USGS
science for a changing world

Characterization of Peak Streamflows and Flooding in Select Areas of Pennsylvania from the Remnants of Hurricane Ida, September 1–2, 2021

Scientific Investigations Report 2023–5086
Version 1.1, September 2023

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

Characterization of Peak Streamflows and Flooding in Select Areas of Pennsylvania from the Remnants of Hurricane Ida, September 1–2, 2021

By Marla H. Stuckey, Matthew D. Conlon, and Mitchell R. Weaver

Scientific Investigations Report 2023–5086
Version 1.1, September 2023

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

Acknowledgments

Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square mile (mi^2)	259.0	hectare (ha)
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)

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

AEP	annual exceedance probability
DEM	digital elevation model
EMA	expected moments algorithm
FEMA	Federal Emergency Management Agency
GIS	geographic information system
HWM	high-water mark
lidar	light detection and ranging
NWS	National Weather Service
RI	recurrence interval
USGS	U.S. Geological Survey

Characterization of Peak Streamflows and Flooding in Select Areas of Pennsylvania from the Remnants of Hurricane Ida, September 1–2, 2021

By Marla H. Stuckey, Matthew D. Conlon, and Mitchell R. Weaver

Abstract

Pennsylvania experienced heavy rainfall on September 1 and 2, 2021, as the remnants of Hurricane Ida swept over parts of the State. Much of eastern and south-central Pennsylvania received 5 to 10 inches of rain, and most of the rainfall fell within little more than 6 hours. Southeastern Pennsylvania experienced widespread, substantial flooding, and the city of Philadelphia and surrounding areas were particularly affected by the flooding. U.S. Geological Survey (USGS) streamgages registered peak streamflows of record at 19 locations, and 52 locations experienced top 5 peak streamflows for the period of record and an annual exceedance probability estimate of at least 10 percent. During this September 2021 flood event, USGS personnel made over 60 streamflow measurements at streamgages in Pennsylvania using direct and indirect methods. Many of those streamflow measurements were made to verify or improve the accuracy, extent, or development of new stage-streamflow relations at streamgages operated by the USGS. After the floodwaters receded, USGS personnel identified and documented a total of 338 high-water marks in Pennsylvania, noting such things as their general description, location, height above land surface, and quality. Many of these high-water marks were used to create five flood-documentation maps for selected communities in southeastern Pennsylvania that experienced substantial flooding because of the remnants of Hurricane Ida. Digital datasets of the inundated areas, mapped boundaries, and water depth are available (Stuckey and Conlon, 2023).

Introduction

The widespread, intense rainfall resulting from the remnants of Hurricane Ida caused historic flooding in eastern and south-central Pennsylvania on September 1–2, 2021. Much of this region received 5 to 10 inches of rain, and most rain fell in little more than 6 hours. Rain from the remnants of Hurricane Ida exceeded the rainfall characteristics of a 100-year (yr) storm at many locations in Pennsylvania—a 100-yr storm has

a 1-percent chance of occurring in any given year (National Centers for Environmental Information, 2023a). This rainfall caused widespread, substantial flooding, and many streams and rivers experienced major flooding as defined by the National Weather Service (NWS) (National Weather Service, 2019). Some streamgages recorded their highest peaks on record, including two streamgages with over 100 years of record. The State of Pennsylvania declared a disaster emergency for the entire State before the storm, and the Federal Emergency Management Agency (FEMA) announced "Major Disaster Declarations" in eight Pennsylvania counties (Bedford, Bucks, Chester, Delaware, Montgomery, Northampton, Philadelphia, and York) (Federal Emergency Management Agency, 2023).

Flooding came in phases over the 2 days. Hours of torrential rainfall near and just west of the storm center's track led to catastrophic flooding over parts of eastern Pennsylvania. Many smaller creeks overflowed their banks during this initial phase, and roads flooded because of overwhelmed drainage systems. The remnants of Hurricane Ida moved out of the region by the evening of September 1; however, the flooding was just beginning in the slower responding larger drainage area, main-stem rivers, which continued to rise during the second phase of flooding (National Weather Service, 2023b). This second phase led to additional flooding of homes and roads into the following day (September 2), and in some places, flooding continued for several days (fig. 1). Many roads were impassable, including parts of major highways such as the Vine Street Expressway running through downtown Philadelphia.

