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Flood-Inundation Maps for Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek at Ithaca, New York

Scientific Investigations Report 2018–5167

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

Cover. Ithaca Falls on Fall Creek in Ithaca, New York. Photograph by Elizabeth Nystrom, U.S. Geological Survey.

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U.S. Geological Survey
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datum

Vertical coordinate information is referenced to (1) stage, the height above an arbitrary datum established at a streamgage, and (2) elevation, the height above the North American Vertical Datum of 1988 (NAVD 88). Lake water-surface elevations are also 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).

Abbreviations

1D	one-dimensional
2D	two-dimensional
AEP	annual exceedance probability
AHPS	Advanced Hydrologic Prediction Service
DEM	digital elevation model
GIS	geographic information system
GNSS	global navigation satellite system
HEC–RAS	Hydrologic Engineering Center-River Analysis System
lidar	light detection and ranging
NWS	National Weather Service
RTN	real-time network
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Flood-Inundation Maps for Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek at Ithaca, New York

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Abstract

Digital flood-inundation maps for a 2.9-square-mile area of Ithaca, New York, were created in 2015–18 by the U.S. Geological Survey in cooperation with the City of Ithaca, New York, and the New York State Department of State. The flood-inundation maps depict estimates of the maximum areal extent and depth of flooding corresponding to selected flood frequencies for Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek and selected water-surface elevations of Cayuga Lake.

Flood profiles for the stream reaches were computed by combining a one-dimensional step-backwater model for the stream channels and a two-dimensional model for the overbank areas. The resulting hydraulic model was calibrated by using water-surface profiles from five observed storm events. The model was then used to compute 15 water-surface profiles for 5 flood frequencies (50-, 10-, 2-, 1-, and 0.2-percent annual exceedance probabilities, or 2-, 10-, 50-, 100-, and 500-year recurrence intervals) and 3 lake levels (representing average conditions, a 2-year-high condition, and a 100-year-high condition). The simulated water-surface profiles were then combined with a digital elevation model (derived from light detection and ranging data having 0.31-foot vertical accuracy and 3.3-foot horizontal resolution) to delineate the maximum area flooded at each water level.

Flood-inundation maps and geographic information system flood-extent polygons and depth grids are available in the data release associated with this report. These maps can provide emergency management personnel and residents with information that is critical for flood-management planning, flood-response activities, and postflood recovery efforts.

Introduction

The city of Ithaca in the Finger Lakes region of central New York State had, in 2010, a year-round population of about 30,000 (U.S. Census Bureau, 2010); Cornell University and Ithaca College are located in or near the city, and attending students add to the population during the school year. The city of Ithaca is in a long, north-south-oriented valley at the southern end of Cayuga Lake; several streams, including Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek (fig. 1) flow through the city. Ithaca has experienced flooding numerous times, including in July 1935, June 1972, January 1996, and, most recently, June 2015. Flooding in Ithaca has several sources, which sometimes interact with each other, including high-flow events in the streams (for example, resulting from intense summer thunderstorms), ice jams that form in the creeks, and water backing up out of storm sewers in low-lying areas because of high water levels in Cayuga Lake. Interactions between lake levels and streamflow can make it difficult to predict the extent of flooding for any given storm event. In 2015–18, the U.S. Geological Survey (USGS), in cooperation with the City of Ithaca and the New York Department of State, developed a library of flood-inundation maps for Ithaca, New York. These maps can provide emergency management personnel and residents with information that is critical for flood-management planning, flood-response activities, and postflood recovery efforts.

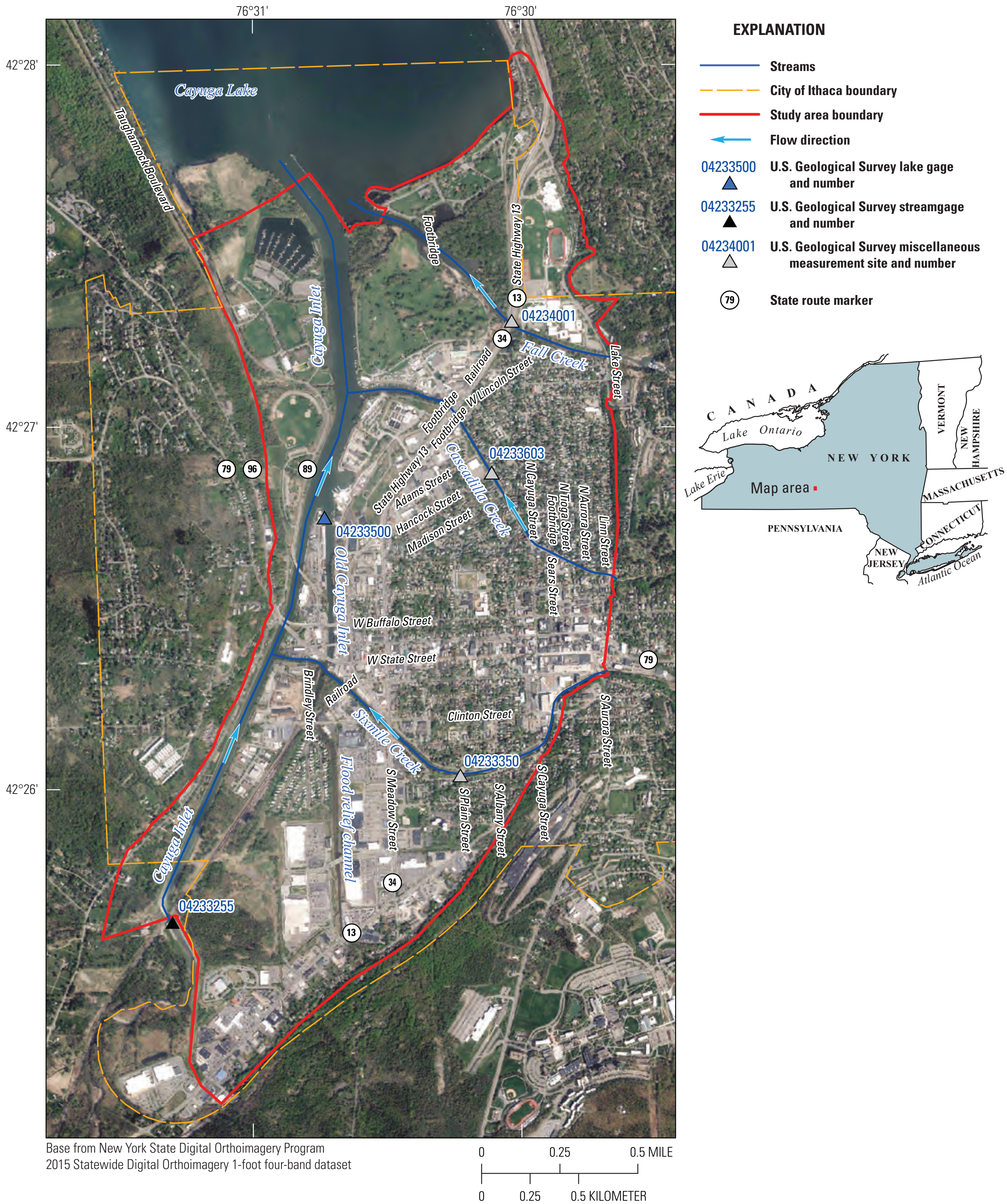

Figure 1. Study area in Ithaca, New York.

Purpose and Scope

This report describes the development of a series of estimated flood-inundation maps for Ithaca, New York, and identifies where on the internet the maps can be found and geographic information system (GIS) flood polygons and depth grids can be downloaded.

The flood-inundation maps show the inundation areas estimated for five annual exceedance probabilities (AEP)—50, 10, 2, 1, and 0.2 percent (table 1)—and three lake levels—380.38, 382.88, and 385.68 feet (ft) (table 2) above the North American Vertical Datum of 1988 (NAVD 88) or 381.00, 383.50, and 386.30 ft above the National Geodetic Vertical Datum of 1929 (NGVD 29). The lake levels were chosen to represent average conditions and 2-year-high and 100-year-high elevations.

Table 1. Estimated peak flows for corresponding annual exceedance probabilities (or recurrence intervals) at upstream end of study reaches used in the hydraulic model of Ithaca, New York.

[Station locations are shown on figures 1 and 2. USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; %, percent; AEP, annual exceedance probability; NY, New York]

USGS station number	Station name	Estimated peak flow (ft^3/s)[1]				
		50% AEP (2-year recurrence interval)	10% AEP (10-year recurrence interval)	2% AEP (50-year recurrence interval)	1% AEP (100-year recurrence interval)	0.2% AEP (500-year recurrence interval)
04233255	Cayuga Inlet at Ithaca, NY	3,300	8,130	14,200	17,300	26,000
04233325	Sixmile Creek at Van Nattas Dam at Ithaca, NY	2,200	4,960	8,240	9,810	14,000
04233602	Cascadilla Creek at East Ithaca, NY	554	1,230	1,990	2,350	3,290
04234000	Fall Creek near Ithaca, NY	3,020	5,720	9,060	10,800	15,700

[1]Peak flow estimates from Wall and others (2014) are through September 2011.

Table 2. Cayuga Lake water-surface elevations used in the hydraulic model of Ithaca, New York.

[ft, foot; NGVD 29, National Geodetic Vertical Datum of 1929; NAVD 88, North American Vertical Datum of 1988]

Lake level condition	Elevation (ft above NGVD 29)	Elevation (ft above NAVD 88)
Average	381.00	380.38
2-year high	383.50	382.88
100-year high	386.30	385.68

Study Area Description

The city of Ithaca is in Tompkins County in the Finger Lakes region of central New York State. Cayuga Lake lies north of the city of Ithaca; the valley that contains Cayuga Lake continues to the south and southwest through and past the city (fig. 2). Cayuga Lake is about 40 miles (mi) long, has a surface area of 66.9 square miles (mi^2), and is regulated at its northern end by a dam and lock on the Cayuga and Seneca Canal (not shown). Lake levels are usually lowest during January and February, when they are typically around 379 ft above NAVD 88, and highest during May, June, and July, when they are typically around 382 ft above NAVD 88 (U.S. Geological Survey, 2018j). The study area covers 2.9 mi^2 in the low-lying areas of the city of Ithaca and the town of Ithaca; much of the study area is flood plain only a few feet above lake level. The valley walls surrounding the study area are steep, and many tributaries are contained in sharply incised gorges, several of which emerge into the valley flats via waterfalls. Much of the valley floor in the city of Ithaca is densely developed with residential and commercial neighborhoods (fig. 3).

Four streams are modeled in the study area: Sixmile Creek and Cascadilla Creek are tributaries to Cayuga Inlet; Fall Creek and Cayuga Inlet are tributaries to Cayuga Lake (fig. 1, table 3). A 2.5-mi reach of Cayuga Inlet is modeled from just downstream of a low-head dam, near where the stream enters the City of Ithaca, to its mouth at Cayuga Lake; the drainage area at the upstream end of the modeled reach is 86.7 mi^2. Sixmile Creek, Cascadilla Creek, and Fall Creek are modeled from close to where they exit their respective gorges to their confluences either with Cayuga Inlet or with Cayuga Lake. A 1.2-mi reach of Sixmile Creek is modeled from just upstream of South Aurora Street to the confluence with old Cayuga Inlet and Cayuga Inlet; the drainage area at the upstream end of the modeled reach is 48.9 mi^2. A 1.1-mi reach of Cascadilla Creek is modeled from just upstream of Linn Street to its confluence with Cayuga Inlet; the drainage area at the upstream end of the modeled reach is 13.1 mi^2. A 0.9-mi reach of Fall Creek is modeled from just upstream of Lake Street to its confluence with Cayuga Lake; the drainage area at the upstream end of the modeled reach is 127 mi^2.

