for streamflow at site number 65 (fig. 7*D*). This site was in backwater during the month of May 2011, which resulted in negative flow during that period. During the flood period, median instantaneous streamflows at site numbers 64, 69, and 73 on the main stem of the lower Mississippi River were approximately two times higher than the historical medians. Median instantaneous streamflows in the Atchafalaya River Basin at site numbers 67, 70, and 71 were about two times higher during the flood compared to historical observations. In the Arkansas River (site number 63), the median instantaneous streamflows were almost 4 times higher than the historical median values. Water-quality samples obtained during the flood period corresponded to well-above-average streamflow at the majority of the stations throughout the Mississippi River Basin.

Flood Period Hydrographs

Upper Mississippi River Subbasin

Increases in streamflow in the Upper Mississippi River Subbasin were influenced by record rainfall and snowmelt (Vining and others, 2013). The upper and lower portions of the subbasin experienced flow increases at differing times because of the timing of snowmelt and rainfall, which resulted in a bimodal hydrograph at site numbers 10, 57, and 58 in the lowermost subbasin (fig. 8). In March 2011, the early flooding in Minnesota (upper Mississippi River Subbasin) was caused by rapid snowmelt and spring rains (Vining and others, 2013). This was followed by above-average precipitation over the entire subbasin from May through July (Vining and others, 2013). In the Missouri River Subbasin, melting of record snowpack in May combined with rainfall throughout the subbasin from May through July resulted in exceptionally large streamflow (Vining and others, 2013). Maximum streamflow in the Mississippi River at Clinton, Iowa (228,000 ft^3/s; site number 6), occurred on April 21, 2011, and then declined throughout the remainder of the flood period. In contrast, streamflow in the Iowa River at Wapello, Iowa (site number 7), reached a maximum on June 16, 2011. The profiles of the hydrographs for site numbers 10, 57, and 58 are similar, indicating flood peaks both in the spring and mid-summer. In this case, the spring peak was caused by rainfall, with relatively minor contribution from Minnesota snowmelt, and the mid-summer peak was caused by relatively equal contributions of snowmelt and rainfall. A streamflow maximum of 274,000 ft^3/s occurred at site number 57 on May 28, 2011, with a secondary peak of 261,000 ft^3/s occurring on July 2. Two streamflow peaks, both measuring 361,000 ft^3/s, occurred at site number 10 on April 30, 2011, and June 19, 2011. A streamflow peak of 853,000 ft^3/s occurred at site number 58 on May 2, 2011, with a secondary peak of 621,000 ft^3/s occurring on July 5.

Missouri River Subbasin

Exceptional snowpack in the upper part of the Missouri River Subbasin, along with heavy rainfall throughout most of the area from May through July 2011 resulted in the release of record amounts of water from 5 of the 6 major dams along the Missouri River in the month of May, and record monthly releases from all 6 dams in June and July 2011 to prevent overflow and possible failure (U.S. Army Corps of Engineers, 2012b). The U.S. Army Corps of Engineers attempted to regulate the release of water over approximately 850 miles of the river from the Garrison Dam in North Dakota to the confluence with the Mississippi River at St. Louis, Missouri. The shape of the hydrograph for the Yellowstone River near Sidney, Montana (site number 15), one of the major river basins draining into the upper Missouri River, shows a substantial peak in late May 2011, caused by record rainfall in the upper part of the Missouri Subbasin (fig. 9) (Vining

