In Cooperation with the Federal Emergency Management Agency

Flood of June 22–24, 2006, in North-Central Ohio, With Emphasis on the Cuyahoga River Near Independence

Scientific Investigations Report 2007–5161

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

Cover: Floodwaters from the Cuyahoga River and Ohio and Erie Canal at the intersection of Canal Road, West Canal Road, and Fosdick Road in Valley View, Ohio (looking east). (Photo taken on June 23, 2006, by Mayor Randall A. Westfall, Valley View, Ohio, reproduced with permission.)

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DIRK KEMPTHORNE, Secretary

U.S. Geological Survey
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Contents

Figures

Tables

Conversion Factors

Multiply	By	To obtain
	Length	
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)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
inch per hour (in/h)	2.54	centimeter per hour (cm/h)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929.

Horizontal coordinate information is referenced to the North American Datum of 1983.

All times referred to in this report are Eastern Daylight Time.

Flood of June 22–24, 2006, in North-Central Ohio, With Emphasis on the Cuyahoga River Near Independence

By James M. Sherwood[1], Andrew D. Ebner[1], G.F. Koltun[1], and Brian M. Astifan[2]

Abstract

Heavy rains caused severe flooding on June 22–24, 2006, and damaged approximately 4,580 homes and 48 businesses in Cuyahoga County. Damage estimates in Cuyahoga County for the two days of flooding exceed $ 47 million; statewide damage estimates exceed $ 150 million. Six counties (Cuyahoga, Erie, Huron, Lucas, Sandusky, and Stark) in northeast Ohio were declared Federal disaster areas. One death, in Lorain County, was attributed to the flooding.

The peak streamflow of 25,400 cubic feet per second and corresponding peak gage height of 23.29 feet were the highest recorded at the U.S. Geological Survey (USGS) streamflow-gaging station Cuyahoga River at Independence (04208000) since the gaging station began operation in 1922, exceeding the previous peak streamflow of 24,800 cubic feet per second that occurred on January 22, 1959. An indirect calculation of the peak streamflow was made by use of a step-backwater model because all roads leading to the gaging station were inundated during the flood and field crews could not reach the station to make a direct measurement. Because of a statistically significant and persistent positive trend in the annual-peak-streamflow time series for the Cuyahoga River at Independence, a method was developed and applied to detrend the annual-peak-streamflow time series prior to the traditional log-Pearson Type III flood-frequency analysis. Based on this analysis, the recurrence interval of the computed peak streamflow was estimated to be slightly less than 100 years. Peak-gage-height data, peak-streamflow data, and recurrence-interval estimates for the June 22–24, 2006, flood are tabulated for the Cuyahoga River at Independence and 10 other USGS gaging stations in north-central Ohio.

Because flooding along the Cuyahoga River near Independence and Valley View was particularly severe, a study was done to document the peak water-surface profile during the flood from approximately 2 miles downstream from the USGS streamflow-gaging station at Independence to approximately 2 miles upstream from the gaging station. High-water marks were identified and flagged in the field. Third-order-accuracy surveys were used to determine elevations of the high-water marks, and the data were tabulated and plotted.

[1] U.S. Geological Survey, Columbus, Ohio.

[2] National Oceanic and Atmospheric Administration, National Weather Service, Cleveland, Ohio.

Introduction

Heavy rains caused severe flooding on June 22–24, 2006, and damaged approximately 4,580 homes and 48 businesses in Cuyahoga County, Ohio (Sartin, 2006). Damage estimates in Cuyahoga County for the 2 days of flooding exceed $47 million; statewide damage estimates exceed $150 million (National Weather Service, 2006). Six counties (Cuyahoga, Erie, Huron, Lucas, Sandusky, and Stark; fig. 1) in northeast Ohio were declared Federal disaster areas (Federal Emergency Management Agency, 2006). Damages due to the flooding were particularly severe along the Cuyahoga River near Independence and Valley View, Ohio (fig. 2). Data collected at the USGS streamflow-gaging station on the Cuyahoga River at Independence, Ohio (station 04208000) indicate that the peak gage height and corresponding peak streamflow were the highest recorded since the gaging station began operation in 1922.

Flood data are needed by Federal, State, and local agencies in order to make informed decisions about flood plain management and to provide information to assist in managing future flood emergencies. Much of this body of data is derived from the stream-gaging program of the U.S. Geological Survey (Wahl and others, 1995). Given the severity of the June 2006 flood, the U.S. Geological Survey (USGS), in cooperation with the Federal Emergency Management Agency, did a study to document gage-height, streamflow, flood-frequency, high-water-mark, and meteorological data associated with the flood.

Purpose and Scope

The purpose of this report is to describe the results of the study. The meteorological factors contributing to the flood are discussed. Data on peak gage height, peak streamflow, and estimated recurrence interval[3] are presented for 11 USGS streamflow-gaging stations in north-central Ohio (fig. 1). Elevations and geographical coordinates of high-water marks are presented for selected locations along the Cuyahoga River near Independence and Valley View (fig. 2).

[3] Recurrence interval, in years, is equal to the reciprocal of the annual exceedance probability for a flood of the given magnitude. It represents a long-term average frequency with which one would expect to experience a flood of the given magnitude and, as such, does not preclude the occurrence of two or more large-recurrence-interval floods in any given shorter timespan.

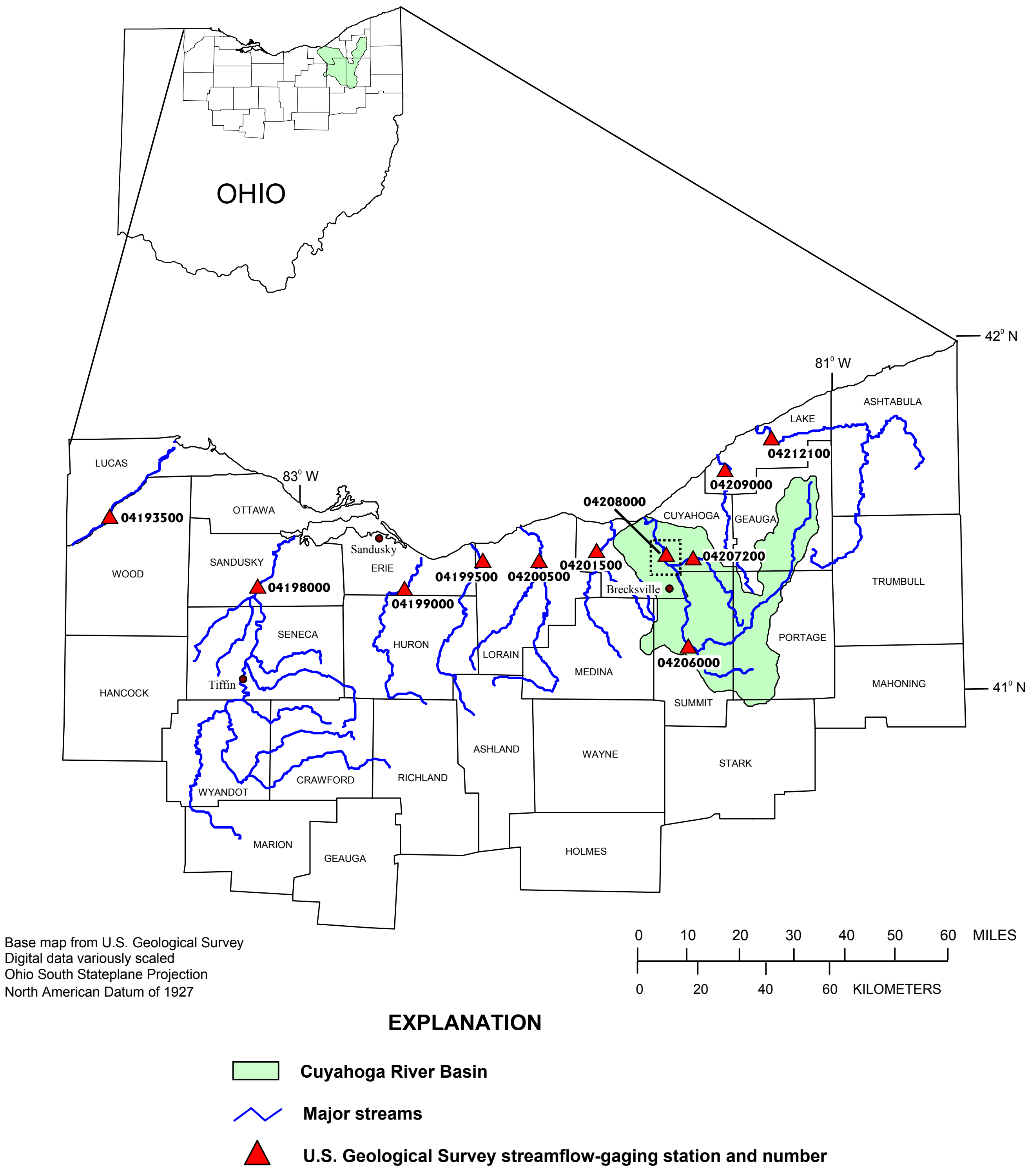

Figure 1. Locations of the 11 U.S. Geological Survey streamflow-gaging stations for which peak-gage-height, peak-streamflow, and recurrence-interval data are presented. (Dashed box indicates area highlighted in fig. 2. Gaging-station names and descriptions are listed in table 1.)