The U.S. Geological Survey (USGS) collects streamflow data from a network of more than 8,000 streamgages nationwide in cooperation with local, State, and Federal agencies. This network includes more than 350 streamgages currently (2022) operating in Pennsylvania. Streamflow data are critical for efforts to warn the population about flooding, forecast the extent and potential effects of flooding, and optimize the allocation of emergency management resources to the most severely affected areas. Long-term systematic streamflow data are essential for engineers conducting studies to mitigate the effects of flooding by designing or repairing roads, bridges,

reservoirs, pipelines, houses, and other infrastructure. In the aftermath of the flooding caused by the remnants of Hurricane Ida, the USGS and FEMA initiated two cooperative studies to flag, survey, and formally document high-water marks (HWMs) and evaluate the flood's magnitude, extent, and probability of occurrence at select USGS streamgages.

Purpose and Scope

The purpose of this report is to document HWM data, flood-peak magnitudes, and flood-mapping products generated by the USGS in support of the FEMA response and recovery operations after the September 1–2, 2021, flooding of eastern and south-central Pennsylvania caused by the remnants of Hurricane Ida. This report includes (1) a description of the atmospheric conditions during the remnants of Hurricane Ida and the temporal and spatial patterns of rainfall that triggered the flooding, (2) a narrative of the flood and its effects, (3) a description of how the 338 HWMs were documented, (4) an analysis of flood-peak magnitudes and their statistical probabilities at 52 USGS streamgages, and (5) a geographic information system (GIS) analysis of HWM locations and elevations to produce flood-documentation maps (areal extent of the maximum depth of flooding) for 5 heavily flooded areas in southeastern Pennsylvania. Data from this study are in tables and a separate data release (Stuckey and Conlon, 2023). The wording and presentation of the material in this report are based on previous USGS reports (Watson and others, 2017, 2018; Austin and others, 2018); the contents of each section are modified from these previous reports based on the specific flooding event.