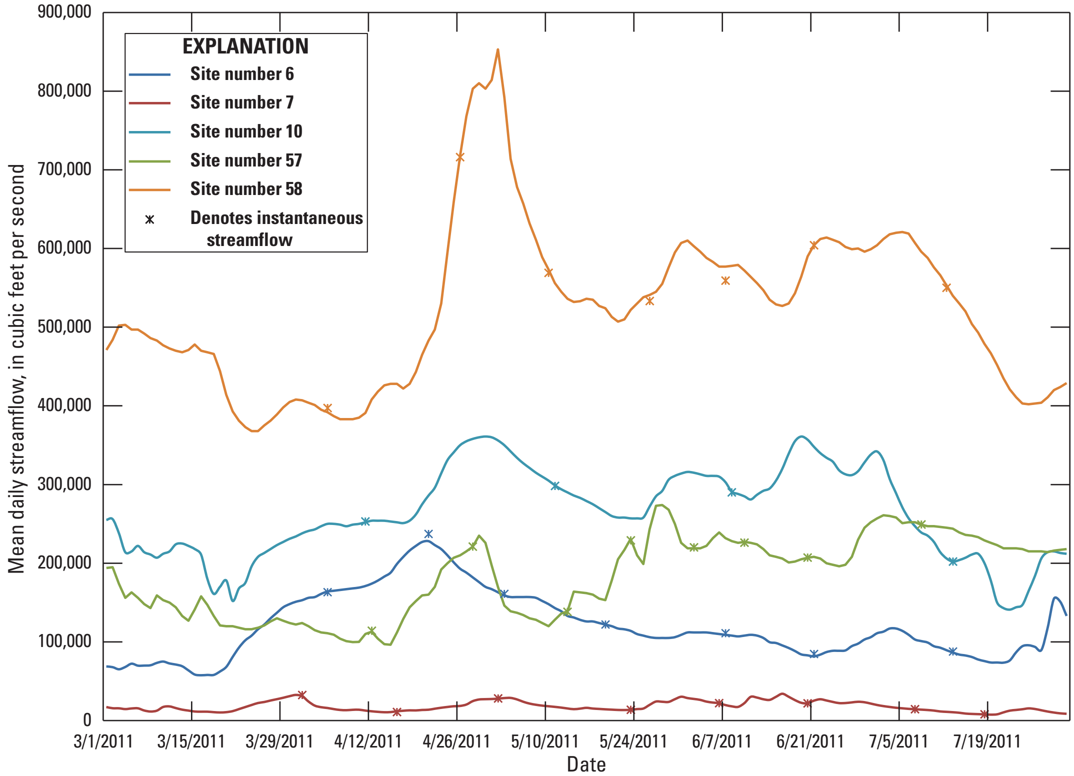

Figure 8. Mean daily streamflow in the upper Mississippi River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection.

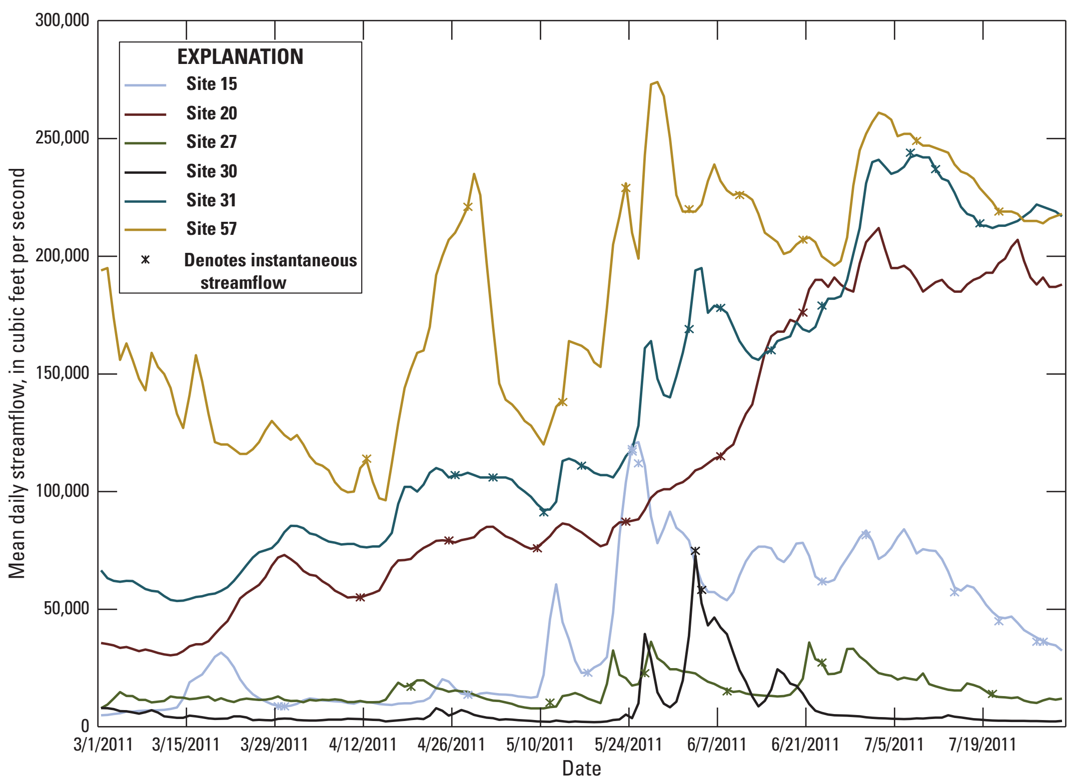

Figure 9. Mean daily streamflow in the Missouri River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection.

and others, 2013). Increasing flows and (or) peaks also begin around the same time period for the following gaging stations: Missouri River at Omaha, Nebraska (site number 20); Missouri River at Kansas City, Kansas (site number 31); and Missouri River at Hermann, Missouri (site number 57). Streamflows remained high at these three sites from June through July 2011 as the U.S. Army Corps of Engineers began releasing water from the six major dams along the upper Missouri River. Of the three sites just mentioned, however, only site number 20 had a record crest (the second highest ever recorded at that site), which was recorded on July 2, 2011, measured 36.29 feet, and had an associated discharge of 212,000 ft^3/s.

Ohio River Subbasin

Streamflow in the Ohio River Subbasin began to increase in March because of precipitation in the subbasin (fig. 10). Further rainfall throughout April increased streamflow in the Ohio River at Metropolis, Illinois (site number 5), to over 1.2 million ft^3/s during the first week of May; site number 5 is the last upstream streamflow monitoring in the Ohio River Subbasin before the confluence of the upper Mississippi and Ohio Rivers. The profiles of the hydrographs at Cannelton Dam (site number 1) and Metropolis (site number 5) were similar; however, peak streamflow occurred a week earlier at site number 1 than at site number 5. The increases and decreases in streamflow at the Tennessee River near Paducah, Kentucky (site number 4) were dependent upon the release of water from dams within the Cumberland River Basin, which is upstream of the Tennessee River. As river stage at Cairo, Illinois, began to increase, additional water was impounded by the dams to try to prevent the stage from exceeding a maximum of 61 feet (Camillo, 2012). Around April 28, 2011, flow from the dams was reduced, and the hydrograph for site number 4 shows this sharp decline in streamflow (fig. 10). As storage capacity in the dams decreased, the water was slowly released to maintain storage; however, by May 1, 2011, water was being released from the dams at a rate 2.5 times greater than that of the previous day (Camillo, 2012). On May 2, 2012, the Birds Point-New Madrid Floodway was activated, which allowed for the release of the remaining impounded water from the dams. Streamflow at site number 4 increased steadily thereafter until reaching a peak of about 184,000 ft^3/s on May 4, 2011.