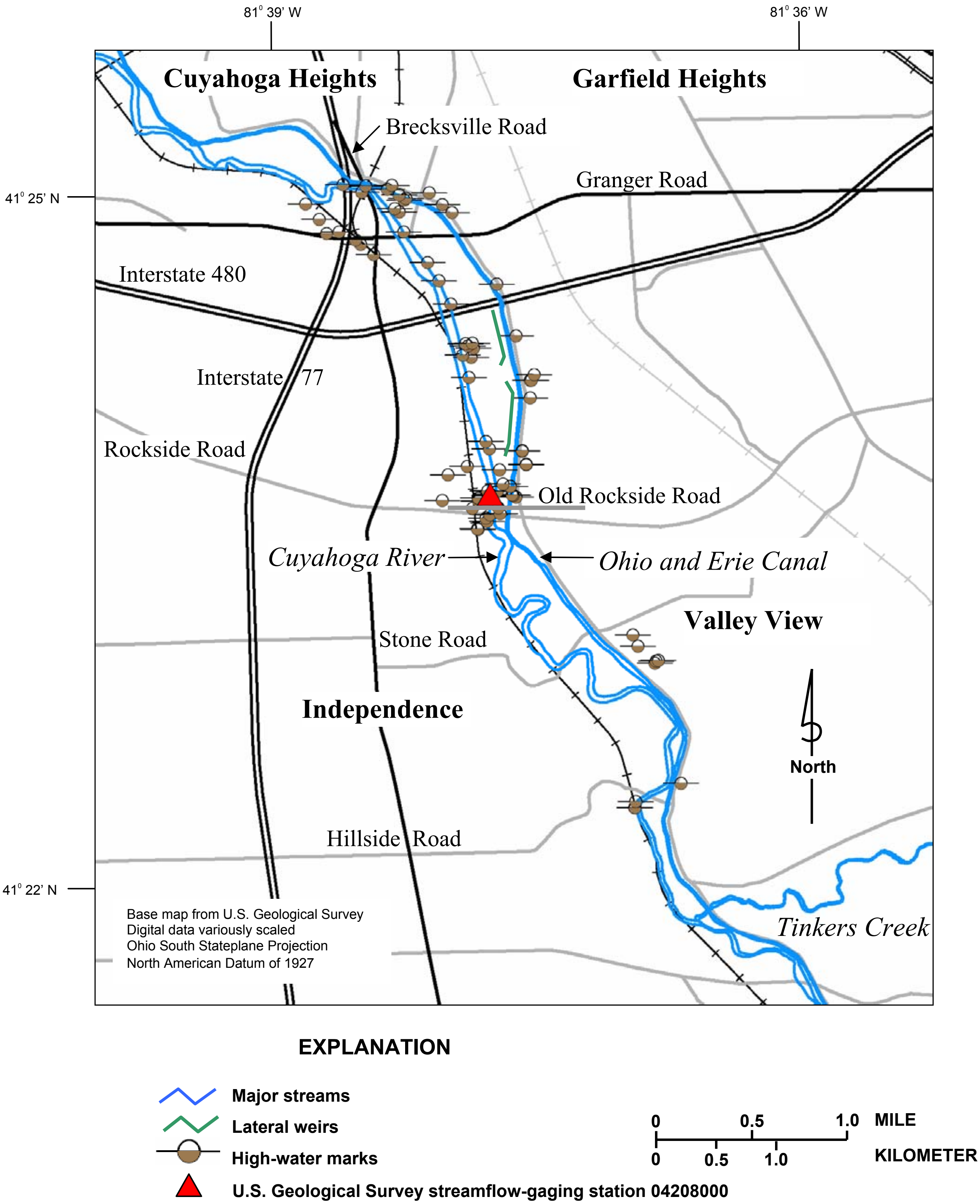

Figure 2. Locations of high-water marks near the Cuyahoga River for the flood of June 22–24, 2006. (Map shows area within the dashed box in fig. 1.)

An indirect calculation of the peak streamflow for the USGS streamflow-gaging station on the Cuyahoga River at Independence (station 04208000) is described and summarized. A description is presented for a method that was developed and applied to detrend the annual-peak-streamflow time series for the Cuyahoga River at Independence prior to the traditional log-Pearson Type III flood-frequency analysis.

Meteorology Associated With the Flood

Two consecutive days of severe thunderstorms in late June brought the worst flooding in nearly 50 years to many areas in northern Ohio. Record flooding occurred on the Cuyahoga River at Independence, and six counties in northern Ohio (Cuyahoga, Erie, Huron, Lucas, Sandusky, and Stark) were declared Federal disaster areas.

Antecedent Conditions

May 2006

Precipitation during May was generally above normal[4] in the northern half of the State and below normal in the southern half. The average for the State as a whole was 4.26 inches, 0.35 inch above normal. The National Oceanic and Atmospheric Administration (NOAA) divides the State into 10 climatological Regions. As shown in figure 3, Regional averages ranged from 5.64 inches (2.15 inches above normal) for the Northwest Region to 2.11 inches (2.05 inches below normal) for the South Central Region. This was the 7th wettest May for the Northwest Region, the 11th wettest for the North Central Region, and the 12th wettest for the Northeast Region during the past 112 years. Tiffin (Seneca County, fig. 1) reported the greatest amount of May precipitation, 6.64 inches. Precipitation fell as showers and scattered thunderstorms, with some storms producing severe weather and large amounts of precipitation. Rain fell during every week of the month, but the middle of the month was the wettest at most locations. Streamflow was above normal across much of the State but below normal in eastern and southeastern Ohio (Kirk, 2006a).

June 2006

Precipitation during June was above normal across much of the State but below normal in south-central, southeastern, and most of northwestern Ohio. The average for the State as a whole was 4.81 inches, 0.96 inch above normal. As shown in figure 3, regional averages ranged from 6.20 inches (2.46 inches above normal) for the North Central Region to 3.22 inches (0.45 inch below normal) for the Northwest Region. This was the 9th wettest June for the North Central Region, the 12th wettest for the Northeast Region, and the 13th wettest for the Northeast Hills Region during the past 112 years. Sandusky (Erie County, fig. 1) reported the greatest amount of June precipitation, 8.28 inches. Precipitation during June fell as showers and thunderstorms, with locally severe weather reported in many areas. Strong storms were common statewide during June 18–23. Most areas of the State received 1 to 2 inches of precipitation during this period, with 3 to 7 inches of rain reported in a large part of the northern third of the State. Streamflow was above normal in most drainage basins but below normal in northwestern Ohio (Kirk, 2006b).

Storms of June 21–22, 2006

A warm front lifted north across the lower Great Lakes Region on June 21, 2006, drawing deep tropical moisture northward into Ohio. Thunderstorms formed along this front during the late afternoon hours and evolved into a nocturnal mesoscale convective complex[5] that remained nearly stationary over northwest and north-central Ohio until the early morning of June 22, 2006, bringing intense rainfall, flash floods, and widespread severe weather. On the afternoon of June 22, 2006, a cold front moved towards the area, triggering a second round of severe weather and flooding. Elsewhere across northern Ohio, widespread straight-line wind downed many trees and powerlines, and several buildings sustained structural damage. The mesoscale convective complex that developed over northern Ohio on June 21 brought torrential rainfall in excess of 4 to 5 inches in 6 hours across much of northern Ohio.

On the afternoon of June 22, intense, nearly stationary thunderstorms developed along a lake breeze boundary that had formed over Cuyahoga and Summit Counties. More than 5 inches of rain fell in less than 2 hours across several southern Cleveland suburbs, with Brecksville (fig. 1) recording 1.64 inches in 15 minutes and 3.38 inches in 1 hour. An isohyetal map showing 48-hour rainfall totals for the June 21–22 period is shown in figure 4 and is based on rainfall data from 35 rain gages operated by several agencies.

[4] Normal refers to the mean of the base period of precipitation data of 1951–2000 (Kirk, 2006a, b).

[5] Mesoscale convective complexes typically form during the afternoon and evening in the form of several isolated thunderstorms, which expand in scale because of extremely divergent flow aloft, such as near the split in an upper-level jet stream. Early in the life cycle of the complexes, the potential for severe weather is greatest. As the system matures, a stratified cloud layer with embedded heavy rain forms behind the leading thunderstorms. During peak intensity, the primary threat shifts toward heavy rain and flooding.