The Cayuga Inlet flood-control channel was built by the U.S. Army Corps of Engineers (USACE) between 1965 and 1970 to convey flood flows through Ithaca and minimize flood damages similar to those that occurred during the inlet's highest period-of-record flood on July 8, 1935 (U.S. Army Corps of Engineers, 2011; New York State Department of Environmental Conservation, 2016). The channel has been infrequently maintained by dredging, and sedimentation has occurred throughout the modeled reach. The modeled reach of Cayuga Inlet is about 160 ft wide upstream of Sixmile Creek, increasing to about 450 ft wide at its confluence with Cayuga Lake; the channel slope computed from the bathymetry used in the HEC–RAS model is extremely low over the modeled reach (averaging 0.0004 ft per ft). The entire modeled reach of Cayuga Inlet is affected by backwater from Cayuga Lake. The banks of Cayuga Inlet are lined with riprap; the channel bottom is largely covered by fine-grained deposits.

Cascadilla Creek is the steepest of the modeled stream reaches, with an average channel slope as computed from the bathymetry used in the HEC–RAS model of 0.0053 ft per ft; Fall Creek and Sixmile Creek are intermediate in slope (average slope of 0.0033 ft per ft and 0.0040 ft per ft, respectively). All three of these stream reaches are much steeper at the upstream ends of their modeled reaches than at their downstream ends—0.0072 ft per ft compared to 0.0036 ft per ft for Sixmile Creek, 0.0160 ft per ft compared to 0.0018 ft per ft for Cascadilla Creek, and 0.0084 ft per ft compared to 0.0012 ft per ft for Fall Creek. Cascadilla Creek is the smallest of the modeled streams (about 25 ft wide at the upstream end of the modeled reach); Sixmile Creek and Fall Creek are somewhat larger (channel widths of about 70 to 100 ft). Substrate in the modeled reaches of these three creeks ranges from large gravel and cobbles in the upstream parts of the creeks to sand and fine muds at the downstream ends of the creeks but is somewhat mixed throughout. The downstream parts of the modeled reaches of all creeks are affected by backwater from Cayuga Lake.

Sixmile Creek and Cascadilla Creek are channelized within the study area, with vertical concrete walls through much of their modeled reaches, and in many locations a slightly elevated berm has been constructed along the channel walls. Because the elevations of the banks along the channels are often higher than the surrounding area, flooding in Ithaca often results from water backing up through storm drains before flows overtop the stream banks.

Table 3. Drainage areas of modeled reaches in Ithaca, New York.

[Blue shading indicates drainage areas corresponding to U.S. Geological Survey (USGS) streamgages (listed with more information in table 4). Yellow shading indicates drainage areas not corresponding to USGS streamgages and calculated with StreamStats (U.S. Geological Survey 2018l), version 4.2.0, on March 29, 2018. mi^2, square mile]

Stream reach	Drainage area at upstream end of modeled reach (mi^2)	Drainage area at downstream end of modeled reach (mi^2)
Cayuga Inlet	86.7	158
Sixmile Creek	48.9	49.3
Cascadilla Creek	13.1	13.7
Fall Creek	127	129

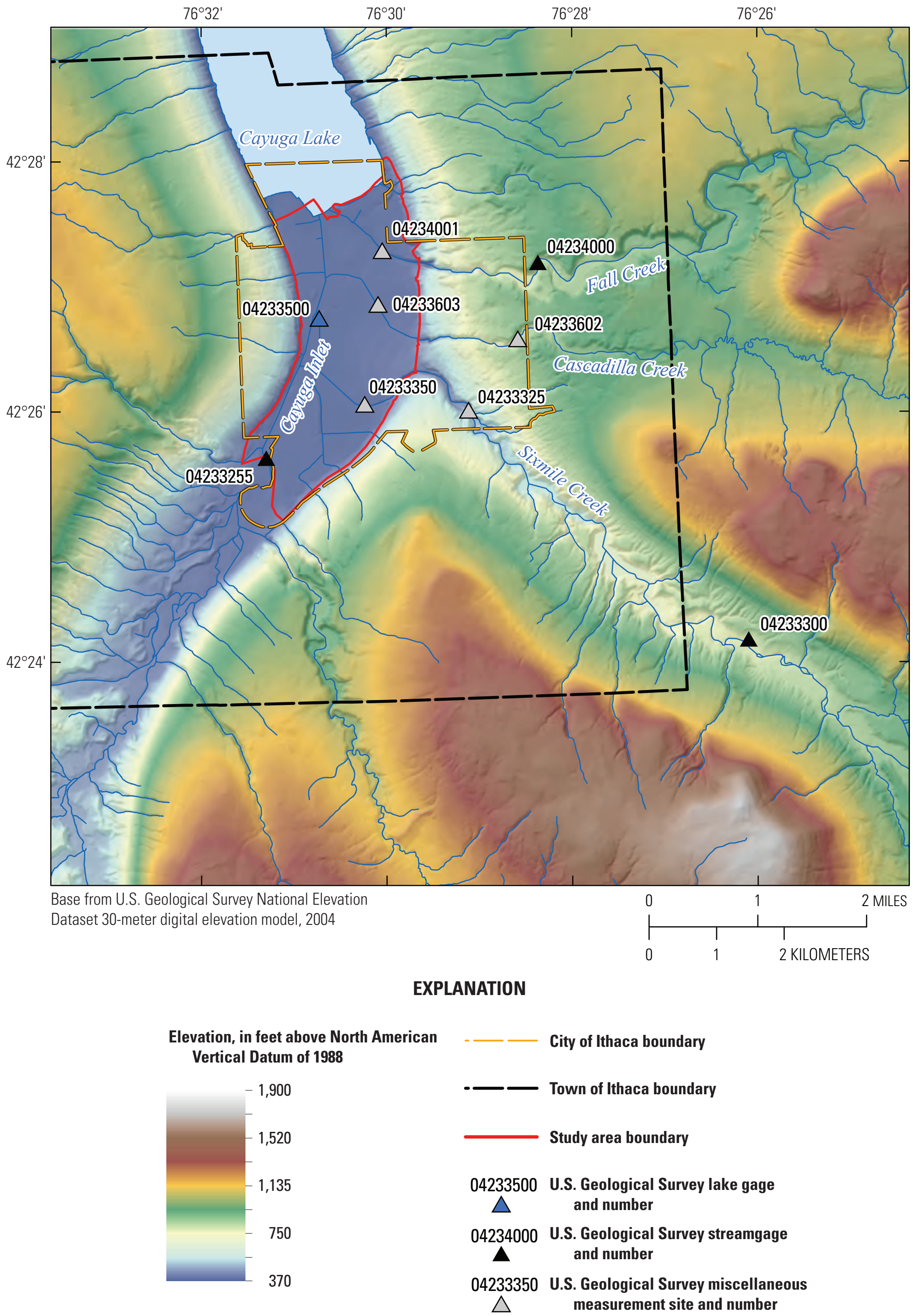

Figure 2. Topography in and around the study area in Ithaca, New York, and locations of nearby U.S. Geological Survey gages.

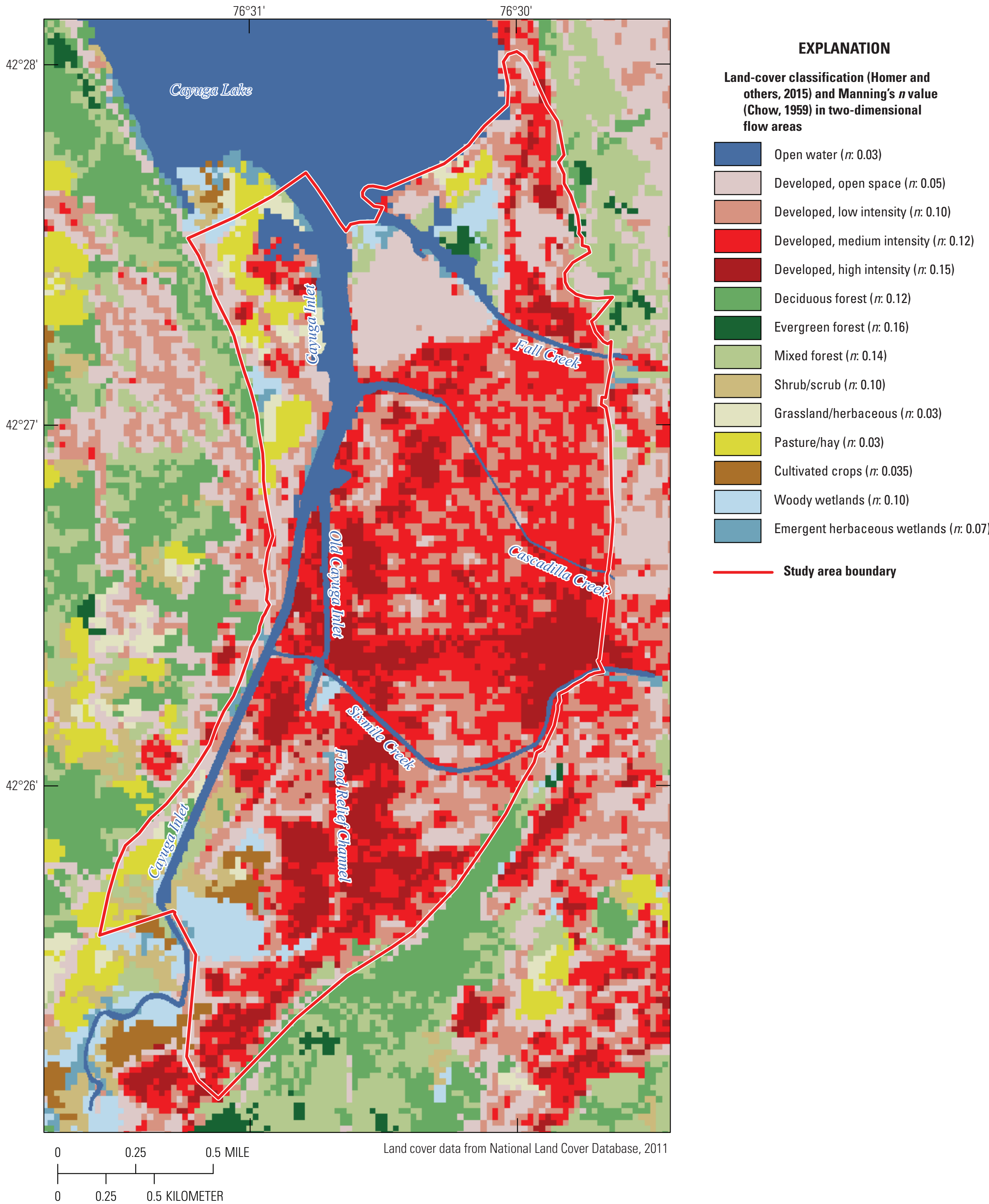

Figure 3. Land cover of the study area in Ithaca, New York.

Several USGS gages are in or near the study area (fig. 2, table 4). Observations of stage at active continuous USGS gages in and near the study area are made every 15 minutes, transmitted hourly by a satellite radio in the gage, and made available online through the USGS National Water Information System (U.S. Geological Survey, 2018k). USGS streamgage 04233255, Cayuga Inlet at Ithaca (U.S. Geological Survey, 2018a), is just upstream of the low-head dam on Cayuga Inlet; elevations from this streamgage could not be used in this study because the modeled reach began downstream of that structure. A lake elevation gage 04233500, Cayuga Inlet (Cayuga Lake) at Ithaca (U.S. Geological Survey, 2018e), is located midway through the study reach on Cayuga Inlet. Miscellaneous measurement site 04233325, Sixmile Creek at Van Nattas Dam at Ithaca (U.S. Geological Survey, 2018c), is 0.7 mi upstream of the study area; the closest active continuous-record streamgage on Sixmile Creek is streamgage 04233300, Sixmile Creek at Bethel Grove (U.S. Geological Survey, 2018b), which is about 4.9 mi upstream of the study area. Miscellaneous measurement site 04233602, Cascadilla Creek at East Ithaca (U.S. Geological Survey, 2018f), is 1.0 mi upstream of the study area; currently (2018) there is no active continuous-record streamgage on Cascadilla Creek. Continuous-record streamgage 04234000, Fall Creek near Ithaca (U.S. Geological Survey, 2018h), is 1.4 mi upstream of the study area.