Streamflow contributed by record rainfall in the Ohio River Subbasin was the primary contributor to flow in the lower Mississippi-Atchafalaya River Subbasin during the months of March, April, and May (fig. 11). Melting of record snowpack during late May in the Missouri River Subbasin and above normal precipitation from May through July in the upper Mississippi River Basin contributed to the majority of streamflow in the lower Mississippi-Atchafalaya River

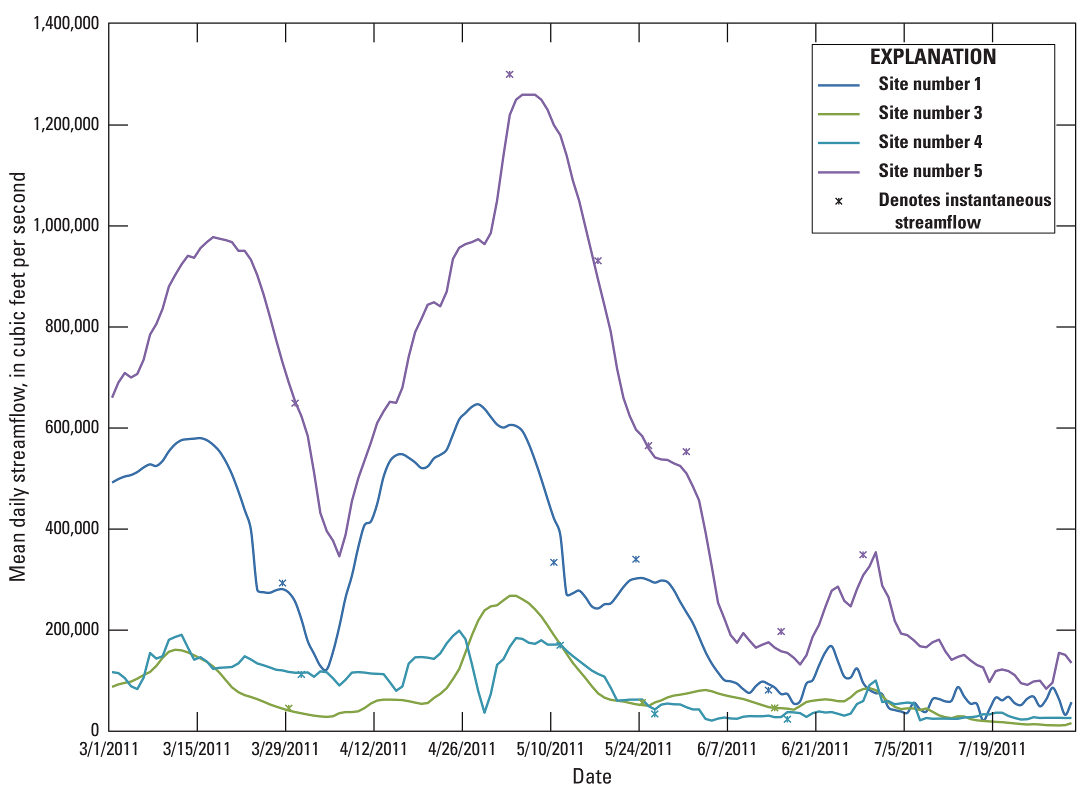

Figure 10. Mean daily streamflow in the Ohio River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection.