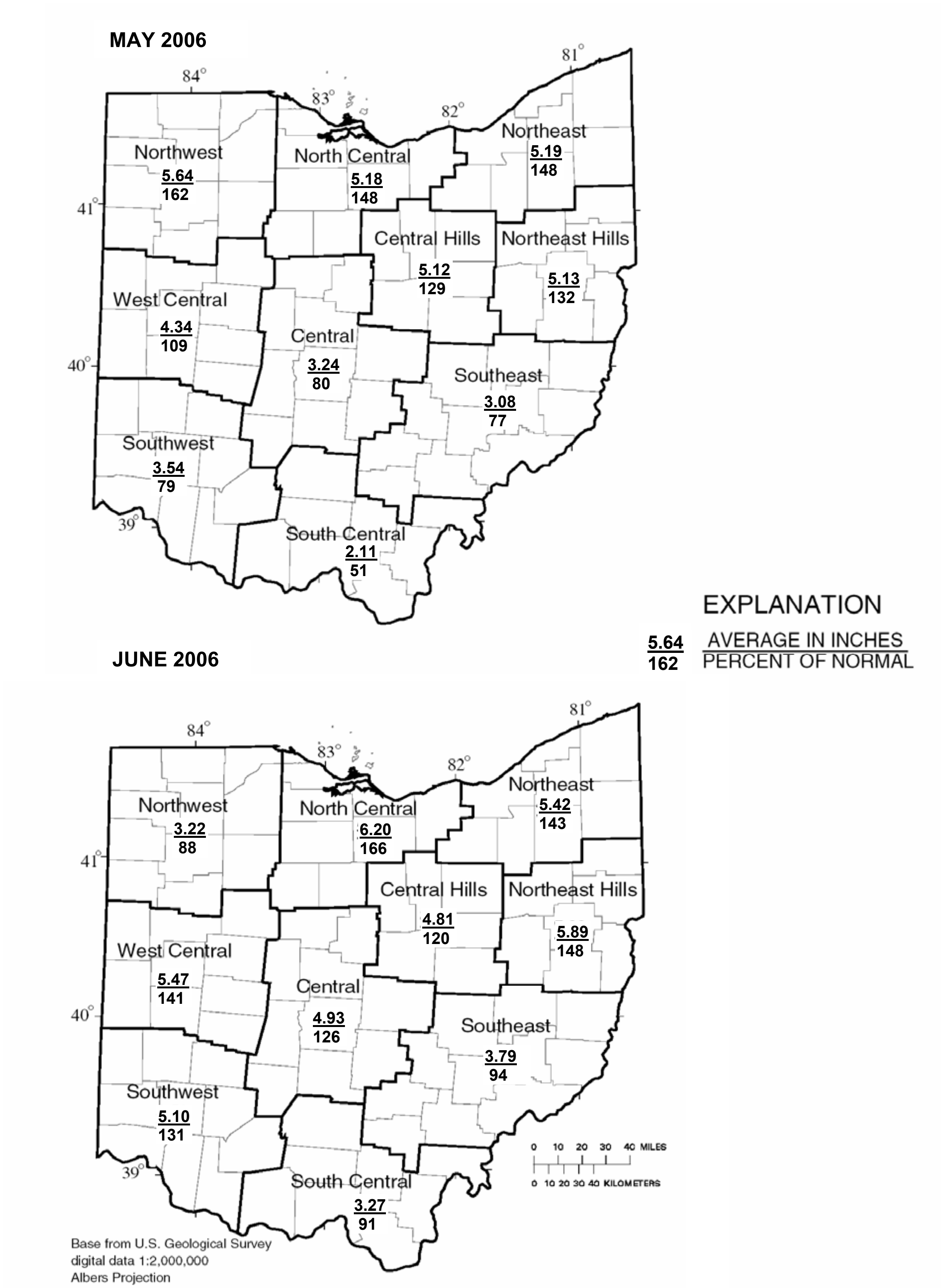

Figure 3. Regionally averaged monthly total precipitation and percentage of normal precipitation by National Weather Service Region, May and June 2006 (from Kirk, 2006a, b).

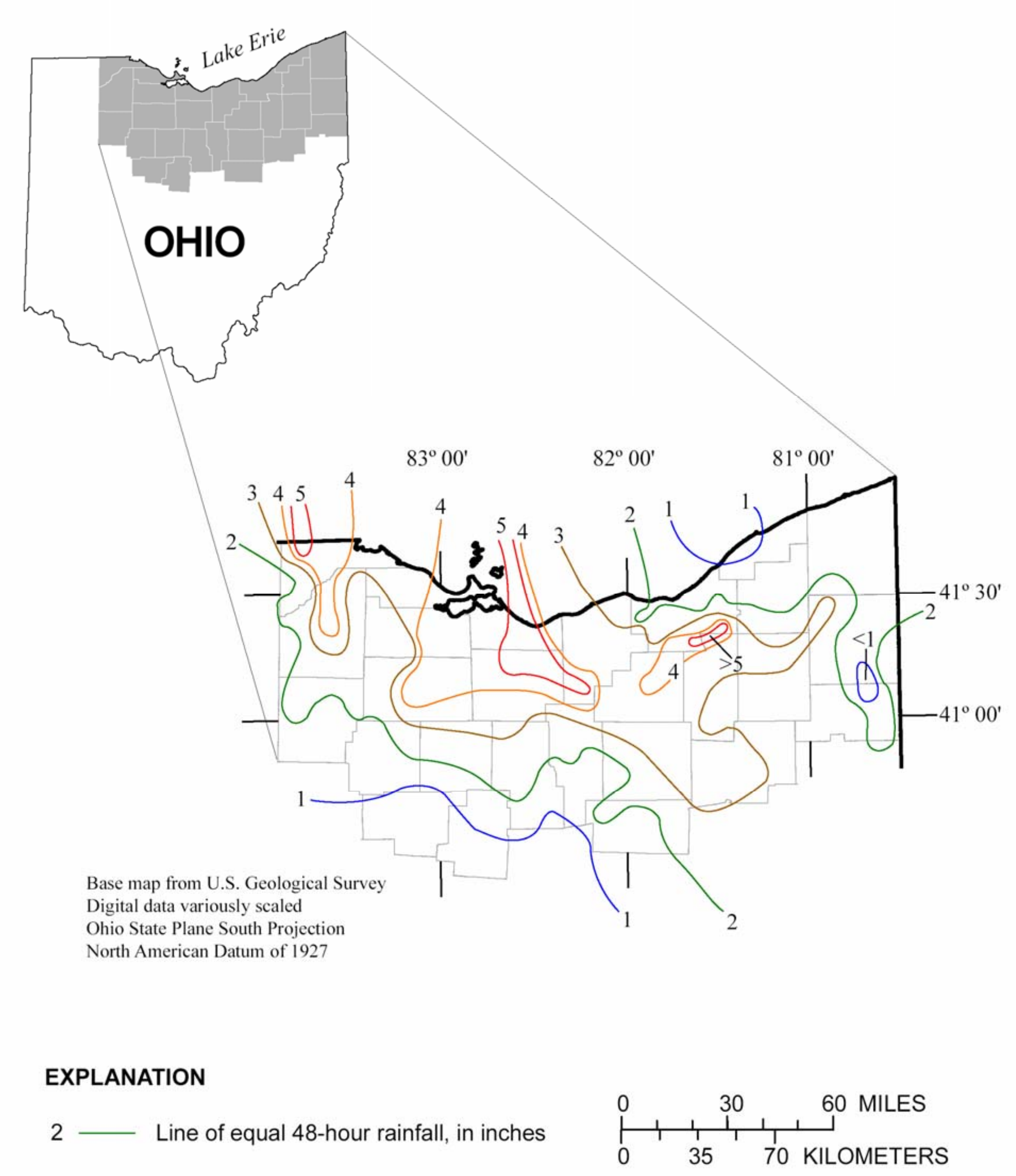

Figure 4. Isohyetal map showing 48-hour rainfall totals for June 21–22, 2006, based on rainfall data from 35 rain gages operated by several agencies.

General Description of the Flood

Water levels in many streams in northern Ohio rose rapidly in response to the large amounts of rainfall. In addition to the flooding previously discussed on the Cuyahoga River at Independence, major urban flooding was reported in Lucas County, where ditches and small streams overflowed their banks as a result of the heavy rainfall. Primary and secondary roads throughout northern Ohio were impassable, and many water rescues and evacuations took place. One death was attributed to the flooding: a rescue diver was overwhelmed by floodwaters while trying to reach and save two teens who had driven into a flooded roadway in southern Lorain County. Flooding across this area was by far the worst since July 1969, when as much as 14 inches of rain fell along a similar axis across northern Ohio.

The USGS streamflow-gaging station on the Huron River at Milan (04199000), which has been in operation for 51 years, recorded its third highest peak gage height of 23.95 feet on June 22, 2006, at 1:15 p.m. On the next major river to the east, the USGS streamflow-gaging station on the Vermilion River at Vermilion (04199500), which has been in operation for 38 years, also recorded its third highest peak gage-height at 11.18 feet on June 23, 2006, at 2:00 a.m. The tremendous amount of water flowing down the Vermilion River washed docks and boats into Lake Erie from their moorings in downtown Vermilion. In the city of Sandusky, at least 40 residents were quickly evacuated during the morning hours of June 23, 2006, when rapidly rising waters flooded several residential areas.

Eleven streamflow-gaging stations (fig. 1) were studied to determine the peak stages, peak streamflows, and flood recurrence intervals. These streams and the localities/counties within their drainage basins experienced damages during the June 22–24, 2006, flood. Of the 11 gaging stations, 10 were accessible during the flood, and either direct measurements were made or the equipment was operational and the established relations between gage height and streamflow were used to calculate streamflow. The Cuyahoga River at Independence (station 04208000) was not accessible so an indirect measurement was made after the flood ended. Standard USGS methods for indirect calculations of peak streamflow were followed (Benson and Dalrymple, 1967). These methods included surveys of high-water marks and the development of a HEC-RAS step-backwater model (U.S. Army Corps of Engineers, 2005), which is described later in this report. The peak streamflow for the Independence gaging station represents a new record.

At the USGS streamflow-gaging station on the Cuyahoga River at Independence (station 04208000), the water level rose 16.15 feet in the 24-hour period from June 22 at 3:00 a.m. to June 23 at 3:00 a.m. and 5.78 feet in the 1-hour period from June 22 at 5:00 p.m.. to June 22 at 6:00 p.m. The peak gage-height for the flood — 23.29 feet, with a corresponding streamflow of 25,400 cubic feet per second — occurred on June 23 at about 1:30 a.m. A gage-height hydrograph for the flood at the Independence gaging station is shown in figure 5, and a streamflow hydrograph is shown in figure 6.

At the USGS streamflow-gaging station on the Cuyahoga River at Old Portage (station 04206000), 7.1 miles upstream from the Independence station, the peak gage height for the flood was 9.66 feet, with a corresponding streamflow of 3,670 cubic feet per second. The peak gage height and streamflow at the Old Portage station occurred on June 22 at 8:00 p.m.