Three streamflow measurement sites were established within the study area—04233350, Sixmile Creek at Ithaca (U.S. Geological Survey, 2018d); 04233603, Cascadilla Creek at Hancock Street, Ithaca (U.S. Geological Survey, 2018g); and 04234001, Fall Creek at Ithaca (U.S. Geological Survey, 2018i). Streamflow measurements were made at these sites during periods of high flow on April 21, 2017, and October 30, 2017, concurrently with measurements of water-surface elevations.

Three of the gages in or near the study area are included in the National Weather Service's (NWS) Advanced Hydrologic Prediction Service (AHPS) network: 04233500 Cayuga Inlet (Cayuga Lake) at Ithaca (AHPS ICYN6, National Weather Service, 2018a), 04233300 Sixmile Creek at Bethel Grove (AHPS SXMN6, National Weather Service, 2018d), and 04234000 Fall Creek near Ithaca (AHPS FLLN6, National Weather Service, 2018b). Forecasts of stage are issued routinely and throughout the year at Cayuga Lake and Fall Creek and are available from the AHPS website (National Weather Service, 2018c).

All modeled reaches have several bridge crossings (table 5). Cayuga Inlet is crossed by three bridges: State Routes 79 (West State Street), 96 (West Buffalo Street/Cliff Street), and 89 (Taughannock Boulevard), which are all elevated well above the inlet and are not expected to constrict flood flows. Sixmile Creek, Cascadilla Creek, and Fall Creek each are crossed by road bridges, railroad bridges, and pedestrian walkway bridges in their modeled reaches (table 5). Most bridges over the creeks do not have piers, and the tops of their roadways are often level with or slightly above the elevated berms along the creek banks.

Previous Studies

The current flood insurance study for the city of Ithaca, New York (Federal Emergency Management Agency, 1981) was completed by the New York State Department of Environmental Conservation in 1978. The current flood insurance study for the town of Ithaca, New York (Federal Emergency Management Agency, 1984) was completed by Edwards and Kelcey Engineers, Inc., in 1983. The town of Ithaca surrounds the city of Ithaca; most of the study area is in the city of Ithaca, but some lies in the town of Ithaca (fig. 2).

A Hydrologic Engineering Center-River Analysis System (HEC–RAS) model of Sixmile Creek was developed by C.T. Male Associates (2012, 2014) as part of the Emergency Action Plans for Sixmile Creek Dam and Potters Falls Dam. This model includes Sixmile Creek downstream of two impoundments in the town of Ithaca through the city of Ithaca to its confluence with Cayuga Inlet. A HEC–RAS model of Cayuga Inlet was developed by the U.S. Army Corps of Engineers (2011) to investigate the potential reduction in flooding resulting from dredging the channel.

Table 4. U.S. Geological Survey stations near Ithaca, New York.

[Station locations are shown in figures 1 and 2. Station types: C, continuous-record streamgage; M, miscellaneous measurement site; L, continuous-record lake gage. USGS, U.S. Geological Survey; AHPS, National Weather Service Advanced Hydrologic Prediction Service; mi^2, square mile; NAD 83, North American Datum of 1983; ft, foot; NAVD 88, North American Vertical Datum of 1988; ft^3/s, cubic foot per second; NY, New York; --, not applicable; °, degrees; ‘, minutes; “, seconds; NA, not available; NGVD 29, National Geodetic Vertical Datum of 1929]

USGS station number	Station name	Site type	AHPS site identifier	Drainage area (mi^2)	Latitude (NAD 83)	Longitude (NAD 83)	Period of record (water years[1])	Maximum recorded lake elevation (ft, NAVD 88) and date	Maximum streamflow (ft^3/s) and date[2]
04233255	Cayuga Inlet at Ithaca, NY	C	--	86.7	42°25’38”	76°31’18”	1971 to 1972, 1975 to 2005, 2013 to present (2018)	--	12,500, Jan. 19, 1996 (higher estimated streamflow of 17,000 on July 8, 1935)
04233300	Sixmile Creek at Bethel Grove, NY	C	SXMN6	39.0	42°24’11”	76°26’06”	1996 to present (2018)	--	6,200, Jan. 19, 1996
04233325	Sixmile Creek at Van Nattas Dam at Ithaca, NY	M	--	47.8	42°26’00”	76°29’07”	NA	--	8,500, Jun. 21, 1905
04233350	Sixmile Creek at Ithaca, NY	M	--	49.5	42°26’03”	76°30’14”	--	--	NA
04233500	Cayuga Inlet (Cayuga Lake) at Ithaca, NY	L	ICYN6	143	42°26’45”	76°30’44”	1906 to 1909, 1957 to present (2018)	385.84 (386.46 NGVD 29) Apr. 26 1993	--
04233602	Cascadilla Creek at East Ithaca, NY	M	--	12.8	42°26’35”	76°28’35”	NA	--	1,400, July 8, 1935
04233603	Cascadilla Creek at Hancock Street at Ithaca, NY	M	--	13.2	42°26’52.3”	76°30’06.8”	--	--	NA
04234000	Fall Creek near Ithaca, NY	C	FLLN6	126	42°27’12”	76°28’22”	1926 to present (2018)	--	11,900, Oct. 28, 1981 (higher estimated streamflow of 15,500 on July 8, 1935)
04234001	Fall Creek at Ithaca, NY	M	--	127	42°27’17.4”	76°30’02.5”	NA	--	NA

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

[2]Wall and others (2014).

Table 5. Bridges and other structures crossing streams in the study area, Ithaca, New York.

[Structures are listed in order, going downstream. Modeled structures are shown in figure 1. NM, not modeled; MG, modeled in a composite group with other bridges]

Cayuga Inlet	Sixmile Creek	Cascadilla Creek	Fall Creek
State Route 79/West State Street (NM)	South Aurora Street	Linn Street	Lake Street
State Route 96/West Buffalo Street (NM)	Footbridge (NM)	North Aurora Street	North Cayuga Street
State Route 89/Taughannock Boulevard (NM)	East Clinton Street	North Tioga Street	North Meadow Street/State Route 13/State Route 34 (MG)
	South Cayuga Street	Footbridge at Sears Street	Railroad (MG)
	South Albany Street	North Cayuga Street	Footbridge
	South Plain Street	Madison Street	
	South Meadow Street/State Route 13/State Route 96/State Route 34 (MG)	Hancock Street	
	Pipe crossing (MG)	Footbridge at Adams Street	
	Railroad	Footbridge at West Lincoln Street (MG)	
	Pipe crossing (NM)	Pipe crossing (MG)	
	Brindley Street (NM)	North Meadow Street/State Route 13/State Route 34 (MG)	
		Railroad (MG)	
		Waterfront Trail footbridge (MG)	

Creation of Flood-Inundation-Map Library

Tasks specific to the development of the flood maps for Ithaca, New York, were (1) acquisition of the hydraulic models that were used for the Sixmile Creek Dam assessments (C.T. Male Associates, 2012, 2014) and the Cayuga Inlet dredging study (U.S. Army Corps of Engineers, 2011), (2) obtaining hydrologic data, including peak flows, flow time series, and lake levels, (3) collection of topographic and bathymetric data for selected cross sections and geometric data for structures and bridges along the study reach, (4) estimation of energy-loss factors (roughness coefficients) in the stream channel and flood plain and determination of steady-flow data, (5) computation of water-surface profiles and production of estimated flood-inundation maps using the USACE HEC–RAS computer program (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2016), and (6) preparation of the maps using GIS data as shapefile polygons that depict the areal extent of flood inundation and as depth grids that provide the depth of floodwaters.

Computation of Water-Surface Profiles

The water-surface profiles used to produce the 15 flood-inundation maps in this study were computed by using HEC–RAS, version 5.0.3 (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2016). HEC–RAS is a one- and two-dimensional (1D and 2D) hydraulic model with options for computing flow under steady-state (gradually varied) and unsteady-state conditions. The hydraulic model for Ithaca was constructed by using 1D and 2D components under unsteady-state flow conditions.

Hydrologic Data

Flood-inundation maps were produced for five AEPs (50, 10, 2, 1, and 0.2 percent, or 2-, 10-, 50-, 100-, and 500-year recurrence intervals) and three lake levels (380.38, 382.88, and 385.68 ft above NAVD 88). The peak flows used in the model simulations (table 1) were obtained from weighted log-Pearson type III regression values published in Wall and others (2014) for streamgages near the study area (fig. 2, table 4). Peak flow information for Cayuga Inlet was obtained from the USGS streamgage 04233255, Cayuga Inlet at Ithaca; flow information from this streamgage was used as input to the model, but observations of stage were not because the streamgage is upstream of a low-head dam and is not in the modeled reach. Peak flow information for Sixmile Creek was derived from observations at miscellaneous measurement site 04233325, Sixmile Creek at Van Nattas Dam at Ithaca. Peak flow information for Cascadilla Creek was derived from observations at miscellaneous measurement site 04233602, Cascadilla Creek at East Ithaca. Peak flow information for Fall Creek was derived from the continuous-record streamgage 04234000, Fall Creek near Ithaca. No major tributaries join the modeled reaches within the 2.9-mi^2 study area; therefore, the streamgage-derived discharges were not adjusted for tributary inflows within the study reaches for a given profile.

Because the unsteady-flow option was used in the HEC–RAS model (see section “Hydraulic Model”), time series of flow were required as input to the model for each modeled reach and flow scenario; these time series were generated on the basis of an observed storm event. The observed storm event occurred from October 29 to November 1, 2017; time series of observed flows were available at streamgages 04233255 Cayuga Inlet at Ithaca, 04233300 Sixmile Creek at Bethel Grove, and 04234000 Fall Creek near Ithaca (fig. 4*A*, streamgage information in table 4). The observed time series from the storm event were smoothed with a moving average of 1 hour and 15 minutes (or five observations) to remove noise and were normalized, with the minimum observed flow for each station assigned a value of 0 and the peak observed flow assigned a value of 1 (fig. 4*B*); to create model input time series, the normalized time series were multiplied by the peak flows for each modeled reach (fig. 4*C*, table 1). Because there are no continuous-record streamgages on Cascadilla Creek, the model input time series for Cascadilla Creek was created by using the time series of flow observed at Sixmile Creek, adjusted for drainage area and time-shifted forward by 2 hours on the basis of field observations of the timing of peak flow.

The lake levels used in the model (table 2) were chosen to represent an average lake elevation and 2-year-high and 100-year-high elevations based on observed values at the lake gage 04233500, Cayuga Inlet (Cayuga Lake) at Ithaca (U.S. Geological Survey, 2018j). The datum of the lake gage is NGVD 29; this study references all elevations to NAVD 88. Elevations referenced to NGVD 29 can be converted to NAVD 88 using a datum shift value, which varies slightly over space. These values can be obtained from VERTCON (National Geodetic Survey, 2018) for locations in the United States. Datum shift values obtained from VERTCON in the Ithaca area vary by a few hundredths of a foot depending on the specific point location referenced; this study used a datum shift value of −0.62 ft throughout. Lake levels were input into the hydraulic model as a time series of constant values.