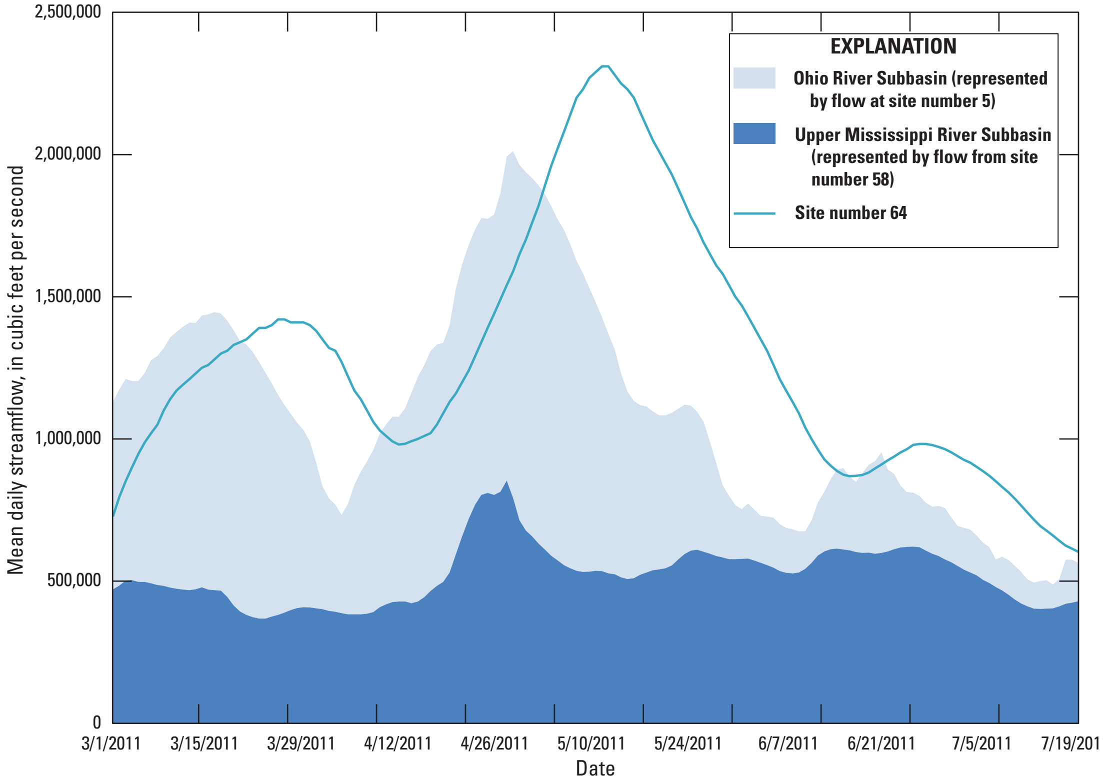

Figure 11 Contribution of streamflow to the lower Mississippi-Atchafalaya River Subbasin from the upper Mississippi River and Ohio River Subbasins. The upper Mississippi River Subbasin flow contribution includes flow from the Missouri River Subbasin. Cumulative streamflow, represented by the two shaded areas, is the combined streamflow from the upper Mississippi and Ohio Rivers.

Subbasin during June and July. Average streamflow leaving the Ohio River Subbasin in April and May was 694,100 and 902,000 ft^3/s, respectively, equaling 58 percent of the total streamflow entering the lower Mississippi-Atchafalaya River Subbasin during those months. The average streamflow contributed to the lower Mississippi-Atchafalaya River Subbasin from the upper Mississippi River Basin during June and July was 580,000 and 507,000 ft^3/s, respectively. These contributions were about 71 percent of the total streamflow in June and 78 percent of the total streamflow in July. Land use in the Ohio River Subbasin is primarily urban and forested land, whereas the Missouri River and upper Mississippi River Basin are primarily agricultural land with some rangeland. The timing and contribution of the streamflow from the two different source areas are important in determining which chemicals and other potential contaminants enter the lower Mississippi-Atchafalaya River Subbasin through overland runoff or receding water from inundated lands.

Between the confluence of the upper Mississippi and Ohio Rivers and the streamgaging station at the Mississippi River at Vicksburg, Mississippi (site number 64), flow was diverted through the Birds Point-New Madrid Floodway from May 2 through June 3, 2011 (fig. 6*A*). The average streamflow during the period that the floodway was open was approximately 170,000 ft^3/s. The highest streamflow measured during the flood period in the lower Mississippi-Atchafalaya River Subbasin was at site number 64, where 2.31 million ft^3/s was measured on May 18, 2011 (fig. 12). Between Vicksburg and Tarbert Landing, Mississippi, the Mississippi River bifurcates, and approximately 27 percent of the streamflow measured during the flood period was diverted into the Atchafalaya River Basin through the Old River Control Structure (Welch and others, 2012). The streamflow diverted through the structure from April through July 2011 averaged about 370,000 ft^3/s. The maximum streamflow during the flood period measured at Tarbert Landing (site number 66) was 1,619,000 ft^3/s on May 21, 2011 (fig. 12). Maximum streamflow at Baton Rouge (site number 69) was 1,429,000 ft^3/s, measured on May 18, 2011. Between site numbers 66 and 69, an average of 66,450 ft^3/s flowed through the Morganza Floodway from May 14 to July 7, 2011. Downstream of Baton Rouge, the Bonnet Carré Spillway was activated on May 9, 2011. This flood-control structure diverted an average of 208,000 ft^3/s of streamflow into Lake Ponchartrain above New Orleans, Louisiana, from May 9 through June 20, 2011. Streamflow at Belle Chasse (site number 73), Louisiana, the lowermost streamgage on the main stem of the Mississippi River, is tidally influenced, which is evident in the daily fluctuation of streamflow shown in fig. 12. Maximum streamflow measured during the flood period at site number 73 was 1.23 million ft^3/s on May 14 and 15, 2011.