The drainage area at the Independence station is 707 square miles, and the corresponding unit (normalized) peak streamflow for the June 2006 flood was 36.5 cubic feet per second per square mile. The drainage area at the Old Portage station is 404 square miles, and the corresponding unit peak streamflow for the June 2006 flood was 9.1 cubic feet per second per square mile. Although the drainage area for the Independence station is 1.75 times larger than the drainage area for the Old Portage station, the unit peak streamflow for the Independence station was 4.00 times larger than the unit peak streamflow for the Old Portage station. A factor contributing to the significantly greater unit peak streamflow at the Independence station and the rapid rise of the Cuyahoga River at Independence is that the heaviest rainfall during June 22–23 was concentrated on the tributaries to the Cuyahoga River that enter between the Independence and Old Portage gaging stations, including Tinkers Creek (fig. 1). As indicated in table 1, the estimated recurrence-interval range for the June 2006 peak streamflow at the USGS streamflow-gaging station on Tinkers Creek at Bedford (station 04207200) was the second highest of those listed (the Cuyahoga River at Independence was the highest).

The following sections provide information about the June 22–24, 2006, storms and flood and their areal extent. Flood information is also given for selected sites, streams, and (or) communities where specific flood-related data were collected. Many more communities and streams were affected by flooding than are mentioned here and their omission is not meant to reflect on the severity of that flooding or the impact on the communities.

Flood Gage Heights, Streamflows, Recurrence Intervals, and High-Water Elevations

Peak-gage-height and peak-streamflow data from the June 22–24 flooding are listed in table 1 for 11 USGS streamflow-gaging stations in northern Ohio. Also listed for each gaging station are the record peak gage height and peak streamflow prior to the June 22–24 flooding and an estimate of the 100-year-recurrence-interval peak streamflow. Estimates of the 100-year peak streamflows in table 1 (unless otherwise noted) were obtained from a published USGS report for estimating flood-peak streamflows (Koltun, 2003), which is based on data collected through water year[6] 2001.

[6] A water year is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends.

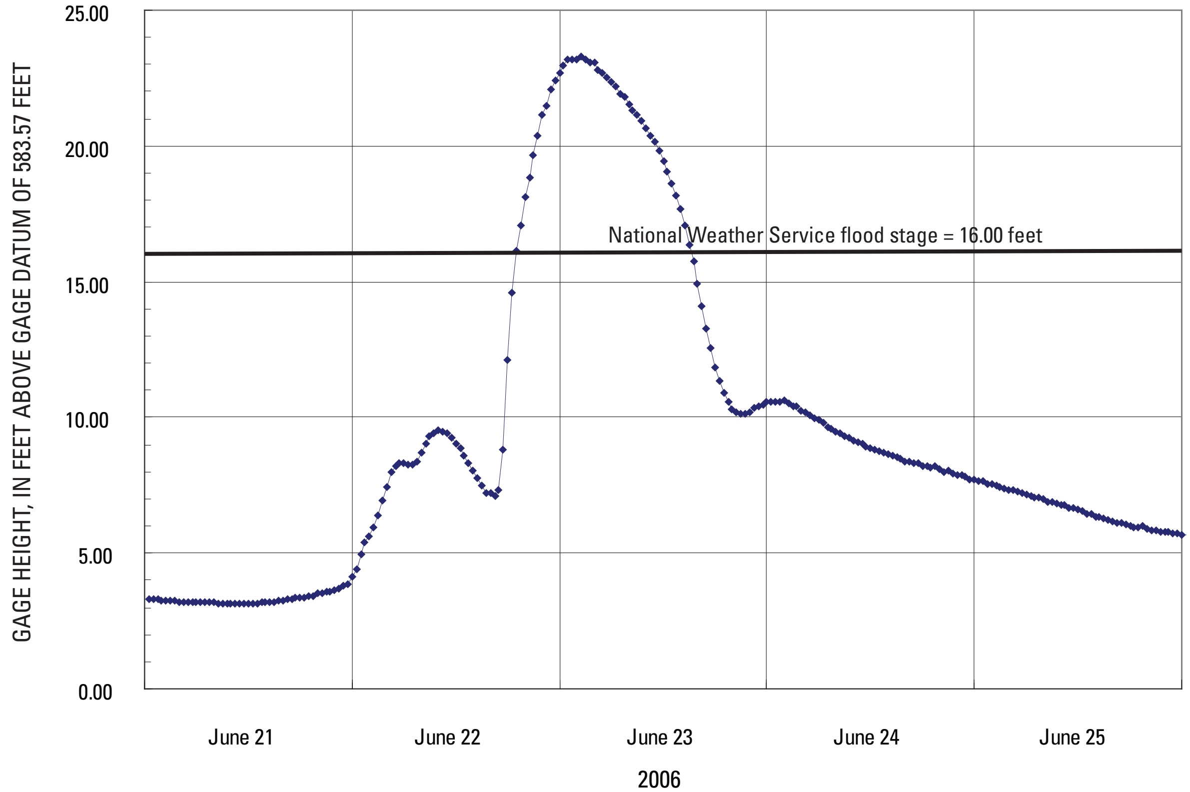

Figure 5. Gage-height hydrograph for the flood of June 22–24, 2006, on the Cuyahoga River near Independence, Ohio.

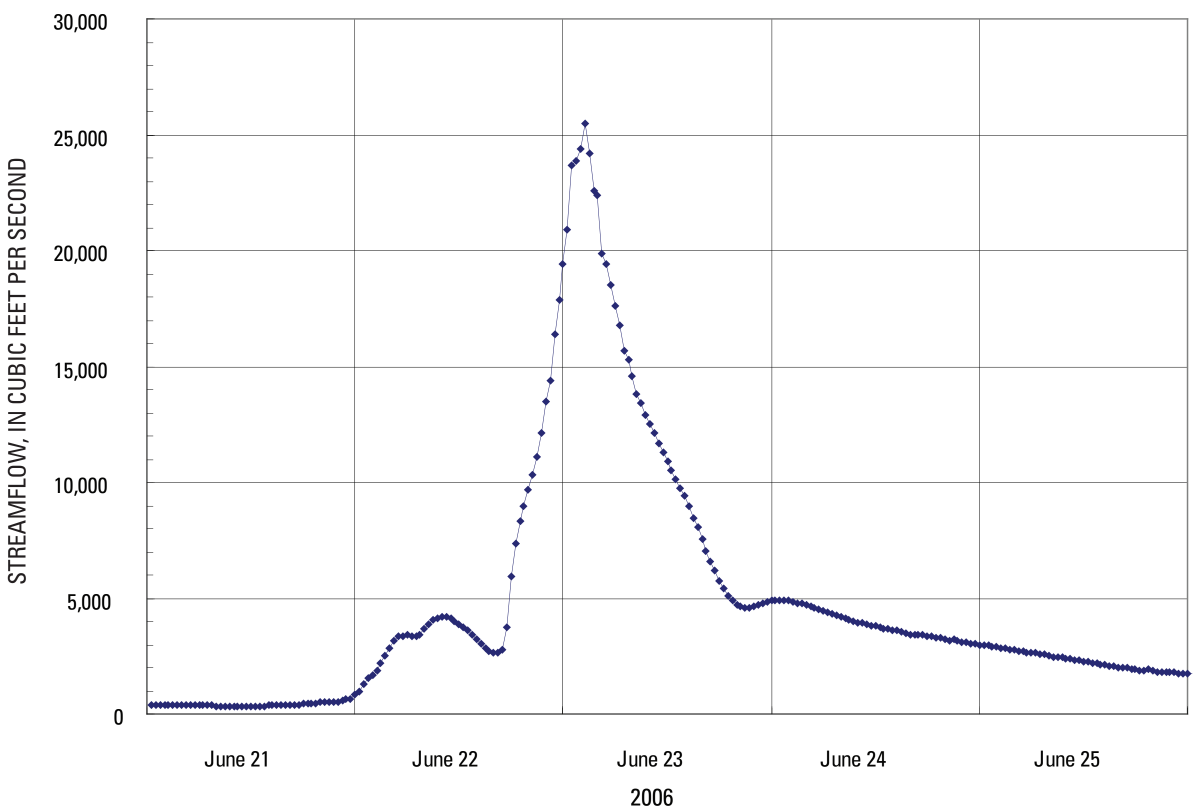

Figure 6. Streamflow hydrograph for the flood of June 22–24, 2006, on the Cuyahoga River near Independence, Ohio.

Table 1. Peak gage heights and peak streamflows at selected USGS streamflow-gaging stations in northern Ohio, June 2006.