Description of Study Area

The study area encompasses eastern and south-central Pennsylvania (fig. 2). Parts of 5 of the 6 physiographic provinces in Pennsylvania were flooded by the remnants of Hurricane Ida: the Appalachia Plateau, the Atlantic Coastal Plain, New England, the Piedmont, and Ridge and Valley (Pennsylvania Department of Conservation and Natural Resources, 2023); the Piedmont experienced most of the flooding across multiple watersheds during the event. The Delaware River Basin flooded, from north to south, in the Appalachian Plateau, Ridge and Valley, New England, Piedmont, and Atlantic Coastal Plain provinces. The northern part of the basin consists of rounded hills and valleys, and flat upper terrace surfaces cut by shallow valleys in the southern part with a mix of rolling lowlands and broad to shallow valleys in between. Land-surface-elevations within the Delaware River Basin range from 0 feet (ft) in the Atlantic Coastal Plain province to 2,690 ft in the Appalachian Plateau province, referenced to the North American Vertical Datum of 1988 (NAVD 88). The Lower Susquehanna and Potomac River Basins flooded in the north and west in the Appalachian Plateau and Ridge and Valley provinces and the south and
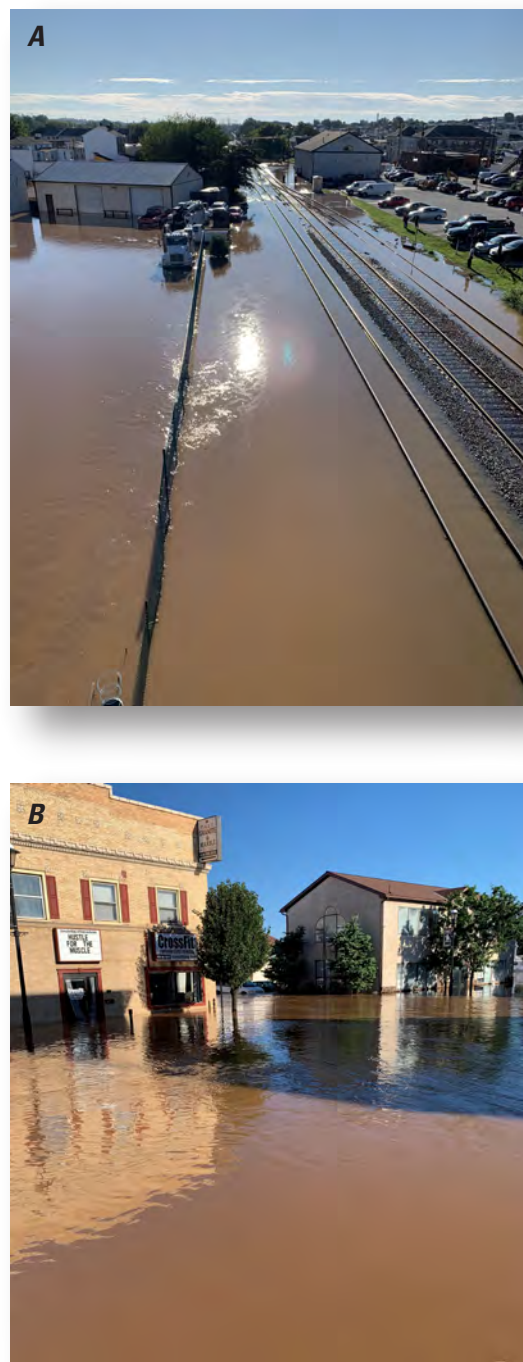
Figure 1.   Photographs showing *A*, flooded railroad tracks and *B*, flood damage in Bridgeport, Pennsylvania, from the remnants of Hurricane Ida, September 2, 2021. Photographs by Andrew Reif, U.S. Geological Survey.
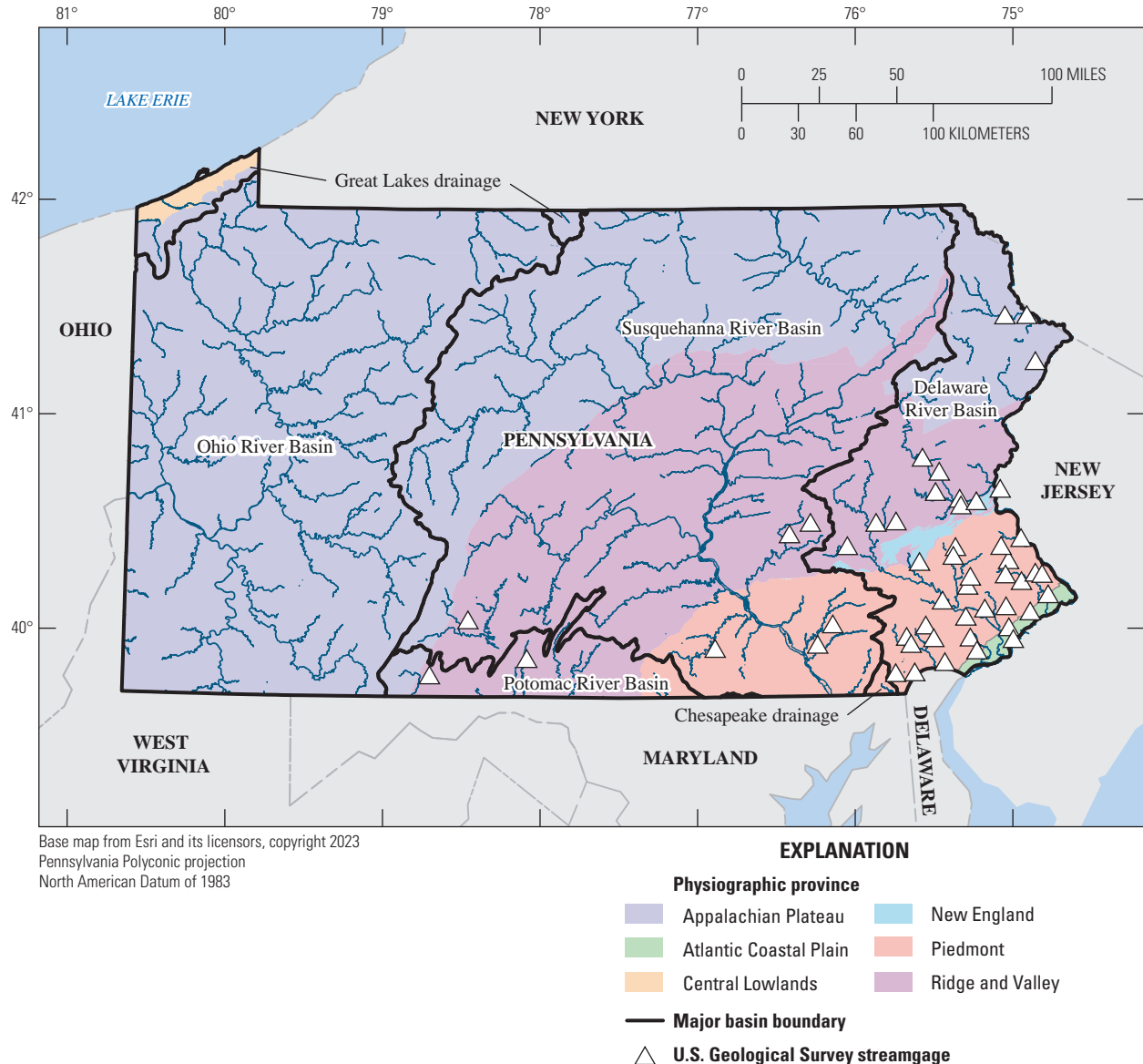
Figure 2. Map showing the location of the U.S. Geological Survey streamgages used in study and physiographic provinces in Pennsylvania (Pennsylvania Bureau of Topographic and Geologic Survey, 1998).