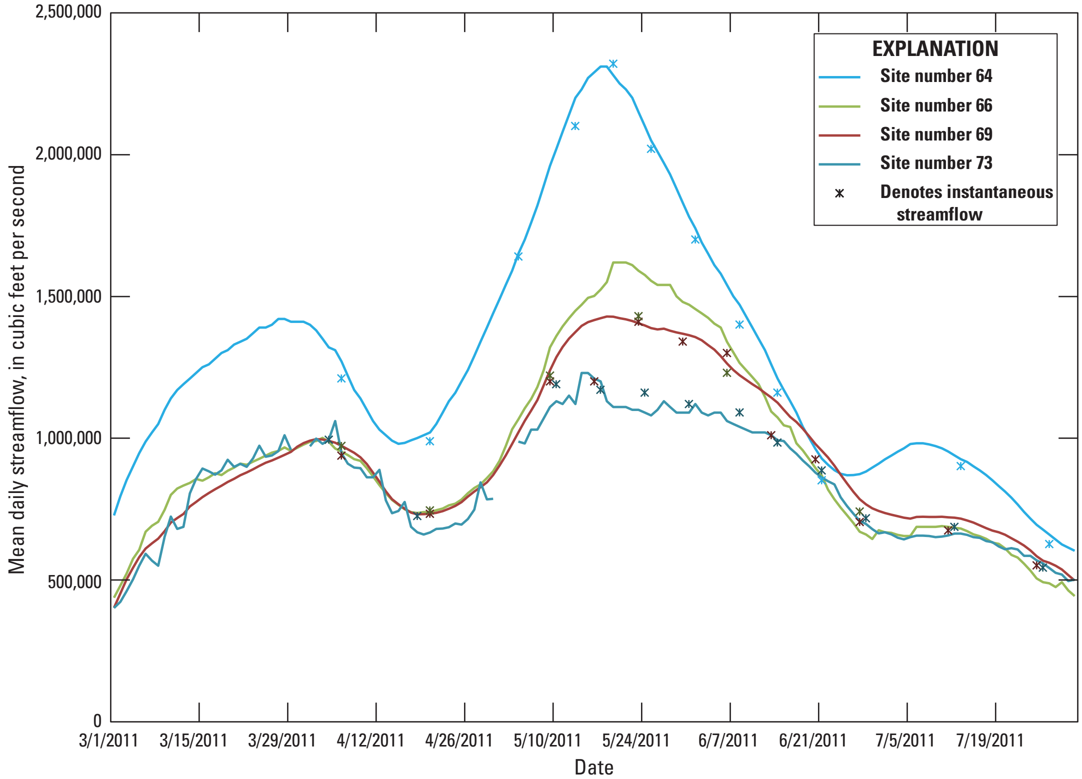

Figure 12. Mean daily streamflow at sites on the main stem in the lower Mississippi-Atchafalaya River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection.

The diverted flow through the Old River Control Structure drains into the Atchafalaya River Basin. The maximum streamflow measured during the flood period at the Old River outflow near Knox Landing, Louisiana, was 671,000 ft^3/s on May 14, 2011. Downstream from the Old River Control Structure, the Red River merges with the Atchafalaya River above the gage at Simmesport, Louisiana (site number 67). The maximum streamflow measured along the Red River at Alexandria, Louisiana, was 65,000 ft^3/s on May 11, 2011. The highest streamflow measured at any site in the Atchafalaya River Basin was 692,000 ft^3/s at site number 67 on May 24, 2011 (fig. 13). Below site number 67, outflow from the Morganza Floodway entered the Atchafalaya River at an average rate of about 66,450 ft^3/s for the period that the floodway was in operation, as previously stated. The Atchafalaya River bifurcates below the outlet of the Morganza Floodway, and water enters the Gulf of Mexico downstream of Morgan City (site number 70) and through the Wax Lake Outlet (site number 71). The maximum streamflows at these two sites, respectively, were 487,000 ft^3/s on May 30, 2011 and 313,000 ft^3/s on May 28, 2011 (fig. 13). Approximately 55 million ft^3 of water entered the Gulf of Mexico through the Atchafalaya River Basin, which is almost half the volume of water that entered the Gulf of Mexico through the main stem past the Bird's Foot Delta (102 million ft^3).

Comparison of Peak Stage and Streamflow of the 2011 Flood to Those of Historic Floods

Missouri River Subbasin

There have been numerous historical floods in the Missouri River Subbasin, with the first detailed account of flooding in 1881. A spring flood caused by rapid snowmelt in April 1943 initiated the Flood Control Act of 1944, also known as the Pick-Sloan Missouri Basin Program. This plan included the construction of numerous dams and reservoirs to provide flow regulation for flood control and navigation. Heavy snowfall in Montana, North Dakota, and South Dakota in the winter of 1951 followed by unseasonably warm weather the following spring led to the flood-of-record at site numbers 17 and 20 in April 1952, with record crests of 44.28 and 40.20 feet, respectively (table 3; U.S. Geological Survey, 2012a). In 1993, record amounts of rain throughout the basin resulted in major flooding from April through October. Record crests were recorded at site number 29 (32.07 feet), site number 31 (48.87 feet), and site number 57 (36.97 feet) (table 3). As previously