[Abbreviations: mi^2, square miles; ft^3/s, cubic feet per second; <, less than; >, greater than. Estimated 100-year peak streamflow and recurrence-interval data from Koltun (2003) unless otherwise noted]

Station number	Station name	Drainage area (mi^2)	Period of record (water years)[1]	Length of record (years)	Peak values for period of record prior to June 2006			Peak values for June 2006		Estimated 100-year peak streamflow (ft^3/s)	Estimated recurrence-interval range for June 2006 peak streamflow (years)
					Date	Gage height (feet above gage datum)	Stream-flow (ft^3/s)	Gage height (feet above gage datum)	Stream-flow (ft^3/s)		
04193500	Maumee River at Waterville	6,330	1900–1901, 1913, 1922–1936, 1939–current	86	03/1913	19.90	180,000	4.60	8,170	118,000	< 2
04198000	Sandusky River near Fremont	1,251	1924–1936, 1939–current	81	03/16/1978	13.57	36,500	7.05	13,100	32,500	< 2
04199000	Huron River at Milan	371	1950–1981, 1988–current	51	07/05/1969	31.10	49,600	23.95	14,300	25,500	5–10
04199500	Vermilion River near Vermilion	262	1950–1981, 2001–current	38	07/06/1969	17.14	40,800	11.18	16,600	20,000	25–50
04200500	Black River at Elyria	396	1945–current	62	07/06/1969	26.40	51,700	16.86	12,500	25,200	5–10
04201500	Rocky River near Berea	267	1924–1935, 1944–current	75	01/22/1959	14.10	21,400	6.33	7,120	19,300	< 2
04206000	Cuyahoga River at Old Portage	404	1922–1936, 1939–current	83	01/21/1959	11.54	6,500	9.66	3,670	6,600[2]	2–5
04207200	Tinkers Creek at Bedford	83.9	1963–current	44	07/20/1969	10.10	7,220	9.84	6,790	7,300	50–100
04208000	Cuyahoga River at Independence	707	1922–1923, 1928–1936, 1940–current	78	01/22/1959	22.41	24,800	23.29	25,400	25,500[3]	50–100
04209000	Chagrin River at Willoughby	246	1913, 1926–1935, 1940–1984, 1988–1993, 1996–1999, 2002–current	72	03/22/1948	17.95	28,000	9.21	8,170	29,400	< 2
04212100	Grand River near Painesville	685	1975–current	32	06/11/1986	13.07	18,700	3.21	805	21,000	< 2

[1] A water year is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends.

[2] Flow slightly regulated by reservoir and lakes. Estimated 100-year peak-streamflow and recurrence-interval data from Webber and Bartlett (1977).

[3] Estimated 100-year peak streamflow and recurrence-interval data based on detrended annual-peak-streamflow data through 2006.

Ranges of recurrence intervals that bracket the estimated recurrence interval associated with the peak streamflow are included in table 1 to indicate the relative magnitude of the June 22–24, 2006, flooding at each of the 11 gaging stations. Locations of the 11 USGS streamflow-gaging stations are shown in figure 1.

USGS personnel were able to obtain direct measurements of the streamflow at most of the gaging stations in northern Ohio during the flood. Peak streamflows for the flood at the streamflow-gaging stations were determined by use of standard USGS techniques (Rantz and others, 1982). This determination generally is accomplished by directly measuring gage height and streamflow simultaneously over a period of time to establish a graphical relation between gage height and streamflow. Interpolation and extrapolation of this relation can then be used to determine streamflow from gage height for all recorded gage heights. Excessive extrapolation of this relation at high gage heights can result in large errors in streamflow. To add a data point to the relation for a large flood that may be impossible to measure directly, various methods are used to calculate the streamflow indirectly. At the Cuyahoga River at Independence (station 04208000), an indirect calculation of the peak streamflow (described later in this report) was made by use of a HEC-RAS step-backwater model (U.S. Army Corps of Engineers, 2005) because all roads leading to the gaging station were inundated during the flood and field crews could not reach the gaging station to make a direct measurement.

After the floodwaters receded near the Cuyahoga River in the vicinity of Independence and Valley View, personnel from the U.S. Geological Survey located high-water marks from approximately 2 miles downstream from the USGS gaging station at Independence to approximately 2 miles upstream from the station. The high-water marks were identified and flagged in the field, and third-order-accuracy surveys were made subsequently by means of standard surveying techniques to determine elevations of the high-water marks (Benson and Dalrymple, 1967). Identifying and qualifying high-water marks and determining how well these marks represent the peak often is subjective. High-water marks were rated as excellent, good, fair, or poor, depending upon the type of mark (debris line, drift line, or mud line), the spread or thickness of the mark, and protection of the mark (that is, whether the mark was created in a protected environment such as the interior wall or window of a building or an unprotected environment such as a tree, utility pole, or fencepost). Approximate quantitative indications of accuracy of the high-water marks rating are as follows: excellent, $\pm$ 0.02 foot; good, $\pm$ 0.05 foot; fair, $\pm$ 0.10 foot; and poor, > 0.10 foot (Lumia and others, 1986). The rating of the high-water marks listed in table 2 does not necessarily indicate the accuracy of the elevation listed in the table; rather, it is an estimate of how distinctly the high-water marks correspond to the listed elevation. The distinctness of a high-water mark depends on the availability of debris or sediment at the time of high water. These data were collected to document peak water-surface elevations during the flood and are listed in table 2. The elevations of the high-water marks were also used to calibrate the HEC-RAS step-backwater model that was used in the indirect calculation of the peak streamflow (described later) for the Cuyahoga River at Independence (station 04208000). A map showing the locations of the high-water marks is shown in figure 2. A flood profile showing the elevations and distances of the high-water marks from the mouth of the Cuyahoga River is shown in figure 7.

Indirect Measurement of Streamflow for the Cuyahoga River Near Independence, Ohio

Field surveys and a triangulated irregular network (TIN) developed from digital elevation data provided by the Cuyahoga County Engineer's office were used to derive cross sections for the development of a HEC-RAS step-backwater model (U.S. Army Corps of Engineers, 2005) from Granger Road upstream to the USGS streamflow-gaging station Cuyahoga River at Independence (fig. 2). Step-backwater modeling is a process whereby water-surface elevations are computed at a series of stream cross sections for a specific value of streamflow. The method is based on an iterative application of the energy equation and the continuity equation. Manning's equation is used to estimate the friction losses between cross sections. The Federal Emergency Management Agency Guidelines and Specifications for Flood Hazard Mapping Partners (2003) explain the step-backwater modeling process in detail. During the flood peak, there was significant flow (about 24 percent of total flow) down the Ohio and Erie Canal. Peak water-surface elevations in the Ohio and Erie Canal reach between Interstate 480 and the gaging station at Independence were also about 0.5 foot higher than those in the Cuyahoga River. To accommodate the split flow and different peak-flow water surfaces, separate and parallel HEC-RAS models were built and were connected by two lateral weirs. The lateral-weir locations, lengths, and crest elevations were based on the intersection of the water-surface profile with the land-surface TIN. The lateral-weir locations are shown in figure 2. For the Cuyahoga River model, land-surface elevations of the cross sections were based on 30 cross sections from the TIN and 3 field-surveyed cross sections. Underwater streambed elevations for the Cuyahoga River were based on the three field-surveyed cross sections. For the Ohio and Erie Canal model, land-surface elevations of the cross sections were based on 39 cross sections from the TIN and 15 field-surveyed cross sections. Underwater streambed elevations for the Ohio and Erie Canal were based on the 15 field-surveyed cross sections. Main-channel cross sections consist of firm sand and gravel with overhanging trees and brush along both banks for the Cuyahoga River and soft mud with trees and brush along both banks for the Ohio and Erie Canal. Manning's roughness coefficients for all cross sections, including main-channel subareas and overbank subareas were based predominantly on field estimates from a method described by Cowan (1956), with some augmentation based on aerial photography. The

Table 2. Elevations, locations, and descriptions of high-water marks for flood of June 22–24, 2006, at selected locations near the Cuyahoga River.

[Vertical coordinate data is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate data is referenced to the North American Datum of 1983. Approximate quantitative indications of accuracy of high-water-mark ratings: excellent, ± 0.02 foot; good, ± 0.05 foot; fair, ± 0.10 foot; and poor, > 0.10 foot (Lumia and others, 1986)]

Community name	Distance from mouth of Cuyahoga River (miles)	Elevation (feet above NGVD 29)	Latitude	Longitude	High-water-mark description	High-water-mark rating	Nearest water course	Bank of nearest water course
Independence	11.30	601.52	41° 24’ 59”	- 81° 38’ 51”	mud line on building	excellent	Cuyahoga	left
Independence	11.33	601.63	41° 24’ 56”	- 81° 38’ 46”	mud line on door	excellent	Cuyahoga	left
Independence	11.35	601.69	41° 24’ 52”	- 81° 38’ 43”	mud line on windowframe	excellent	Cuyahoga	left
Independence	11.36	601.66	41° 24’ 52”	- 81° 38’ 39”	mud line on doorframe	excellent	Cuyahoga	left
Independence	11.43	601.67	41° 24’ 50”	- 81° 38’ 33”	mud line on bridge pier	excellent	Cuyahoga	left
Independence	11.48	602.46	41° 24’ 49”	- 81° 38’ 32”	flood witness observation	fair	Cuyahoga	left
	11.50	Interstate 77						
Independence	11.52	601.84	41° 24’ 46”	- 81° 38’ 27”	mud line on bridge pier	fair	Cuyahoga	left
Independence	11.58	602.83	41° 25’ 03”	- 81° 38’ 31”	mud line on bridge pile	excellent	Cuyahoga	left
Cuyahoga Heights	11.60	603.38	41° 25’ 04”	- 81° 38’ 29”	mud line on bridge pile	poor	O&E Canal	left
	11.60	State Route 21 - Brecksville Road						
Cuyahoga Heights	11.67	603.24	41° 25’ 04”	- 81° 38’ 20”	mud line on sign	excellent	O&E Canal	right
Cuyahoga Heights	11.67	603.35	41° 25’ 04”	- 81° 38’ 22”	mud line on bridge pile	excellent	O&E Canal	right
Cuyahoga Heights	11.73	603.33	41° 25’ 02”	- 81° 38’ 18”	mud line on fence	good	O&E Canal	left
Cuyahoga Heights	11.77	603.30	41° 24’ 59”	- 81° 38’ 20”	mud line on building	good	Cuyahoga	right
Cuyahoga Heights	11.79	603.47	41° 24’ 58”	- 81° 38’ 18”	mud line on doorframe	fair	Cuyahoga	right
Garfield Heights	11.81	603.73	41° 25’ 02”	- 81° 38’ 07”	mud line on building	excellent	O&E Canal	right
Garfield Heights	11.89	603.83	41° 24’ 59”	- 81° 38’ 03”	mud line on windowframe	excellent	O&E Canal	right
	11.92	State Route 17 - Granger Road						
Garfield Heights	11.94	603.79	41° 24’ 57”	- 81° 38’ 00”	mud line on doorframe	excellent	O&E Canal	right
Garfield Heights	11.94	603.79	41° 24’ 57”	- 81° 38’ 00”	mud line on doorframe	excellent	O&E Canal	right
Valley View	12.09	604.00	41° 24’ 44”	- 81° 38’ 08”	flood witness observation	fair	Cuyahoga	right
Valley View	12.19	604.08	41° 24’ 39”	- 81° 38’ 04”	mud line on steel frames	good	Cuyahoga	right