east in the Piedmont province. Land-surface-elevations within the Lower Susquehanna and Potomac River Basins range in elevation from 20 ft in the Piedmont province to 3,210 ft in the Appalachian Plateau province, referenced to NAVD 88. In Pennsylvania, the 30-year normal annual rainfall (1991–2020) varied from 36.38 inches in Tioga County at Tioga Hammond Dam to 55.93 inches in Somerset County at Hidden Valley (National Centers for Environmental Information, 2023b).

Weather Conditions Before and During the Flood

Hurricane Ida made landfall on the Louisiana coast as a powerful Category 4 hurricane with sustained winds of 150 miles per hour on August 29, 2021. The storm weakened into a tropical depression as it moved inland in a northeast direction. As Ida entered the mid-Atlantic region on September 1, 2021, it restrengthened into a post-tropical

cyclone when it interacted with a stalled frontal system, resulting in heavy rainfall and widespread historic flooding (National Weather Service, 2023b). Leading up to the event, many of the streams and rivers had daily streamflow greater than the 75th percentile because of multiple flooding events from a wet summer, including substantial rainfall from Tropical Storm Fred a few weeks before Hurricane Ida in August (National Weather Service, 2023b). Fed by remnant tropical moisture from Hurricane Ida, torrential rain fell near and just west of the storm center's track (fig. 3), becoming one of the area's worst observed natural disasters (National Weather Service, 2023b). The rainfall from the remnants of Hurricane Ida exceeded the amount of rainfall considered to be a 100-yr storm at many locations in Pennsylvania (National Centers for Environmental Information, 2023a). Much of eastern and southeastern Pennsylvania received 5 to 10 inches of rain (fig. 3), mostly within little more than 6 hours. At USGS streamgage 01480617 West Branch Brandywine Creek at Modena in Chester County, over 8 inches of rain (maximum intensity of over 2.5 inches in 1 hour) was recorded on September 1, 2021 (U.S. Geological Survey, 2023c). Highest rainfall totals per county in eastern Pennsylvania as reported by the National Weather Service (NWS) in Mount Holly, New Jersey, are shown in table 1. Downingtown, Chester County, had the greatest amount of rainfall at 10.10 inches followed by Hatfield, Montgomery County, at 8.41 inches and Newtown, Bucks County, at 8.36 inches (table 1).

Methods

The methods used to identify, document, and reference HWMs from the flooding caused by the remnants of Hurricane Ida and to create flood-documentation maps using these HWMs are discussed in this section. Also discussed are flood magnitude and frequency estimation methods using the annual peak streamflows of 52 streamgages operated by the USGS. All streamflow data used in this report may be accessed from the USGS National Water Information System (U.S. Geological Survey, 2023c).

Annual exceedance probability (AEP) flood for a streamgage is the probability of a streamflow being equaled or exceeded during a given year and is determined from the recorded annual peak streamflow for the streamgage. For example, an AEP of 0.01 means there is a 1-percent chance that a specific peak streamflow will occur at a given location in a given year. Stated another way, the odds are 1 in 100 that the indicated streamflow will be equaled or exceeded in a given year. AEP is directly related to the traditional concept of defining floods by recurrence interval, which is the average

number of years between floods of a certain size. By definition, the recurrence interval (in years) is equal to one divided by the AEP. For example, the AEP of 0.01 (or 1 percent) flood corresponds to what has historically been termed "the 100-year flood" (a flood with a 100-year recurrence interval) (Holmes and Dinicola, 2010).