Topographic and Bathymetric Data

All topographic data used in this study are referenced vertically to NAVD 88 and horizontally to the North American Datum of 1983 (NAD 83). Cross-section elevation data were obtained from a digital elevation model (DEM) that was derived from lidar data collected during May 2008 by Pictometry International Corp. (Rochester, N.Y.). Postprocessing of these data was completed in 2009

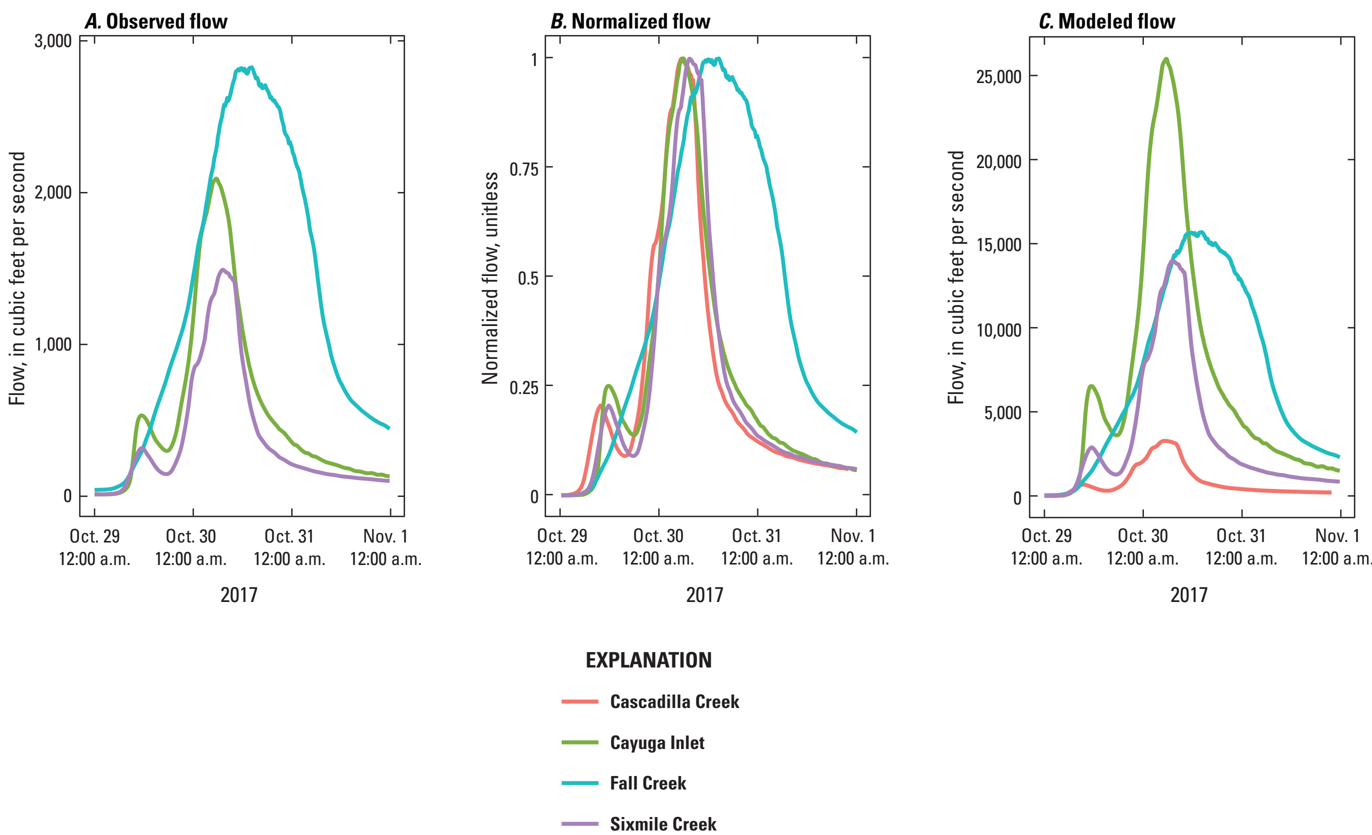

Figure 4. Unsteady-flow time series used in the hydraulic model for Ithaca, New York. *A*, Observed flow. *B*, Normalized flow. *C*, Modeled flow.

(Pictometry International Corp., 2009). The lidar data have a horizontal resolution of 3.3 ft (1 meter) and an overall vertical accuracy of 0.31 ft (Institute for the Application of Geospatial Technology, 2009). By these criteria, the lidar data support production of 2-ft contours (Dewberry, 2012). Elevation data were extracted from the DEM for the hydraulic model in HEC–RAS.

Because the lidar data did not provide ground elevations below a stream's water surface, bathymetric data were measured or obtained by several means. The bathymetry of Cayuga Inlet was surveyed by USGS field personnel during 2016 (Wernly and Nystrom, 2016; Wernly and others, 2017). Cross-sectional depths were measured by using hydroacoustic instrumentation—a SonTek RiverSurveyor M9 with a 0.5-megahertz vertical beam, and two sets of four-beam Janus configuration slant beams, one at 1.0 and one at 3.0 megahertz (SonTek, 2018). Depth data were collected from a manned boat in Cayuga Inlet and in the navigable parts of Sixmile Creek, Cascadilla Creek, and Fall Creek. A global navigation satellite system (GNSS) with real-time network (RTN) technology was used to derive horizontal locations; channel bottom elevations were determined from measured equipment offsets and by using observed lake elevations recorded at the lake gage 04233500, Cayuga Inlet (Cayuga Lake) at Ithaca, during the times of the bathymetric survey. Depth and elevation information measured at 25,562 points were combined in a GIS to create a triangulated irregular network and raster of the bathymetry. Bathymetry for the nonnavigable upstream part of Sixmile Creek was obtained from an existing HEC–RAS model (C.T. Male Associates, 2012, 2014). Bathymetry for the upstream parts of Cascadilla and Fall Creeks was obtained from field measurements of the channel by USGS personnel using differential level surveys tied to reference points established with RTN GNSS; Cascadilla Creek was surveyed in December 2015, and Fall Creek was surveyed in February 2016. Additional depth points in the downstream reaches of Fall Creek were collected by wading and by kayak in April 2016. The bathymetric data from all of the sources were combined in a GIS to create a raster grid, which was merged in HEC–RAS Mapper into the DEM derived from lidar data to create a terrain model for use throughout the hydraulic model, which is included in the data release associated with this publication (Nystrom and others, 2018).

Hydraulic Structures

Many structures, including 20 road crossings, 3 railroad crossings, and 5 footbridge crossings (table 5) have the potential to affect water-surface elevations during floods in the study area. Bridge-geometry data for Cascadilla Creek and Fall Creek were obtained from field surveys conducted by USGS personnel in December 2015 (Cascadilla Creek) and February 2016 (Fall Creek); bridge-geometry data for Sixmile Creek were obtained from an existing HEC–RAS model (C.T. Male Associates, 2012, 2014). Most bridges in the study area are single-span structures without piers. Some bridges in the study area are close together and were therefore represented in the model as a single bridge because there was not enough space between them to include the necessary cross sections—for example, in one location, Cascadilla Creek flows through two pedestrian footbridges, a pipe crossing, a highway crossing, and a railroad crossing within about 210 ft. The three road bridges on Cayuga Inlet were not included in the hydraulic model because they remain well above flood elevation; they have one or two piers each, but the piers do not appreciably obstruct flow in the channel.

Energy-Loss Factors

Hydraulic analyses require the estimation of energy losses that result from frictional resistance exerted by a channel on flow. These energy losses are quantified by the Manning's roughness coefficient (*n* value). Initial (precalibration) channel *n* values were selected on the basis of field observations and high-resolution aerial photographs. Flood plain *n* values were set by using mapped land cover from the National Land Cover Database (NLCD) (fig. 3; Homer and others, 2015) and published tables of *n* values (Chow, 1959).

The HEC–RAS model was calibrated to observed water-surface elevations along Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek. As part of the calibration process, the initial channel *n* values were adjusted until the differences between simulated and observed water-surface elevations were minimized. The final *n* values were 0.014 to 0.030 in the channel of Cayuga Inlet, 0.020 to 0.026 in the channel of Sixmile Creek, 0.018 to 0.043 in the channel of Cascadilla Creek, and 0.018 to 0.030 in the channel of Fall Creek; *n* values in the 2D overbank areas were from 0.030 to 0.160.

Hydraulic Model

The study area is hydraulically complex, with largely 1D flow in the channels but 2D flow in the flood plain; at high flows, water from adjacent streams interacts in the flood plain in the downstream parts of each modeled reach. Some features of the study area, including the channel reaches and their bridge crossings, are therefore best suited to the 1D simulation by HEC–RAS, whereas others, for example the flood plain near where flood flows from two adjacent streams come together, are best represented by the 2D part of HEC–RAS. Additionally, if all study reaches were included in a single 1D model, at high flows, flood elevations would be mismatched along the boundaries between reaches. Therefore, it was determined that the best approach for the study area was to use a combined 1D/2D model, with channels modeled as 1D and overbank areas between streams modeled as 2D (fig. 5); the 1D and 2D parts of the model were then connected in HEC RAS by lateral structures.

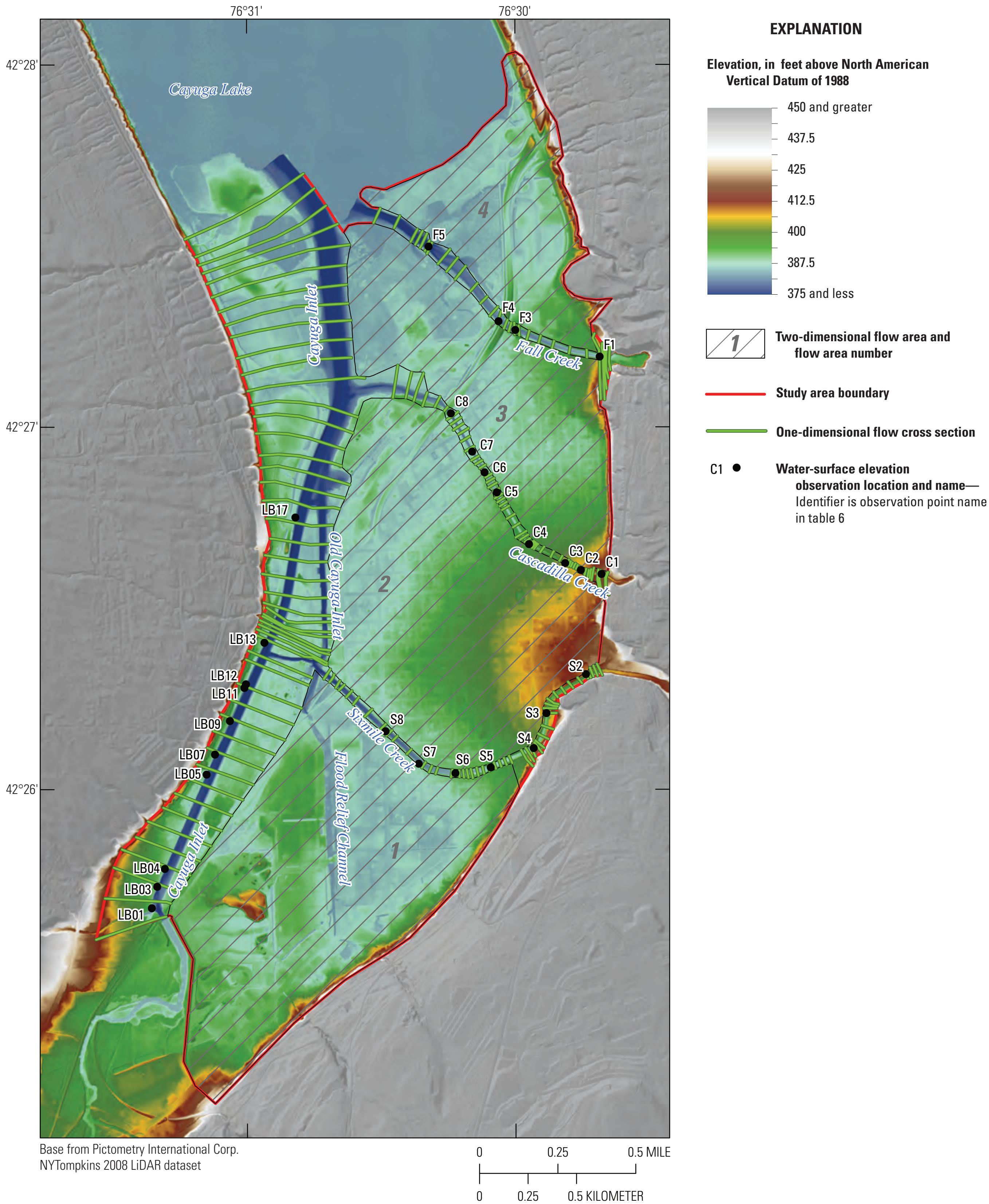

Figure 5. Topography and hydraulic model geometry for the study area in Ithaca, New York.