Table 2. Elevations, locations, and descriptions of high-water marks for flood of June 22–24, 2006, at selected locations near the Cuyahoga River.—Continued

[Vertical coordinate data is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate data is referenced to the North American Datum of 1983. Approximate quantitative indications of accuracy of high-water-mark ratings: excellent, ± 0.02 foot; good, ± 0.05 foot; fair, ± 0.10 foot; and poor, > 0.10 foot (Lumia and others, 1986)]

Community name	Distance from mouth of Cuyahoga River (miles)	Elevation (feet above NGVD 29)	Latitude	Longitude	High-water-mark description	High-water-mark rating	Nearest water course	Bank of nearest water course
Valley View	12.32	604.65	41° 24’ 33”	- 81° 38’ 00”	mud line on signpost	excellent	Cuyahoga	right
	12.37			Interstate 480				
Independence	12.53	605.16	41° 24’ 23”	- 81° 37’ 55”	mud line on building	good	Cuyahoga	right
Independence	12.54	605.19	41° 24’ 22”	- 81° 37’ 54”	mud line on doorframe	good	Cuyahoga	right
Independence	12.56	605.13	41° 24’ 22”	- 81° 37’ 53”	mud line on sign	good	Cuyahoga	right
Independence	12.60	605.42	41° 24’ 19”	- 81° 37’ 53”	mud line on doorframe	fair	Cuyahoga	right
Independence	12.70	605.21	41° 24’ 14”	- 81° 37’ 54”	drift line on fence	fair	Cuyahoga	right
Valley View	12.76	606.29	41° 24’ 14”	- 81° 37’ 31”	mud line on doorframe	excellent	O&E Canal	right
Valley View	12.78	606.21	41° 24’ 13”	- 81° 37’ 33”	mud line on building	good	O&E Canal	right
Valley View	12.78	606.25	41° 24’ 13”	- 81° 37’ 33”	mud line on building	excellent	O&E Canal	right
Valley View	12.87	606.10	41° 24’ 08”	- 81° 37’ 33”	mud line on doorframe	excellent	O&E Canal	right
Valley View	13.03	605.82	41° 23’ 57”	- 81° 37’ 49”	mud line on fencepost	poor	Cuyahoga	right
Valley View	13.08	605.79	41° 23’ 55”	- 81° 37’ 47”	mud line on fencepost	good	Cuyahoga	right
Valley View	13.13	606.65	41° 23’ 55”	- 81° 37’ 36”	mud line on window	excellent	O&E Canal	right
Valley View	13.13	606.67	41° 23’ 54”	- 81° 37’ 36”	mud line on building	excellent	O&E Canal	right
Valley View	13.19	606.33	41° 23’ 50”	- 81° 37’ 44”	mud line on door	good	Cuyahoga	right
Valley View	13.20	606.73	41° 23’ 51”	- 81° 37’ 35”	mud line on building	excellent	O&E Canal	right
Valley View	13.26	606.68	41° 23’ 46”	- 81° 37’ 43”	mud line on electical box	good	O&E Canal	left
Valley View	13.27	606.36	41° 23’ 45”	- 81° 37’ 40”	mud line on building	good	O&E Canal	right
Independence	13.28	606.88	41° 23’ 44”	- 81° 37’ 48”	mud line on building	excellent	Cuyahoga	left
Independence	13.28	606.86	41° 23’ 51”	- 81° 37’ 55”	mud line on doorframe	excellent	Cuyahoga	left
Valley View	13.29	606.39	41° 23’ 44”	- 81° 37’ 45”	drift line on fence	fair	Cuyahoga	right
Independence	13.30	606.87	41° 23’ 48”	- 81° 38’ 00”	mud line on doorframe	excellent	Cuyahoga	left

Table 2. Elevations, locations, and descriptions of high-water marks for flood of June 22–24, 2006, at selected locations near the Cuyahoga River.—Continued

[Vertical coordinate data is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Horizontal coordinate data is referenced to the North American Datum of 1983. Approximate quantitative indications of accuracy of high-water-mark ratings: excellent, ± 0.02 foot; good, ± 0.05 foot; fair, ± 0.10 foot; and poor, > 0.10 foot (Lumia and others, 1986)]

Community name	Distance from mouth of Cuyahoga River (miles)	Elevation (feet above NGVD 29)	Latitude	Longitude	High-water-mark description	High-water-mark rating	Nearest water course	Bank of nearest water course
Independence	13.30	606.86	41° 23’ 43”	- 81° 37’ 47”	mud line in USGS gage house	excellent	Cuyahoga	left
	13.30	USGS streamflow-gaging station 04208000						
Independence	13.31	606.92	41° 23’ 43”	- 81° 37’ 47”	mud line on building	excellent	Cuyahoga	left
Independence	13.31	606.92	41° 23’ 43”	- 81° 37’ 47”	mud line on building	excellent	Cuyahoga	left
Valley View	13.31	606.75	41° 23’ 43”	- 81° 37’ 40”	mud line on sign	excellent	O&E Canal	left
Valley View	13.32	606.65	41° 23’ 43”	- 81° 37’ 40”	debris line on screening	good	O&E Canal	left
Independence	13.32	606.86	41° 23’ 42”	- 81° 37’ 52”	mud line on building	excellent	Cuyahoga	left
Independence	13.34	607.09	41° 23’ 41”	- 81° 37’ 51”	mud line on windowframe	excellent	Cuyahoga	left
	13.36	Old Rockside Road						
Independence	13.37	607.04	41° 23’ 40”	- 81° 37’ 53”	mud line on doorframe	excellent	Cuyahoga	left
Valley View	13.37	607.16	41° 23’ 40”	- 81° 37’ 44”	mud line on downspout	excellent	Cuyahoga	right
Valley View	13.40	607.17	41° 23’ 38”	- 81° 37’ 44”	mud line on building support	excellent	Cuyahoga	right
	13.41	Rockside Road						
Independence	13.41	607.16	41° 23’ 38”	- 81° 37’ 47”	mud line on bridge pier	good	Cuyahoga	left
Independence	13.44	607.42	41° 23’ 36”	- 81° 37’ 49”	mud line on sign	excellent	Cuyahoga	left
Independence	13.46	607.50	41° 23’ 34”	- 81° 37’ 52”	mud line on building	excellent	Cuyahoga	left
Independence	13.46	607.65	41° 23’ 34”	- 81° 37’ 52”	mud line on building	good	Cuyahoga	left
	14.67	Stone Road						
Valley View	14.84	611.56	41° 23’ 06”	- 81° 36’ 58”	mud line on doorframe	excellent	O&E Canal	right
Valley View	15.33	611.67	41° 22’ 58”	- 81° 36’ 50”	mud line on tree	good	O&E Canal	right
Valley View	15.34	611.67	41° 22’ 59”	- 81° 36’ 50”	mud line on tree	good	O&E Canal	right
Valley View	15.88	613.10	41° 22’ 27”	- 81° 36’ 42”	flood witness observation	fair	O&E Canal	right
	16.01	Hillside Road						
Independence	16.08	614.75	41° 22’ 22”	- 81° 36’ 58”	mud line on tree	poor	Cuyahoga	left
Independence	16.09	614.78	41° 22’ 21”	- 81° 36’ 58”	mud line on tree	poor	Cuyahoga	left
Independence	16.10	615.17	41° 22’ 21”	- 81° 36’ 58”	mud line on signpost	good	Cuyahoga	left