Collection of High-Water-Mark Data

High-water marks are the evidence of the maximum water levels observed during a flood, and they are valuable for efforts to understand flood events. The USGS followed the guidance provided in Koenig and others (2016) to identify and document HWMs. Small seeds or debris carried by flood waters that adhere to smooth surfaces or lodge in tree bark to form a distinct line are the best HWMs. Stain lines on buildings, fences, and other structures also provide excellent HWMs. HWMs are best identified immediately after the peak stage of a flood event because they may blow or wash away from the weather (wind, rain, or sun) or fade away with time.

Working with FEMA under the direction of a Mission Assignment immediately after the flood, USGS field crews identified 255 HWMs in Pennsylvania on stream and river reaches that were selected using input obtained from FEMA, the NWS, U.S. Army Corps of Engineers, Delaware and Susquehanna River Basin Commissions, and Pennsylvania Emergency Management Agency. Examples of the identified HWMs are shown in fig. 4. Of those 255 HWMs, 198 were surveyed to determine the elevation above land surface using NAVD 88. HWMs were identified and marked beginning September 5, 2021, and continuing through September 16, 2021. Written descriptions, sketches, photographs, and global positioning system horizontal measurements (obtained with a hand-held global positioning system unit) were made so these marks could be easily found later and surveyed to the standard vertical datum (NAVD 88). Descriptions and photographs of these HWMs are available for viewing or download from the USGS Flood Event Viewer (U.S. Geological Survey 2021). In addition, 83 HWMs were identified and surveyed by the USGS as part of indirect computations of peak flow at select streamgages, bringing the total number of HWMs documented from the flooding that occurred on September 1–2, 2021, to 338. Indirect computations of peak flows are sometimes needed when a direct measurement of streamflow cannot be made because of unsafe conditions, lack of access, or timing issues and are made after a flood. The number of identified and surveyed HWMs and associated water bodies are listed in table 2 and are individually shown in fig. 5. A full listing of all HWMs is in Stuckey and Conlon (2023).
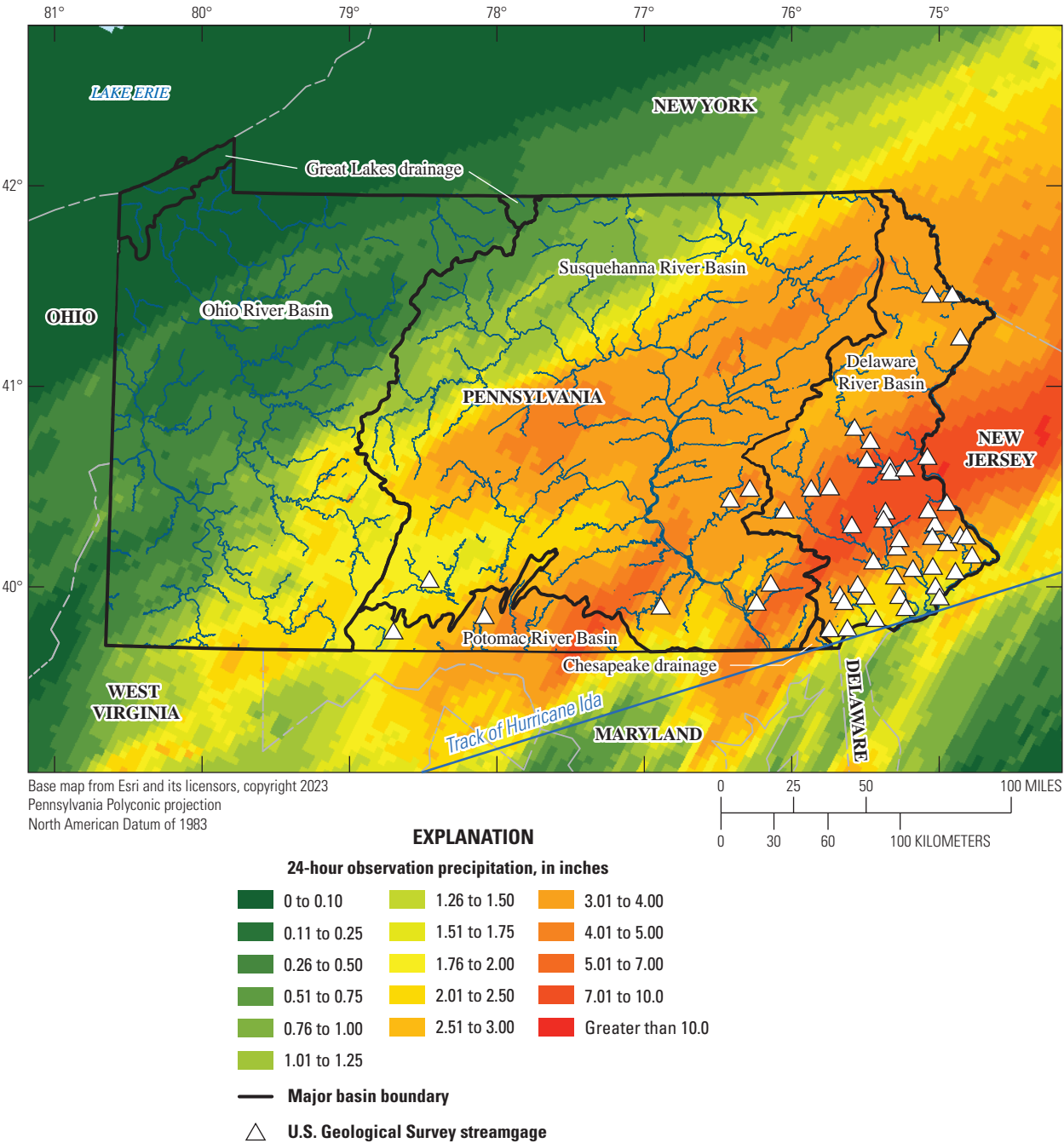
Figure 3. Map showing precipitation over a 24-hour period, ending at 1200 coordinated universal time, September 2, 2021 (National Weather Service, 2023a).