The 2D part of the HEC–RAS model (fig. 5) consists of four 2D flow areas in the flood plain bounded by (1) Cayuga Inlet and Sixmile Creek; (2) Sixmile Creek, Cayuga Inlet, and Cascadilla Creek; (3) Cascadilla Creek, Cayuga Inlet, and Fall Creek; and (4) Fall Creek, Cayuga Inlet, and Cayuga Lake. The 2D part of the model generally uses 100-ft cell sizes, with breaklines added along linear features. The 1D part of the HEC–RAS model consists of the stream channels, bridges, and some overbank areas near the channels. In Cayuga Inlet, the 1D cross sections extend across the entire left (western) bank of the study area; on the right bank, they extend to the boundaries of the 2D flow areas. On Sixmile Creek, Cascadilla Creek, and Fall Creek, the 1D cross sections extend only across the channels to high ground close to the banks of the stream. Cross-section spacing is typically about 300 ft on Cayuga Inlet (49 cross sections), 130 ft on Sixmile Creek (44 cross sections), 95 ft on Cascadilla Creek (49 cross sections), and 190 ft on Fall Creek (26 cross sections).

Because only unsteady flow can be simulated by the 2D part of HEC–RAS, the hydraulic model was constructed by using the unsteady-flow option in HEC–RAS. Boundary conditions for the unsteady-flow data consisted of flow hydrographs for the upstream ends of the modeled reaches and constant stage hydrographs for the convergence of streams with Cayuga Lake at their downstream ends. The peak flows, lake levels, and flow hydrographs that were used in the model were described previously in the section "Hydrologic Data" and are shown in tables 1 and 2 and figure 4. Input time series of flows and lake levels were 15-minute time series of points, which were interpolated by HEC–RAS. The model was run at 2- to 5-second computational time steps, with a 5-minute output time step.

The HEC–RAS model was calibrated to observed water-surface elevations along each modeled reach. High-water marks on Cayuga Inlet were surveyed by using RTN GNSS following the storm of June 14, 2015, which was a larger event than the 10 percent AEP (10-year recurrence interval) event. Water-level observation locations were established on Sixmile Creek, Cascadilla Creek, and Fall Creek in late 2015, and reference marks were surveyed by using RTN GNSS; water-surface elevations were observed during four events: on February 25, 2016, April 7, 2017, April 21, 2017, and October 30, 2017. Because of the limited ranges of flow on these streams during the study period, all of these events had less flow than the lowest simulated AEP flow of 50 percent (or 2-year recurrence interval). Streamflow measurements were made within the study reaches during the April 21, 2017, and October 30, 2017, events at Sixmile Creek at Ithaca (station 04233350), Cascadilla Creek at Hancock Street in Ithaca (station 04233603), and Fall Creek at Ithaca (station 04234001). The model was calibrated by adjusting Manning's *n* values until the results of the hydraulic computations closely agreed with the observed water-surface elevations for given flows (figs. 6 to 9, table 6). Differences between observed and simulated elevations of high-water marks in the study reaches had a range of −0.45 to 0.63 ft, with a median value of 0.13 ft and a median absolute value of 0.13 ft, for Cayuga Inlet; a range of −0.50 to 1.83 ft, with a median value of 0.10 and a median absolute value of 0.26 ft, for Sixmile Creek; a range of −0.43 to 0.58 ft, with a median value of 0.17 ft and a median absolute value of 0.26 ft, for Cascadilla Creek; and a range of −0.20 to 0.54 ft, with a median value of 0.25 ft and a median absolute value of 0.25 ft, for Fall Creek. The calibrated hydraulic model (Nystrom and others, 2018) was used to generate water-surface profiles for five peak flows (table 1) and three lake levels (table 2) for a total of 15 mapped scenarios.

Table 6. Calibration of model to water-surface elevations at selected locations in Ithaca, New York, along Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek for the high flows of June 14, 2015, February 25, 2016, April 7, 2017, April 21, 2017, and October 30, 2017.

[Observation point locations are shown on figure 5. NAVD 88, North American Vertical Datum of 1988; --, no observation]

Observation point	June 14, 2015			February 25, 2016			April 7, 2017			April 21, 2017			October 30, 2017		
	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)
	Observed	Simulated		Observed	Simulated		Observed	Simulated		Observed	Simulated		Observed	Simulated	
Cayuga Inlet															
LB01	387.04	387.05	0.01	--	--	--	--	--	--	--	--	--	--	--	--
LB03	386.80	386.35	−0.45	--	--	--	--	--	--	--	--	--	--	--	--
LB04	385.93	385.96	0.03	--	--	--	--	--	--	--	--	--	--	--	--
LB05	384.40	384.59	0.20	--	--	--	--	--	--	--	--	--	--	--	--
LB07	384.46	384.48	0.02	--	--	--	--	--	--	--	--	--	--	--	--
LB09	384.14	384.27	0.13	--	--	--	--	--	--	--	--	--	--	--	--
LB11	383.96	384.06	0.09	--	--	--	--	--	--	--	--	--	--	--	--
LB12	383.46	384.04	0.58	--	--	--	--	--	--	--	--	--	--	--	--
LB13	384.08	383.96	−0.12	--	--	--	--	--	--	--	--	--	--	--	--
LB17	383.09	383.73	0.63	--	--	--	--	--	--	--	--	--	--	--	--
Sixmile Creek															
S2	--	--	--	399.98	400.07	0.09	--	--	--	401.01	400.75	−0.26	401.69	401.69	0.00
S3	--	--	--	393.23	393.31	0.08	393.23	393.49	0.26	394.01	394.19	0.18	394.93	395.36	0.43
S4	--	--	--	391.40	391.60	0.20	391.56	391.73	0.17	392.17	392.28	0.11	393.07	393.17	0.10
S5	--	--	--	388.06	387.59	−0.47	388.14	387.64	−0.50	388.67	388.30	−0.37	389.46	389.20	−0.26
S6	--	--	--	385.23	385.15	−0.08	385.39	385.28	−0.11	385.97	385.85	−0.12	386.83	386.63	−0.20
S7	--	--	--	382.01	382.35	0.34	381.74	383.57	1.83	382.09	383.69	1.60	382.80	384.10	1.30
S8	--	--	--	381.24	380.98	−0.26	382.74	383.48	0.74	383.09	383.43	0.34	382.38	383.35	0.97

Table 6. Calibration of model to water-surface elevations at selected locations in Ithaca, New York, along Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek for the high flows of June 14, 2015, February 25, 2016, April 7, 2017, April 21, 2017, and October 30, 2017.—Continued

[Observation point locations are shown on figure 5. NAVD 88, North American Vertical Datum of 1988; --, no observation]

Observation point	June 14, 2015			February 25, 2016			April 7, 2017			April 21, 2017			October 30, 2017		
	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)	Water-surface elevation (feet above NAVD 88)		Model error (feet)
	Observed	Simulated		Observed	Simulated		Observed	Simulated		Observed	Simulated		Observed	Simulated	
Cascadilla Creek															
C1	--	--	--	405.00	404.77	−0.23	--	--	--	405.44	405.33	−0.11	405.80	405.92	0.12
C2	--	--	--	399.67	399.39	−0.28	--	--	--	400.44	400.02	−0.42	400.47	400.72	0.25
C3	--	--	--	396.97	397.25	0.28	--	--	--	397.58	398.00	0.42	(1)	(1)	(1)
C4	--	--	--	391.25	391.18	−0.07	--	--	--	392.19	391.76	−0.43	392.43	392.33	−0.10
C5	--	--	--	385.19	385.52	0.33	--	--	--	385.87	386.14	0.27	386.23	386.81	0.58
C6	--	--	--	383.39	383.27	−0.12	--	--	--	384.16	384.16	0.00	384.41	384.67	0.26
C7	--	--	--	382.07	382.04	−0.03	--	--	--	383.08	383.25	0.17	383.26	383.47	0.21
C8	--	--	--	381.06	381.41	0.35	--	--	--	382.76	383.06	0.30	382.44	382.92	0.48
Fall Creek															
F1	--	--	--	389.20	389.31	0.11	389.28	389.31	0.03	389.63	390.10	0.47	390.05	390.00	−0.05
F3	--	--	--	384.18	384.61	0.43	384.63	384.66	0.03	384.74	385.28	0.54	384.95	385.20	0.25
F4	--	--	--	--	--	--	383.52	384.02	0.50	384.48	384.49	0.01	384.57	384.37	−0.20
F5	--	--	--	379.70	380.13	0.43	382.79	383.16	0.37	382.79	383.00	0.21	382.10	382.51	0.41

[1]Field observation invalid.

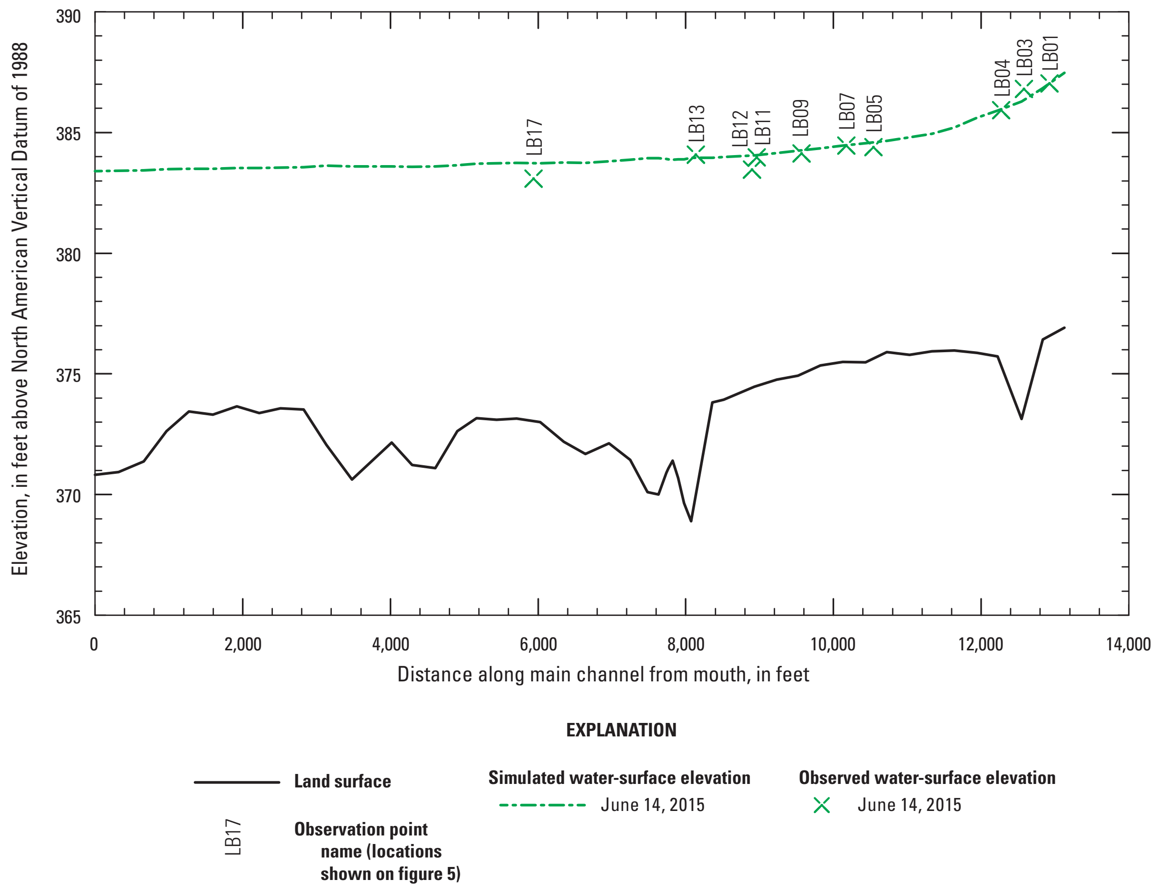

Figure 6. Observed water-surface elevations and simulated water-surface profiles for the flood of June 14, 2015, for Cayuga Inlet at Ithaca, New York. Bridges are not shown because they are elevated above the inlet and are not expected to affect flows.