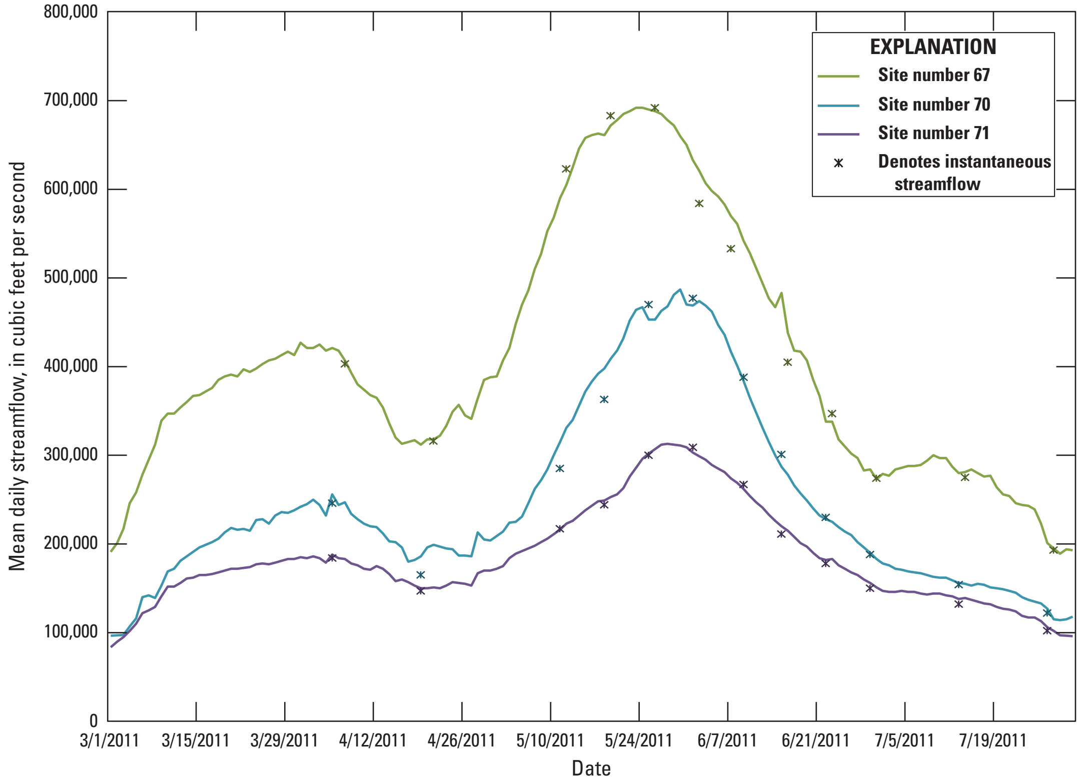

Figure 13. Mean daily streamflow at sites on the Atchafalaya River in the lower Mississippi-Atchafalaya River Subbasin from March through July 2011 and the instantaneous streamflow at the time of water-quality data collection.

described, flooding occurred in the summer of 2011 as the result of several factors: heavy snow pack, excessive rainfall in May, and record water releases from reservoirs in the upper Missouri River Subbasin. During June and July 2011, the Missouri River was above flood stage at some point in time within every state it crosses (U.S. Geological Survey, 2011); however, the volume of water in the river was less than that during the 1952 flood. During the 1952 flood, maximum discharge at site number 20 occurred on April 18, and was 396,000 ft^3/s, compared to 217,000 ft^3/s on July 2, 2011 (fig. 7*B*) (U.S. Geological Survey, 2012a). On April 22, 1952, streamflow at site number 29 was 397,000 ft^3/s, compared to 230,000 ft^3/s on July 28, 2011 (table 3; U.S. Geological Survey, 2012b).

Ohio River Subbasin and the Lower Mississippi-Atchafalaya River Subbasin

The Great Flood of 1927 was the most devastating flood in U.S. history and resulted in the Mississippi River and Tributaries Project, which was authorized by the Flood Control Act of 1928. The project called for the creation of a levee system to prevent overflow on developed alluvial lands, floodways to divert excess streamflow past critical reaches, channel improvements and stabilization, and tributary basin improvement (Mississippi River Commission, 2008). The system was tested 84 years later during the 2011 flood, when the stage at Vicksburg (site number 64) reached a height exceeded only by what the stage would have been in 1927 if the levees had held (fig. 14).

Because of its size, flooding in parts of the lower Mississippi-Atchafalaya River Subbasin may result in little or no change in streamflow conditions in downstream reaches of the river. To put the 2011 flood in perspective, peak streamflow at selected sites (site number 5, 7, 58, 64, and 66) in the upper Mississippi River Subbasin, the Ohio River Subbasin, and the lower Mississippi-Atchafalaya River Subbasin (figs. 2, 4, and 5) were compared to peak streamflow at those same stations during the floods of 1973, 1993, and 2008 (table 3). The effects of the 1993 and 2008 floods were largely realized in the upper Mississippi River Subbasin, whereas the 1973 flood had a basin-wide influence. All seemed to result from wet antecedent conditions during the months prior to peak streamflow, which left the ground saturated and resulted in large runoff events (Chin and others, 1975; Parrett and others, 1993; National Climate Data Center, 2008).

Prior to 2011, peak streamflow at site number 5 was 989,000 ft^3/s, during the 1973 flood on March 26, 1973 (table 3). On May 6, 2011, peak streamflow at the site was 1.28 million ft^3/s, a 29-percent increase over the peak streamflow measured during the 1973 flood. In contrast, peak streamflow at site numbers 7 and 58 occurred prior to

Table 3. Maximum stages and streamflows for 2011 and selected largest-flood years at select U.S. Geological Survey streamflow stations in the Mississippi River Basin.