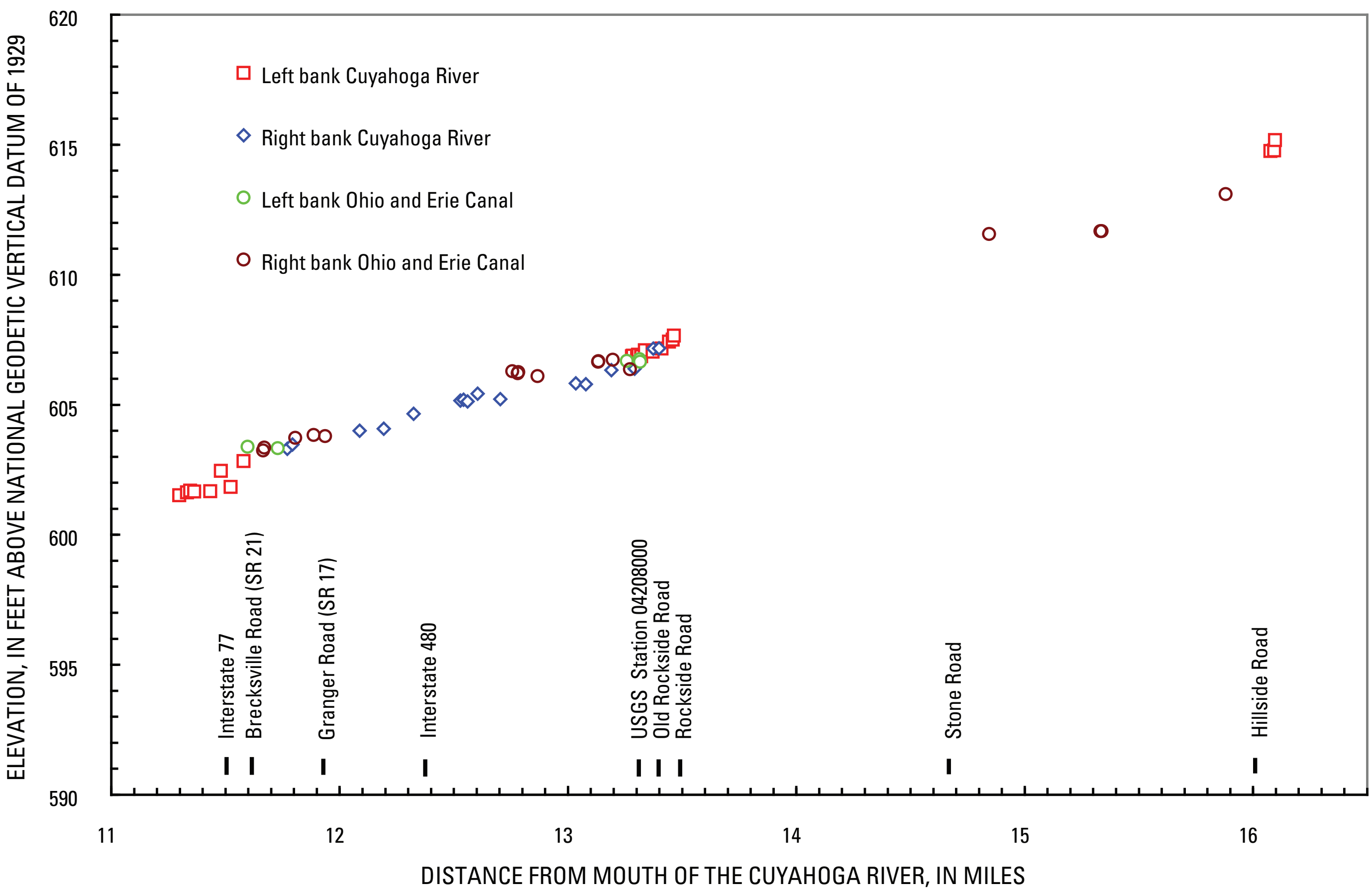

Figure 7. Flood profile showing elevations and distances of high-water marks from the mouth of the Cuyahoga River for the flood of June 22–24, 2006.

total reach length of the Cuyahoga River model is 7,140 feet and the total fall in the reach is 3.29 feet. The total reach length of the Ohio and Erie Canal model is 8,640 feet, and the total fall in the reach is 3.13 feet.

A starting water-surface elevation of 603.57 feet was used for the Cuyahoga River step-backwater computations and was based on fair high-water marks near the most downstream cross section at Granger Road. A starting water-surface elevation of 603.73 feet was used for the Ohio and Erie Canal step-backwater computations and was based on an excellent high-water mark at the most downstream cross section. During the calibration process for both models, an input streamflow value was iteratively adjusted until the computed water-surface profile matched the high-water marks at the gaging station (606.86 feet, rated excellent) and nearly matched selected excellent-rated high-water marks downstream from the gaging station. This procedure resulted in a streamflow of 19,370 cubic feet per second and 5,980 cubic feet per second for the Cuyahoga River and Ohio and Erie Canal models, respectively. Figure 8 shows the flood profile of the selected high-water marks used for the HEC-RAS model calibration and the computed HEC-RAS model water surface for the Cuyahoga River for the flood of June 22–24, 2006.

Flow over the upstream lateral weir (fig. 2) flowing from the Ohio and Erie Canal to the Cuyahoga River was computed as 3,410 cubic feet per second, leaving 2,570 cubic feet per second flowing in the canal between the upstream and downstream weirs. Flow over the downstream lateral weir (fig. 2) flowing from the Ohio and Erie Canal to the Cuyahoga River was computed as 840 cubic feet per second, leaving 1,730 cubic feet per second flowing in the canal below the downstream weir.

The final streamflow value at the Independence gaging station was determined to be 25,400 cubic feet per second, computed as the sum of the flows from the Cuyahoga River and Ohio and Erie Canal step-backwater computations rounded to three significant figures. The peak streamflow of 25,400 cubic feet per second exceeds the prior peak of record of 24,800 cubic feet per second on January 22, 1959, by 600 cubic feet per second. The peak gage height of 23.29 feet exceeds the prior peak of record of 22.41 feet on January 22, 1959, by 0.88 foot.

Flood-Frequency Characteristics of the Cuyahoga River Near Independence, Ohio

Flood-frequency estimates traditionally are determined by means of a log-Pearson Type III (LP-III) analysis, as described by the Interagency Advisory Committee on Water

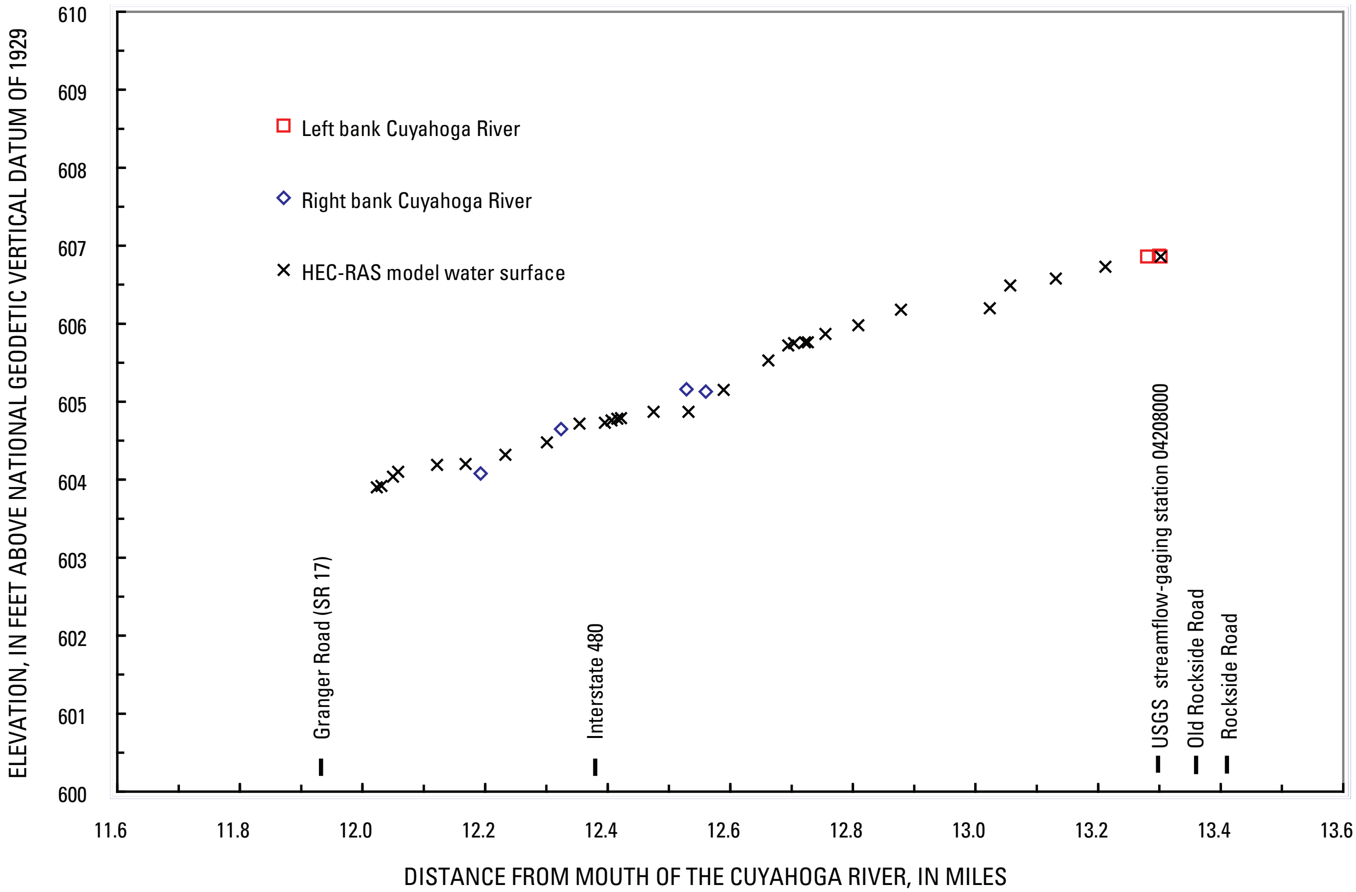

Figure 8. Flood profile of selected high-water marks used for the HEC-RAS model calibration and the computed HEC-RAS model water surface for the flood of June 22–24, 2006.

Data (1982). Some assumptions that are implicit in that analysis are (1) the annual peak streamflows are random and independent, (2) the processes affecting the peak streamflows are stationary with respect to time, and (3) the statistical sampling of annual peak streamflows is homogenous and representative of long-term characteristics.