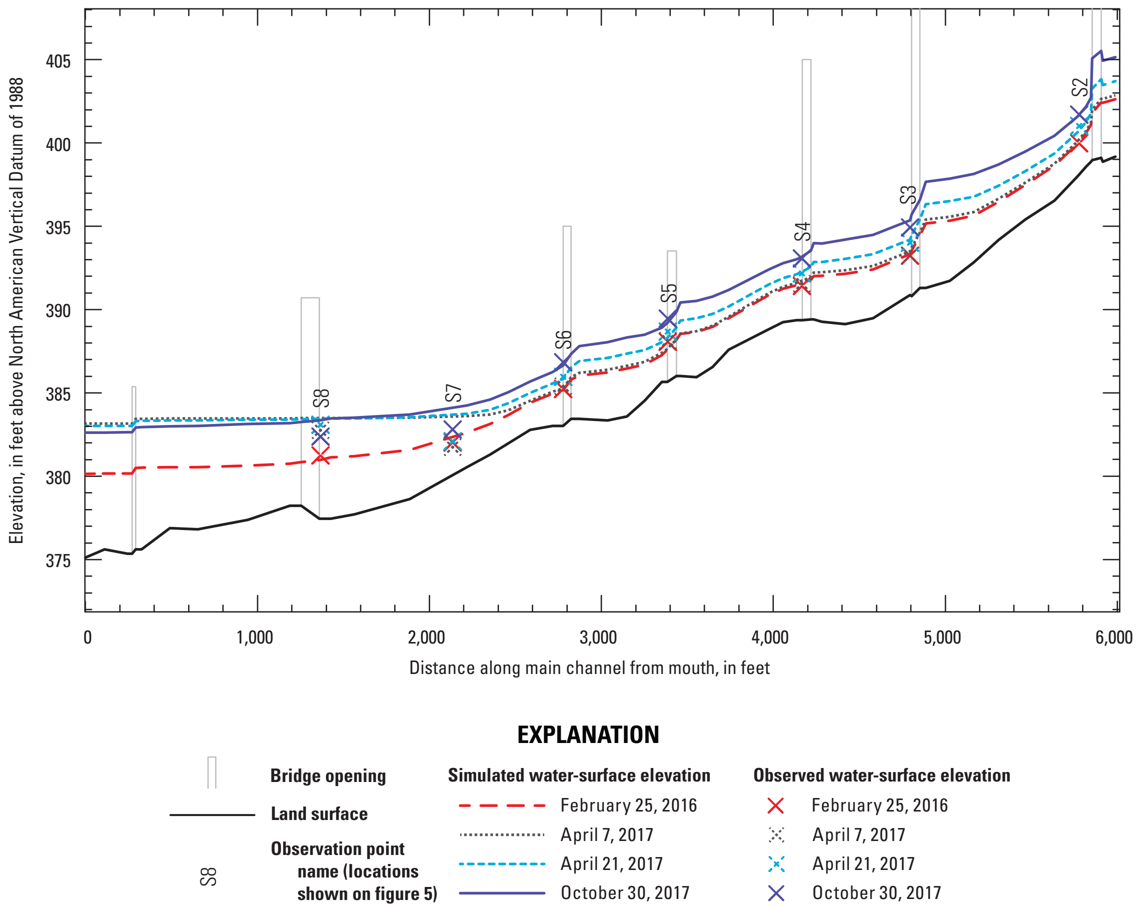

Figure 7. Observed water-surface elevations and simulated water-surface profiles for the floods of February 25, 2016, April 7, 2017, April 21, 2017, and October 30, 2017, for Sixmile Creek at Ithaca, New York.

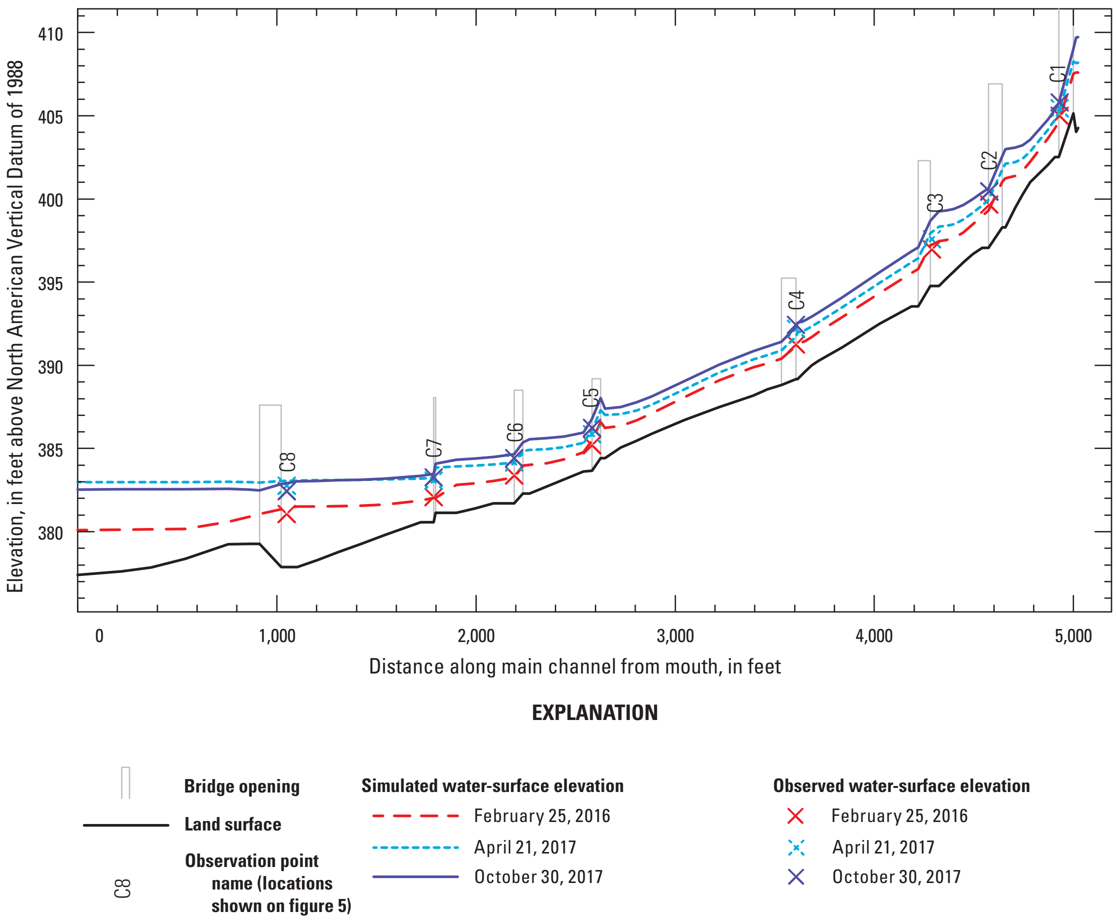

Figure 8. Observed water-surface elevations and simulated water-surface profiles for the floods of February 25, 2016, April 21, 2017, and October 30, 2017, for Cascadilla Creek at Ithaca, New York.

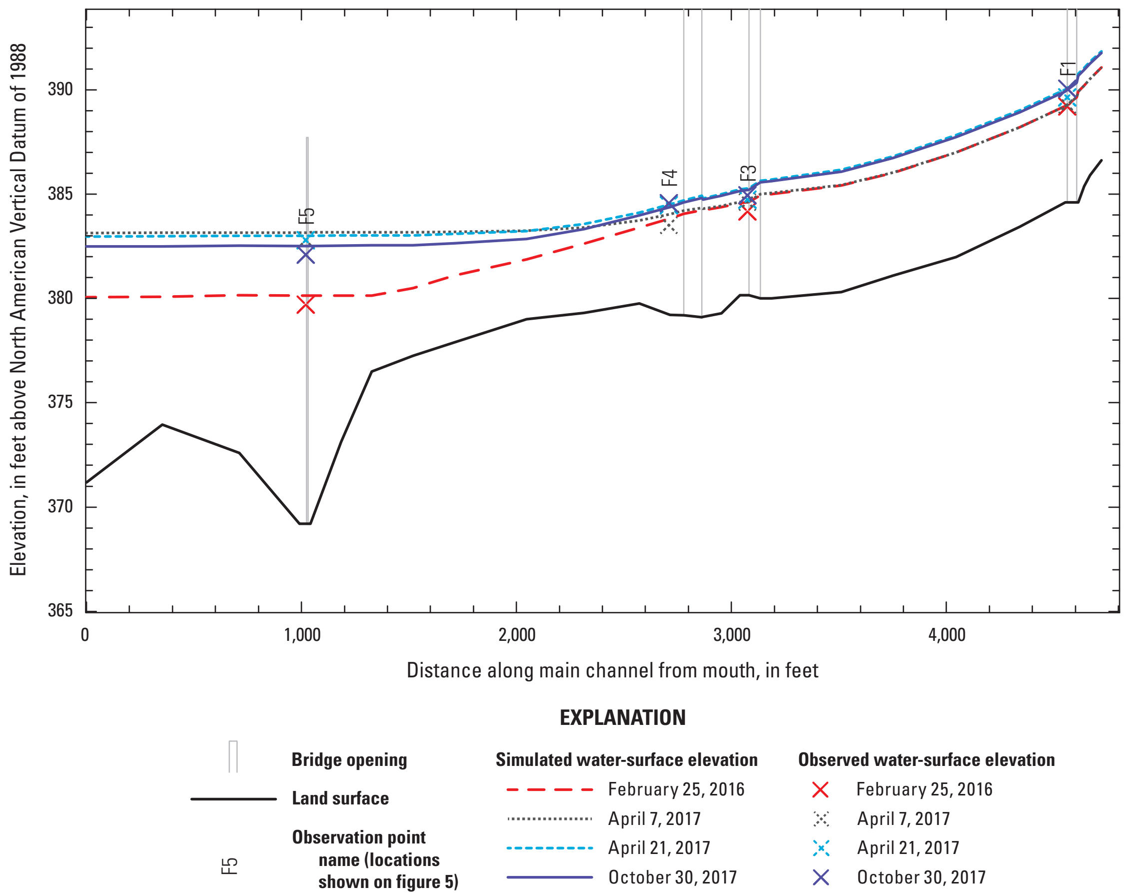

Figure 9. Observed water-surface elevations and simulated water-surface profiles for the floods of February 25, 2016, April 7, 2017, April 21, 2017, and October 30, 2017, for Fall Creek at Ithaca, New York.

Development of Flood-Inundation Maps

Flood-inundation maps were created by using HEC–RAS Mapper (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2016) by combining the simulated water-surface profiles and terrain data. The terrain data were derived as described previously in the section "Topographic and Bathymetric Data." Composite flood maps showing inundation areas for each modeled AEP at the three simulated lake elevations are presented in figures 10 to 14. The inundation maps contain numerous disconnected polygons—that is, areas shown as inundated that are not directly connected to other inundated areas or to the stream channel. These disconnected areas result from the structure of the model and from inundation computations and may not be inundated during an actual flooding event. However, because backwater flooding through storm sewers often occurs in Ithaca, these areas are vulnerable to flooding and have been left in the inundation maps.