[The complete list of water-quality station numbers are shown in table 1 and site locations are shown in figures 2–6. USGS, U.S. Geological Survey; mi², square mile; ft, foot; ft³/s, cubic foot per second; –, data not available]

Water-quality station number	USGS streamgage number and name	Period of peak flow record (water years)	Drainage area (mi²)	Date of peak measurement	Peak stage (ft)	Peak streamflow (ft³/s)
5	03611500 Ohio River at Metropolis, Illinois	1928-2011	203,000	3/26/1973	–	989,000
				4/2/1993	–	823,000
				4/11/2008	–	988,000
				5/6/2011	–	1,280,000
7	05465500 Iowa River at Wapello, Iowa	1914-2011	12,500	7/7/1993	29.53	–
				6/14/2008	32.15	188,000
				6/16/2011	–	34,100
17	06486000 Missouri River at Sioux City, Iowa	1897-2011	314,600	4/10/1943	38.72	–
				4/14/1952	44.28	–
				7/15/1993	27.33	–
				7/21/2011	35.25	–
20	06610000 Missouri River at Omaha, Nebraska	1928-2011	322,800	4/18/1952	40.20	–
				7/10/1993	30.26	–
				7/2/2011	36.29	–
29	06818000 Missouri River at St. Joseph, Missouri	1928-2011	[1]426,500	4/22/1952	26.82	–
				7/26/1993	32.07	–
				6/28/2011	29.97	–
31	06893000 Missouri River at Kansas City, Missouri	1897-2011	[1]484,100	4/24/1952	40.60	–
				7/27/1993	48.87	–
				7/10/2011	32.65	–
57	06934500 Missouri River at Hermann, Missouri	1897-2011	[1]522,500	4/28/1944	30.90	–
				7/31/1993	36.97	–
				5/28/2011	26.60	–
58	07022000 Mississippi River at Thebes, Illinois	1932-2011	713,200	4/30/1973	43.43	886,000
				8/7/1993	45.51	996,000
				7/3/2008	40.95	717,000
				[2]5/3/2011	45.52	876,000
64	07289000 Mississippi River at Vicksburg, Mississippi	1928-99, 2008-11	[3]1,144,500	[4]5/13/1973	51.60	1,962,000
				4/21/1993	42.80	1,333,000
				4/20/2008	51.00	1,820,000
				5/19/2011	57.10	2,330,000
66	011000 Mississippi River at Tarbert Landing, Mississippi[5]	1961-2011	1,124,900	5/16/1973	–	1,498,000
				5/21/1993	–	1,202,000
				4/25/2008	–	1,456,000
				5/19/2011	–	1,619,000

[1]Drainage area does not include the 3,959 mi² in the Great Divide basin.
[2]Peak streamflow was measured on May 2, 2011.
[3]4,000 mi² is probably noncontributing (is from the Great Divide basin in Southern Wyoming).
[4]Peak streamflow was measured on May 12, 1973.
[5]Streamflow data collected by the U.S. Army Corps of Engineers.

the 2011 flood. Peak streamflow at site number 7 occurred in June 2008 during a period of flooding in the Midwest. The peak streamflow measured at site number 7 on June 16, 2011, is 81 percent less than the peak streamflow measured during the 2008 flood. The highest streamflow ever recorded at site number 58 occurred during the 1993 flood. The peak streamflow measured on May 2, 2011 (876,000 ft^3/s) is 12 percent less than the peak streamflow measured at site number 58 on August 7, 1993. In the lower Mississippi-Atchafalaya River Subbasin, streamflow measured during the 2011 flood exceeded streamflow measured during prior floods in the region. At site number 64, streamflow measured on May 19, 2011 (2.33 million ft^3/s) is 18 percent greater than the prior record streamflow of 1.96 million ft^3/s measured during the 1973 flood (table 3). Similarly, streamflow measured at site number 66 on May 19, 2011 (1.62 million ft^3/s), is 8 percent greater than the prior record streamflow of 1.498 million ft^3/s measured on May 16, 1973 (table 3).

Figure 14. U.S. Army Corps of Engineers documents the height of all major floods of the Mississippi River on the levee wall at Vicksburg, Mississippi. The only mark higher than the stage measured on May 19, 2011, is that of the 1927 flood.

Concentrations of Selected Water-Quality Constituents in the Subbasins during the 2011 Flood

Concentrations of suspended sediment, nutrients, and atrazine varied among the four subbasins during the flood period. The maximum suspended-sediment concentration measured was 8,490 mg/L at a site in the Missouri River Subbasin, and the highest median suspended-sediment concentration (450 mg/L) was from the Missouri River Subbasin when compared to the three other subbasins (table 4). Median suspended-sediment concentrations in the Ohio River and the lower Mississippi-Atchafalaya River Subbasins were about one-half the median concentration of samples collected in the upper Mississippi River Subbasin.

Median concentrations of total nitrogen and nitrate were higher in the upper Mississippi River Subbasin, when compared to the three other subbasins (table 4). However, the highest concentration of total nitrogen and nitrate were measured in the Missouri River Subbasin. The maximum and highest median concentrations of total phosphorus were measured within the Missouri River Subbasin (table 4). Although, the highest orthophosphate concentration measured was at a site in the Missouri River Subbasin (1.94 mg/L), the upper Mississippi River Subbasin had the highest median orthophosphate when compared to the other three subbasins. Median concentrations of the four nutrients were generally lower in the Ohio River and lower Mississippi-Atchafalaya River Subbasins.

The median concentration of atrazine measured was highest in the upper Mississippi River Subbasin (table 4). The maximum concentration of atrazine measured was 13.8 µg/L from a site within the Ohio River Subbasin. The lowest median concentration of atrazine was in the Missouri River Subbasin.