Table 1. Rainfall totals reported from meteorological stations in eastern Pennsylvania during the September 1–2, 2021, flood (Data source National Weather Service, 2023b).

[Time is given as military time. Dates are given as month/day/year. in., inch; EST, eastern standard time; CWOP, Citizen Weather Observer Program; COCO-RAHS, Community Collaborative Rain, Hail, and Snow Network; ASOS, Automated Surface Observing Systems]

Location	County	Rainfall amount (in.)	Time (EST)	Date	Meteorological station operator
Huffs Church	Berks	7.43	1200	9/2/2021	Trained Spotter
Newtown	Bucks	8.36	1330	9/2/2021	CWOP
Lake Harmony 2.4 WNW	Carbon	5.66	0700	9/2/2021	COCORAHS
Downingtown	Chester	10.10	2140	9/1/2021	Trained Spotter
Thornton	Delaware	4.00	1326	9/2/2021	CWOP
Center Valley	Lehigh	6.99	1325	9/2/2021	CWOP
Mt. Pocono	Monroe	5.56	0653	9/2/2021	ASOS
Hatfield	Montgomery	8.41	0850	9/2/2021	CWOP
Bethlehem	Northampton	7.50	1200	9/2/2021	Public
Philadelphia 4.7 NE	Philadelphia	3.70	0530	9/2/2021	COCORAHS

Peak-Flow Data and Streamgage Selection

During the Hurricane Ida remnant storm that resulted in flooding across eastern and southcentral Pennsylvania on September 1–2, 2021, USGS personnel made over 50 streamflow measurements using direct methods at streamgages in the study area (Rantz, 1982; Turnipseed and Sauer, 2010). In addition, in the months after the storm, USGS personnel computed streamflow measurements using indirect methods (Benson and Dalrymple, 1967; Rantz, 1982) at 12 locations. Many of the streamflow measurements were made to verify the accuracy of the stage-streamflow rating curve or extend the stage-streamflow rating curve for a given streamgage (Rantz, 1982). The stage-streamflow rating curve for a given streamgage is used to produce instantaneous streamflow values for a given streamgage, and the maximum instantaneous value for a given year is termed the annual peak streamflow (U.S. Geological Survey, 2023c). Streamgages with a long, annual peak streamflow record (more than 40 years) are considered the most reliable for estimating AEPs.

Magnitude and frequency statistics for floods were determined from annual peak streamflows measured or recorded at 52 USGS streamgages (fig. 2). Streamgages with at least 10 years of continuously recorded data were included in this study if those datasets met at least one of the following criteria: (1) the instantaneous peak from the September 1–2, 2021, flood event was the largest peak recorded during the period of record (peak of record) or (2) the recurrence interval of the instantaneous peak of September 1–2, 2021, was estimated to be at least 10-percent AEP and 1 of the 5 largest peak streamflow magnitudes recorded at the site over the period of record. If streamflow was regulated by a flood control reservoir during the period of record at a site, only the period after regulation was included in the analysis. The periods of record for the selected 52 streamgages ranged from 10 to 107 years, with a mean of 45 years. Annual peak-flow data for these streamgages were retrieved from the USGS National Water Information System (NWIS) website and carefully reviewed for completeness of record and appropriateness of historic peaks and qualification codes (U.S. Geological Survey, 2023c).