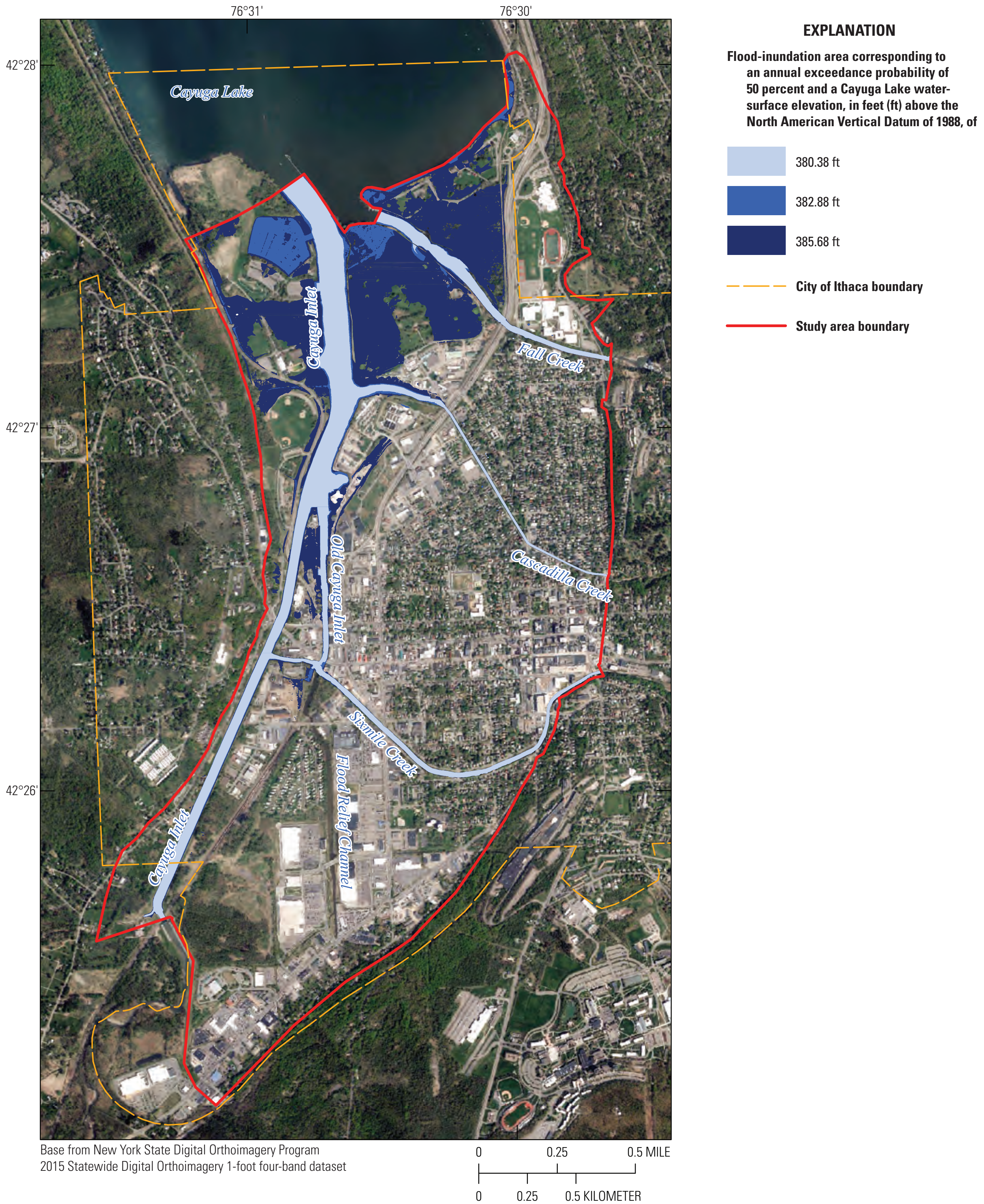

Figure 10. Flood-inundation map for Ithaca, New York, corresponding to an annual exceedance probability of 50 percent (or a 2-year recurrence interval) and to Cayuga Lake water-surface elevations of 380.38 feet (ft), 382.88 ft, and 385.68 ft.

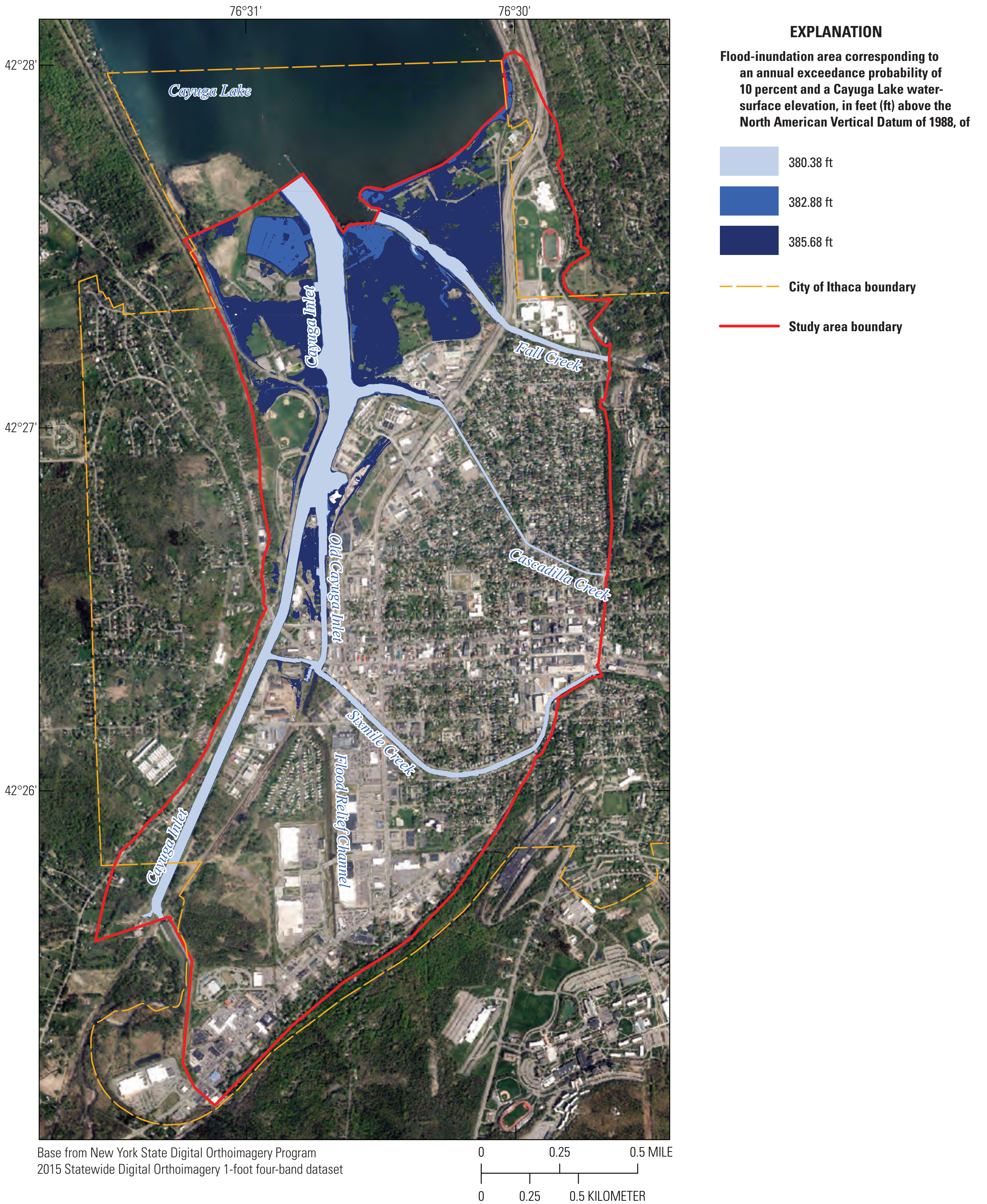

Figure 11. Flood-inundation map for Ithaca, New York, corresponding to an annual exceedance probability of 10 percent (or a 10-year recurrence interval) and to Cayuga Lake water-surface elevations of 380.38 feet (ft), 382.88 ft, and 385.68 ft.

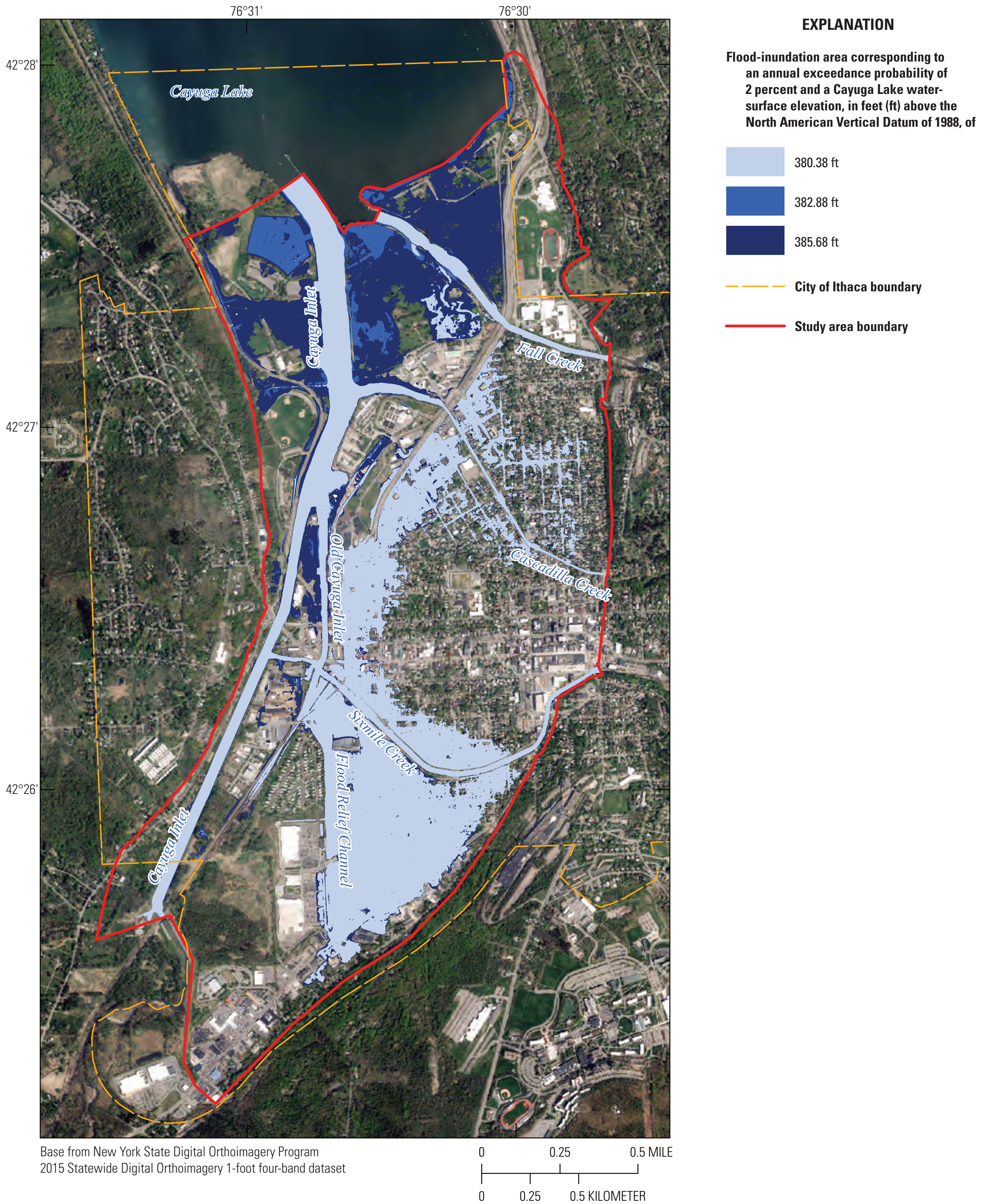

Figure 12. Flood-inundation map for Ithaca, New York, corresponding to an annual exceedance probability of 2 percent (or a 50-year recurrence interval) and to Cayuga Lake water-surface elevations of 380.38 feet (ft), 382.88 ft, and 385.68 ft.