Summary and Conclusions

The high streamflow associated with the flooding of 2011 in the Mississippi River Basin from April through July forced the simultaneous opening of three major flood-control structures for the first time in history in the lower Mississippi-Atchafalaya River Subbasin, and the additional regulation of water released from dams within the Missouri River and Ohio River Subbasins in order to manage the large amount of water moving through the system. Peak streamflow was measured at the USGS streamflow-monitoring stations at the Ohio River at Metropolis and the Mississippi River at Vicksburg and at the U.S. Army Corps of Engineers streamflow-monitoring station at the Mississippi River at Tarbert Landing. However, the 1952 flood moved a larger volume of water in the Missouri River Subbasin than was moved in the subbasin during the 2011 flood. Historical peak stages were measured

Table 4. Concentrations of selected constituents measured in each of the four subbasins during the 2011 Mississippi River flood, April through July.

[mg/L, milligrams per liter; µg/L, microgram per liter]

Subbasin	Number of samples	Constituent concentration			
		Minimum	Maximum	Mean	Median
Suspended sediment, in mg/L					
Upper Mississippi River	130	39	2,630	380	240
Missouri River	228	<1	8,490	780	450
Ohio River	26	10	400	120	110
Lower Mississippi-Atchafalaya River	96	9	340	130	120
Nutrients, in mg/L					
Total nitrogen, as nitrogen					
Upper Mississippi River	39	2.5	10	5.63	5.30
Missouri River	161	0.25	15	2.96	1.90
Ohio River	20	0.59	4.10	1.82	1.81
Lower Mississippi-Atchafalaya River	91	0.73	3.10	1.92	1.90
Nitrate, as nitrogen					
Upper Mississippi River	39	1.46	8.98	4.58	4.20
Missouri River	214	<0.008	9.82	1.55	1.55
Ohio River	27	0.17	3.22	1.49	1.49
Lower Mississippi-Atchafalaya River	94	0.07	2.17	1.27	1.27
Total phosphorus, as phosphorus					
Upper Mississippi River	39	0.13	0.88	0.28	0.24
Missouri River	211	<0.02	5.00	0.58	0.34
Ohio River	27	0.06	0.30	0.18	0.18
Lower Mississippi-Atchafalaya River	95	0.09	0.34	0.20	0.19
Orthophosphate, as phosphorus					
Upper Mississippi River	39	<0.004	0.19	0.09	0.09
Missouri River	215	<0.005	1.94	0.12	0.06
Ohio River	27	<0.004	0.09	0.04	0.04
Lower Mississippi-Atchafalaya River	94	0.03	0.12	0.07	0.06
Pesticides, in µg/L					
Atrazine					
Upper Mississippi River	40	0.02	5.56	1.40	0.82
Missouri River	68	<0.008	7.54	0.67	0.20
Ohio River	27	0.03	13.8	1.42	0.42
Lower Mississippi-Atchafalaya River	96	0.06	1.43	0.51	0.49

during the 2011 flood at the Mississippi River at Thebes, Illinois, and the Mississippi River at Vicksburg, Mississippi, USGS streamflow-monitoring stations. Higher stages were observed during the 1993 flood in portions of the Missouri River Subbasin and in the upper Mississippi River Subbasin than during the 2011 flood. Record rainfall in the Ohio River Subbasin was the primary contributor to streamflow in the lower Mississippi-Atchafalaya River Subbasin during the months of March, April, and May 2011. Record melting of snowpack in late May in the Missouri River Subbasin and above-normal precipitation from May through July in the upper Mississippi River Subbasin contributed to the majority of streamflow in the lower Mississippi-Atchafalaya River Subbasin during June and July.

To characterize water-quality during the flood, surface-water samples were collected at weekly to monthly intervals from 69 water-quality stations and 3 flood-control structures. During the 2011 flood, most of the sampled sites remained above flood stage for 2 ½ to 3 months, and instantaneous streamflow measurements at the time of sample collection were higher than historical median streamflow measurements at the time of corresponding water-quality sample collection. The Ohio River Subbasin is more urban and forested in land use, whereas the Missouri River Subbasin and upper Mississippi River Subbasin are primarily agricultural, with some rangeland. The timing and contribution of the streamflow from the two different source areas are important in determining which chemicals and other contaminants enter the lower Mississippi-Atchafalaya River Subbasin through overland runoff or water receding from inundated lands.

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Appendixes

Appendixes 1–8 are available for download at *http://pubs.usgs.gov/of/2013/1106/* in the following formats:

1. Relative percent difference between environmental and replicate samples collected during the 2011 Mississippi River flood, April through July ....MS Excel
2. Field parameters and inorganic data collected during the 2011 Mississippi River flood, April through July ....MS Excel
3. Suspended sediment, turbidity, and particle size data collected during the 2011 Mississippi River flood, April through July ....MS Excel
4. Nutrient concentration data collected during the 2011 Mississippi River flood, April through July ....MS Excel
5. Concentrations of detected pesticides in samples collected during the 2011 Mississippi River flood, April through July ....MS Excel
6. Pesticides analyzed for, but not detected in samples collected during the 2011 Mississippi River flood, April through July ....MS Excel
7. Sediment data from the Morganza Floodway and Bonnet Carré Spillways collected during the 2011 Mississippi River flood, April through July ....MS Excel
8. Oil and gas data collected in the Atchafalaya River basin from May through June 2011 ....MS Excel

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USGS Publishing Service Center staff:
Mike Deacon, Editor
Kim Swidarski, Illustrations and layout

Welch and Barnes—**Streamflow Characterization and Summary of Water-Quality Data Collection during the Mississippi River Flood**—OFR 2013–1106