The annual peak flows of the 52 streamgages were analyzed to determine whether trends existed in their respective periods of record using a Mann-Kendall statistical test. Trends in annual peak flows can affect a flood frequency analysis by violating the assumption that the annual peak-flow data are a reliable and representative time sample of random homogeneous events (England and others, 2018). The results of the Mann-Kendall test showed that 17 of the 52 streamgages (33 percent) exhibited significant trends at the 90-percent confidence interval ($p<0.10$) (fig. 6). Data were evaluated for autocorrelation to confirm there was no serial correlation in the annual time series that would affect the results of the trend test (England and others, 2018). All significant trends were positive, indicating annual peak flows were increasing over time. Of the remaining 35 streamgages without a significant trend, 27 had a positive trend and 8 had a negative (decreasing streamflow) trend. A comparison of streamgages that were evaluated for trends by Roland and Stuckey (2020) and this current study show five streamgages that had changes in trend significance (at the 90-percent confidence interval); four streamgages now have a significant positive trend and one streamgage no longer has a significant positive trend. These trends in annual peak flows may be characterized by several

Figure 4. Photographs of select high-water marks identified after the flooding of the Schuylkill River and East Branch Perkiomen Creek on September 1–2, 2021. *A*, a mud line outside of a building; *B*, a seed line on a windowpane; *C*, a seed line on the back of a sign; and *D*, a seed line inside of a building. White dashed line represents high-water line. Photograph by the U.S. Geological Survey.

factors, including length of the period of record, variations in precipitation over time, land use changes, or single causal factors (for example, the construction of a dam). Because the cause and longevity of the significant trends are uncertain to continue in the future, no streamgages were excluded from this flood-frequency analysis because of significant trends.

Flood-Frequency Analysis

The magnitude and frequency of flood flows at the 52 streamgages were computed using the expected moments algorithm (EMA) methodology (England and others, 2018), which fits a log-Pearson Type III probability distribution curve to annual peak streamflow data. The Interagency Advisory

Committee on Water Data provides standard methods for computing peak streamflow frequency in its "Bulletin 17C" (England and others, 2018). Although Bulletin 17C maintains the moments-based approach of the previous Bulletin 17B procedures (Interagency Advisory Committee on Water Data, 1982), the method outlined in Bulletin 17C uses the EMA procedure (Cohn and others, 1997), which incorporates a generalized version of the multiple Grubbs-Beck test for the detection of low outliers (Cohn and others, 2013). EMA can also incorporate interval peak-flow data, which simplifies the analysis of datasets containing censored observations, historical data, low outliers, and uncertain data points, while providing enhanced confidence intervals for the estimated streamflows (Veilleux and others, 2014).

Table 2.   Site descriptions and number of high-water marks identified and surveyed in Pennsylvania after the September 1–2, 2021, flood.

[Twp, township; --, not applicable]

Associated waterbody	Community or communities	County or counties	Number of high-water marks identified and marked[1]	Number of high-water marks surveyed[1]	Number of additional high-water marks identified and surveyed[2]
Brandywine Creek Basin					
Brandywine Creek	Birmingham Twp, Pocopson Twp, Pennsbury Twp, Chadds Ford Twp	Chester, Delaware	32	22	--
West Branch Brandywine Creek	Valley Twp, Coatesville City, Modena Twp, Modena Borough, East Fallowfield Twp, Newlin Twp	Chester	14	11	35
East Branch Brandywine Creek	Uwchlan Twp, Downingtown Borough, Caln Twp, East Caln Twp, West Bradford Twp, East Bradford Twp, East Brandywine Twp	Chester	13	12	31
Lackawaxen River Basin					
Lackawaxen River	Hawley Borough, Palmyra Twp	Wayne	5	0	--
Lehigh River Basin					
Jordan Creek	Allentown City	Lehigh	12	12	--
Little Lehigh Creek	Allentown City	Lehigh	9	8	--
Lehigh River	Easton City	Northampton	15	13	--
Neshaminy Creek Basin					
Neshaminy Creek	Wrightstown Twp, Northampton Twp	Bucks	4	3	--
Schuylkill River Basin					
East Branch Perkiomen Creek	East Rockhill Twp, Sellersville Borough, Lower Salford Twp, Perkasie Borough, Skippack Twp	Montgomery	15	14	--
Perkiomen Creek	Perkiomen Twp, Skippack Twp, Lower Providence Twp, Upper Providence Twp, Collegeville Borough	Montgomery, Bucks	26	21	--
Pickering Creek	Schuylkill Twp	Chester	3	3	--
Schuylkill River	West Norristown Twp, Norristown Borough, Bridgeport Borough, Whitemarsh Twp, Conshohocken Borough, West Conshohocken Borough, Lower Merion Twp, Philadelphia City	Montgomery, Philadelphia	59	52	17
Codorus Creek Basin					
Codorus Creek	Spring Garden Twp, West Manchester Twp, York City, Manchester Twp, Springettsbury Twp	York	8	7	--
Conestoga River Basin					
Conestoga River	Lancaster City, Manheim Twp, Lancaster Twp, East Lampeter Twp, West Lampeter Twp	Lancaster	12	9	--