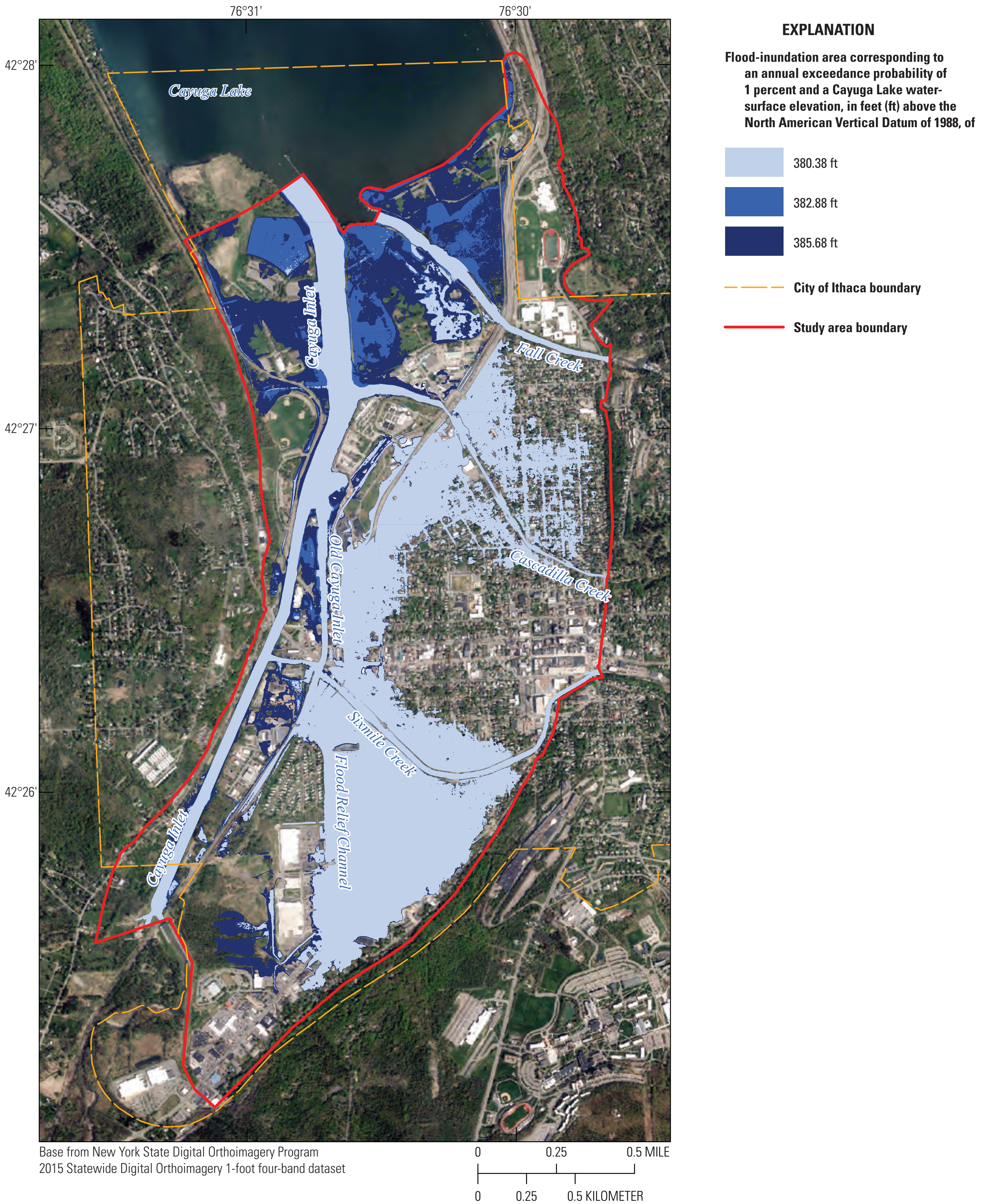

Figure 13. Flood-inundation map for the Ithaca, New York, corresponding to an annual exceedance probability of 1 percent (or a 100-year recurrence interval) and to Cayuga Lake water-surface elevations of 380.38 feet (ft), 382.88 ft, and 385.68 ft.

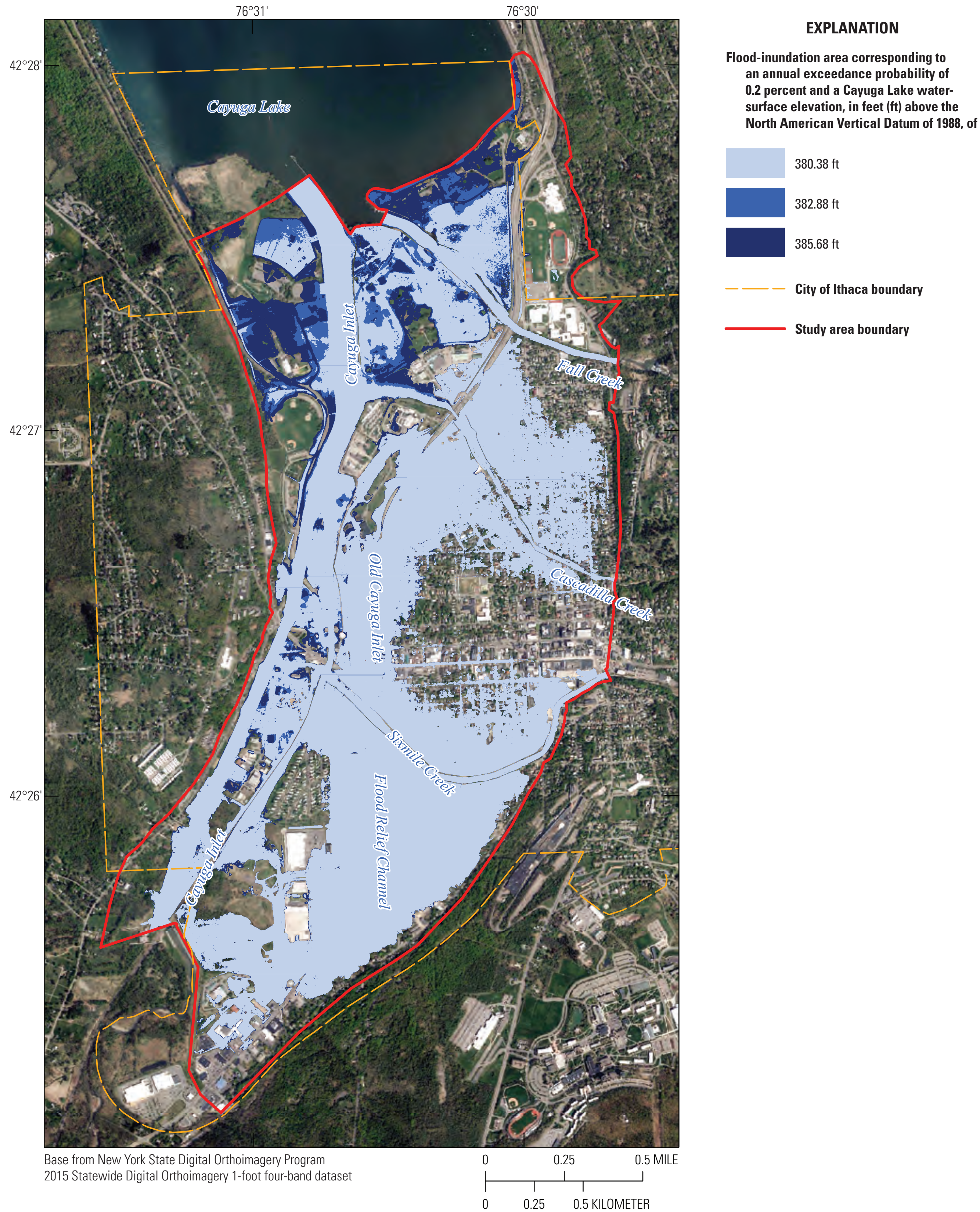

Figure 14. Flood-inundation map for the Ithaca, New York, corresponding to an annual exceedance probability of 0.2 percent (or a 500-year recurrence interval) and to Cayuga Lake water-surface elevations of 380.38 feet (ft), 382.88 ft, and 385.68 ft.

Shapefiles of estimated flood-inundation boundaries, depth grids, and water-surface elevations for each peak flow and lake level were exported from HEC–RAS Mapper and are available for download from the data release associated with this publication at https://doi.org/10.5066/P9V8ED23 (Nystrom and others, 2018). These flood-inundation areas can be overlaid on high-resolution, georeferenced, aerial photographs of the study area in a GIS and can be displayed in sufficient detail so that preparations for flooding and decisions for emergency response can be performed efficiently. Depending on the flood magnitude, roadways are shown as shaded (inundated and likely impassable) or not shaded (dry and passable) to facilitate emergency planning and use. Bridge surfaces are displayed as inundated regardless of the actual water-surface elevation in relation to the lowest structural chord of the bridge or the bridge deck. A building shown as inundated should not be interpreted to mean that the structure is completely submerged but, rather, that bare earth surfaces in the vicinity of the building are inundated. In these instances, the water depth from the raster depth grid near the building is an estimate of the water level inside the structure, unless flood-proofing measures have been implemented.

Disclaimer For Flood-Inundation Maps

The flood-inundation maps should not be used for navigation, regulatory, permitting, or other legal purposes. The USGS provides these maps “as-is” for a quick reference, emergency planning tool but assumes no legal liability or responsibility resulting from the use of this information.

Uncertainties and Limitations Regarding Use of Flood-Inundation Maps

Although the flood-inundation maps represent the boundaries of inundated areas with a distinct line, some uncertainty is associated with these maps. The flood boundaries shown were estimated on the basis of water stages and streamflows at selected USGS streamgages. Water-surface elevations along the stream reaches were estimated by unsteady-state hydraulic modeling, assuming unobstructed flow, and used streamflows and hydrologic conditions anticipated at the USGS streamgages. The hydraulic model reflects the land-cover characteristics and any bridge, dam, levee, or other hydraulic structure existing as of February 2016. Unique meteorological factors (timing and distribution of precipitation) may cause actual streamflows along the modeled reach to vary from those assumed during a flood, which may lead to deviations from the water-surface elevations and inundation boundaries shown. Additional areas may be flooded due to unanticipated conditions such as changes in the streambed elevation or roughness, backwater into major tributaries along a main-stem river, or backwater from localized debris or ice jams. The accuracy of the floodwater extent portrayed on these maps will vary with the accuracy of the digital elevation model used to simulate the land surface.

If this series of flood-inundation maps will be used in conjunction with NWS river forecasts, the user should be aware of additional uncertainties that may be inherent or factored into NWS forecast procedures. The NWS uses forecast models to estimate the quantity and timing of water flowing through selected stream reaches in the United States. These forecast models (1) estimate the amount of runoff generated by precipitation and snowmelt, (2) simulate the movement of floodwater as it proceeds downstream, and (3) predict the flow and stage (and water-surface elevation) for the stream at a given location (AHPS forecast point) throughout the forecast period (every 6 hours and 3 to 5 days out in many locations). For more information on AHPS forecasts, please see https://water.weather.gov/ahps/pcpn_and_river_forecasting.pdf.

Additional uncertainties and limitations pertinent to this study may be present and are described elsewhere in this report.

Summary

A series of 15 digital flood-inundation maps was developed in 2015–18 by the U.S. Geological Survey, in cooperation with the City of Ithaca and the New York State Department of State, for Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek in Ithaca, New York. The maps cover a 2.9-square-mile study area and were developed by using the U.S. Army Corps of Engineers’ Hydrologic Engineering Center-River Analysis System hydraulic model to compute water-surface profiles, to delineate estimated flood-inundation areas, and to compute depths of flooding for selected peak flows and water-surface elevations at Cayuga Lake. Flood profiles for the stream reaches were computed by combining a one-dimensional step-backwater model for the stream channels and a two-dimensional model for the overbank areas. The resulting hydraulic model was calibrated to observed water-surface elevations along Cayuga Inlet, Sixmile Creek, Cascadilla Creek, and Fall Creek during five high-flow events during 2015–17. The model was then used to compute 15 water-surface profiles for 5 flood frequencies (50-, 10-, 2-, 1-, and 0.2-percent annual exceedance probabilities, or 2-, 10-, 50-, 100-, and 500-year recurrence intervals) and 3 lake levels (representing average conditions and 2-year-high and 100-year-high conditions). The simulated water-surface profiles were then combined with a digital terrain model derived from lidar data and measured bathymetric data to delineate estimated flood-inundation areas as shapefile polygons and as grids of water depths for each profile. These data and the calibrated Hydrologic Engineering Center-River Analysis System hydraulic model are available for download in the data release associated with this report. These maps can help guide emergency responders and the general public in flood preparedness planning, response, and recovery efforts.

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