Examination of the annual peak streamflows from the gaging station on the Cuyahoga River at Independence (station 04208000) indicated a statistically significant upward trend in peak streamflows with time (Kendall's tau = 0.25, p = 0.001), which also is approximately linear with time (fig. 9A). Annual-peak streamflow time series from nearby stations on the Chagrin River (station 04209000), Rocky River (station 04201500), Grand River (station 04212100), and Black River (station 04200500) did not exhibit significant trends. Because the trend in peak streamflows on the Cuyahoga River is temporally persistent and does not appear to be due to cyclical climatic variation (as indicated by the lack of concurrent trend in adjacent basins), the data violate the LP-III assumptions of independence and stationarity. Consequently, annual-peak streamflow time series from the station on the Cuyahoga River at Independence had to be detrended prior to an LP-III analysis.

As of this writing (2007), there is no generally accepted method for detrending an annual-peak streamflow time series. The detrending technique devised for use in this study was based on analysis of stationary time series to which was added a linear trend with time of known magnitude. This detrending technique, described below, was shown to be able to replicate the stationary time series that had been adjusted to reflect the level of trend present during the last year of observation. Consequently, the technique is applicable to time series that increase (or decrease) as a linear function of time, as appears to be the case for the Cuyahoga River at Independence.

The equation for computing the detrended annual-peak streamflows is

$$Q_i = \frac{Q_i'}{1 + r(i)}(1 + r(Y_T - 1)) \qquad (1)$$

where

- Q_i is peak streamflow for year sequence number i, adjusted to current conditions,
- Q_i' is observed trend-effected peak discharge for year sequence number i,
- i is year sequence number (year – first year of observation),
- Y_T is total number of years from the first year of observation to the last year of observation,

and

- r is annual trend rate expressed in decimal form (for example, 0.02 = 2% annual increase).

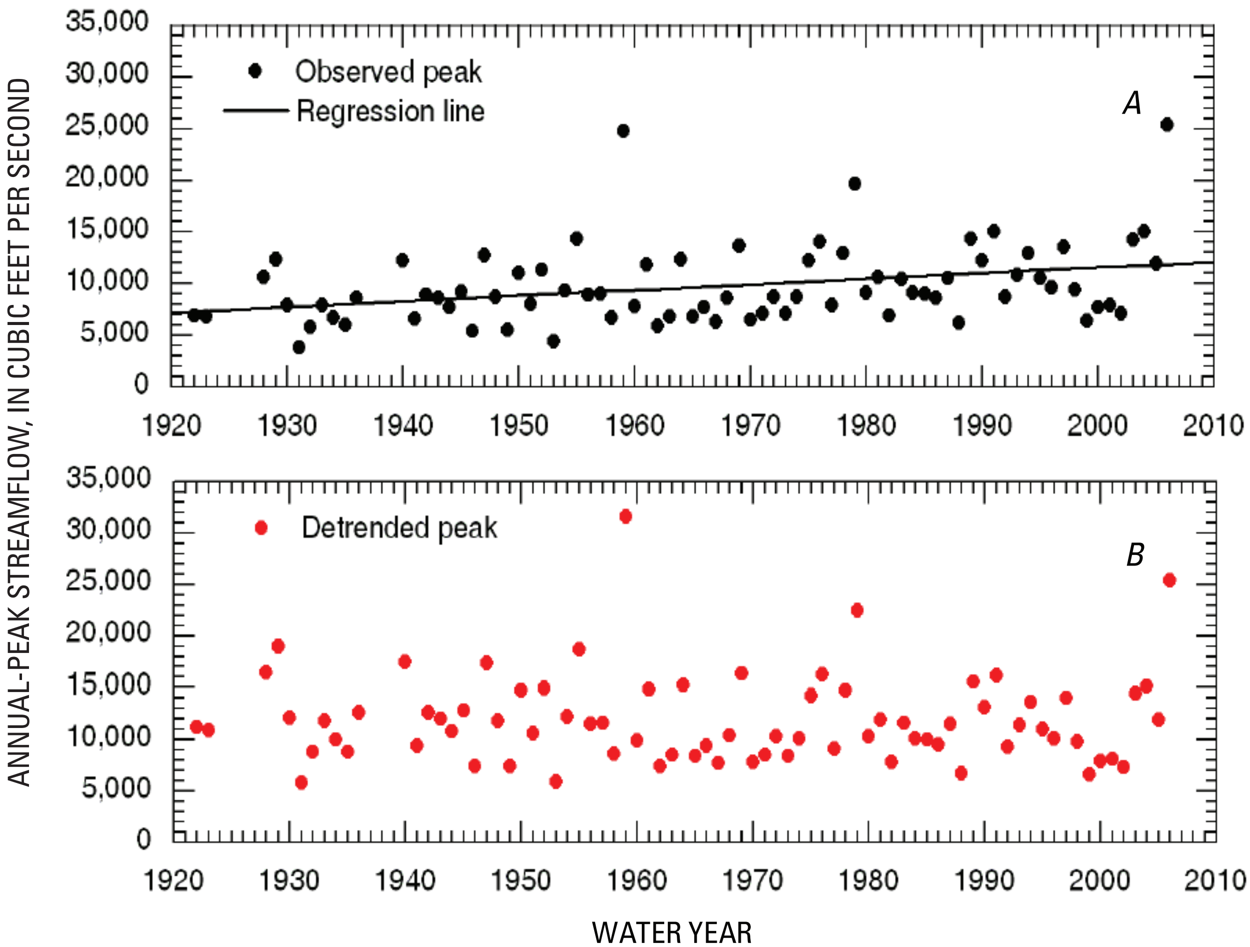

Figure 9. Observed and detrended annual peak streamflows for the Cuyahoga River at Independence, Ohio, plotted as a function of water year.

The annual trend rate for annual-peak streamflows at the Cuyahoga River at Independence was estimated from an ordinary least-squares regression of annual-peak streamflow on year sequence number. The resulting equation was statistically significant ($p = 0.003$), with a slope of 54.31 and an intercept of 7,345.35. The annual trend rate (0.0074 = 0.74% annual increase) was estimated as the ratio of the slope to the intercept.

Equation 1 was applied to the observed annual peak-streamflow time-series data through 2006 from the Cuyahoga River at Independence to compute detrended peaks (fig. 9B), which were subsequently used in an LP-III analysis to compute flood-frequency estimates (table 3). The effect of detrending was to increase the estimated streamflows associated with each recurrence interval compared to the recurrence interval based on the observed (unadjusted) annual peaks. Based on the flood-frequency estimates listed in table 3, the recurrence interval for the June 2006 peak streamflow (25,400 cubic feet per second) at the Cuyahoga River at Independence is slightly less than 100 years.

Table 3. Flood-frequency characteristics of the Cuyahoga River at Independence, as determined from detrended annual-peak streamflow data.

[ft^3/s, cubic feet per second]

Recurrence interval (years)	Exceedance probability	Streamflow (ft^3/s)
2	0.5	11,100
5	.2	14,600
10	.1	17,100
25	.04	20,400
50	.02	22,900
100	.01	25,500
500	.002	31,900

Summary

Heavy rains caused severe flooding on June 22–24, 2006, and damaged approximately 4,580 homes and 48 businesses in Cuyahoga County, Ohio. Damage estimates in Cuyahoga County for the two days of flooding exceed $ 47 million and statewide damages estimates exceed $ 150 million. One death was attributed to the flooding.

The largest accumulations of rainfall in Ohio for the June 21–22, 2006, storms were recorded in Cuyahoga, Summit, Erie, Huron, and Lorain Counties; rainfall totals exceeded 5 inches in many areas. Most other counties in north central Ohio along Lake Erie received more than 3 inches of rainfall during this period. The most severe flooding within Ohio was observed on tributaries to Lake Erie in north central Ohio. Estimated flood-recurrence intervals at selected USGS streamflow-gaging stations in northern Ohio ranged from less than 2 years to 100 years. Peak-gage-height data, peak-streamflow data, and recurrence-interval estimates for the June 22–24, 2006, flood are tabulated for 11 USGS gaging stations in north central Ohio.

Because flooding along the Cuyahoga River near Independence and Valley View was particularly severe, a study was done by the U.S. Geological Survey (USGS), in cooperation with the Federal Emergency Management Agency, to document the gage-height, streamflow, flood-frequency, high-water-mark, and meteorological data associated with the flood. The peak water-surface elevations associated with the flood were documented in a reach extending from approximately 2 miles downstream from the USGS gaging station on the Cuyahoga River at Independence to approximately 2 miles upstream from the USGS gaging station at Independence. High-water marks were identified and flagged in the field, and third-order-accuracy surveys were used to determine elevations of the high-water marks. The elevations of the high-water marks were also used to calibrate the step-backwater model that was used in the indirect calculation of the peak streamflow for the Cuyahoga River at Independence (station 04208000).

The peak streamflow of 25,400 cubic feet per second and the corresponding peak gage height of 23.29 feet occurred on June 23 at about 1:30 a.m. and were the highest recorded at the USGS streamflow-gaging station Cuyahoga River at Independence (04208000) since the gaging station began operation in 1922, exceeding the previous peak streamflow of 24,800 cubic feet per second that occurred on January 22, 1959. The peak streamflow at the gaging station was determined by use of an indirect method (step-backwater computation) because all roads leading to the gaging station were inundated during the flood and field crews could not reach the gaging station to make a direct measurement. Examination of the annual-peak-streamflow time series for the Cuyahoga River at Independence indicated a statistically significant and persistent positive trend. Consequently, a method was developed and applied to detrend the annual-peak-streamflow time series prior to the traditional log-Pearson Type III flood-frequency analysis. Based on this analysis, the recurrence interval of the computed peak streamflow of 25,400 cubic feet per second was estimated to be slightly less than 100 years.

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