Table 2.   Site descriptions and number of high-water marks identified and surveyed in Pennsylvania after the September 1–2, 2021, flood.—Continued

[Twp, township; --, not applicable]

Associated waterbody	Community or communities	County or counties	Number of high-water marks identified and marked[1]	Number of high-water marks surveyed[1]	Number of additional high-water marks identified and surveyed[2]
Juniata River Basin					
Frankstown Branch	Williamsburg Borough, Catharine Twp	Blair	6	6	--
Raystown Branch	Liberty Twp	Bedford	6	5	--
Lackawanna River Basin					
Lackawanna River	Old Forge Borough, Scranton City	Lackawanna	8	0	--
Swatara Creek Basin					
Swatara Creek	East Hanover Twp, North Annville Twp	Lebanon	8	0	--

[1]Collected as part of a Federal Emergency Management Agency Mission Assignment.

[2]Collected as part of U.S. Geological Survey indirect streamflow measurements, included in flood-documentation map development.

The log-Pearson Type III analyses were performed using the USGS program PeakFQ version 7.4 (Veilleux and others, 2014), following methods outlined in Bulletin 17C (England and others, 2018). Estimates of the annual peak-flow probabilities were computed in PeakFQ by determining the mean, standard deviation, and skew of the log-transformed annual peak-flow data and inserting the three statistics of the frequency distribution into the following equation:

$$\log Qp \ = \ X + KpS$$

where

Q_p is the flood magnitude at a selected   (1) exceedance probability p;

X is the mean of the logarithms of the annual peak flows;

K_p is a factor based on the skew coefficient and the selected percentage AEP; and

S is the standard deviation of the logarithms of the annual peak flows.

As recommended in Bulletin 17C, a weighted average of the station skew and regional skew was used to determine flood frequencies for most streamgages, unless noted below. A regional skew of 0.343 (mean standard error of 0.178) was determined for Pennsylvania by Roland and Stuckey (2020) and used in this analysis. Note, potential computational issues related to the weighted skew calculation in PeakFQ remain unresolved at the time of preparation for publication (February 2023) (U.S. Geological Survey, 2023b). In some cases, the regional skew may be given too much weight over the station skew, particularly if the regional and station skew have a large difference (greater than 0.50). In this study, large differences between the regional and station skew were observed at eight streamgages (01467042, 01472198, 01472199, 01472620, 01472810, 01473000, 01474000, 01572025; table 3. One of these eight streamgages (01473000) had over 40 years of record, and the station skew coefficient option was used to avoid the potential weighting issue; the PeakFQ output for the remaining seven streamgages was evaluated for reasonableness and included in the analysis. The station skew coefficient option was used for streamgages with flow regulated by an upstream flood control reservoir because the regional skew was developed using unregulated watersheds and is not appropriate for use in regulated watersheds. A regulated watershed has at least 10 percent of the area upstream of its streamgage controlled by a reservoir.

The resulting flood frequencies for unregulated streamgages were weighted using the variance of independent estimates to reduce uncertainty as described in Bulletin 17C (England and others, 2018). Observed at-site flood-frequency estimates and predicted regression estimates from Roland and Stuckey (2020) are weighted in inverse proportion to their respective independent variances. Flood frequencies for regulated streamgages are not weighted because regression equations are not applicable. Flood frequencies associated with the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs for the 52 streamgages in Pennsylvania are available in Stuckey and Conlon (2023).
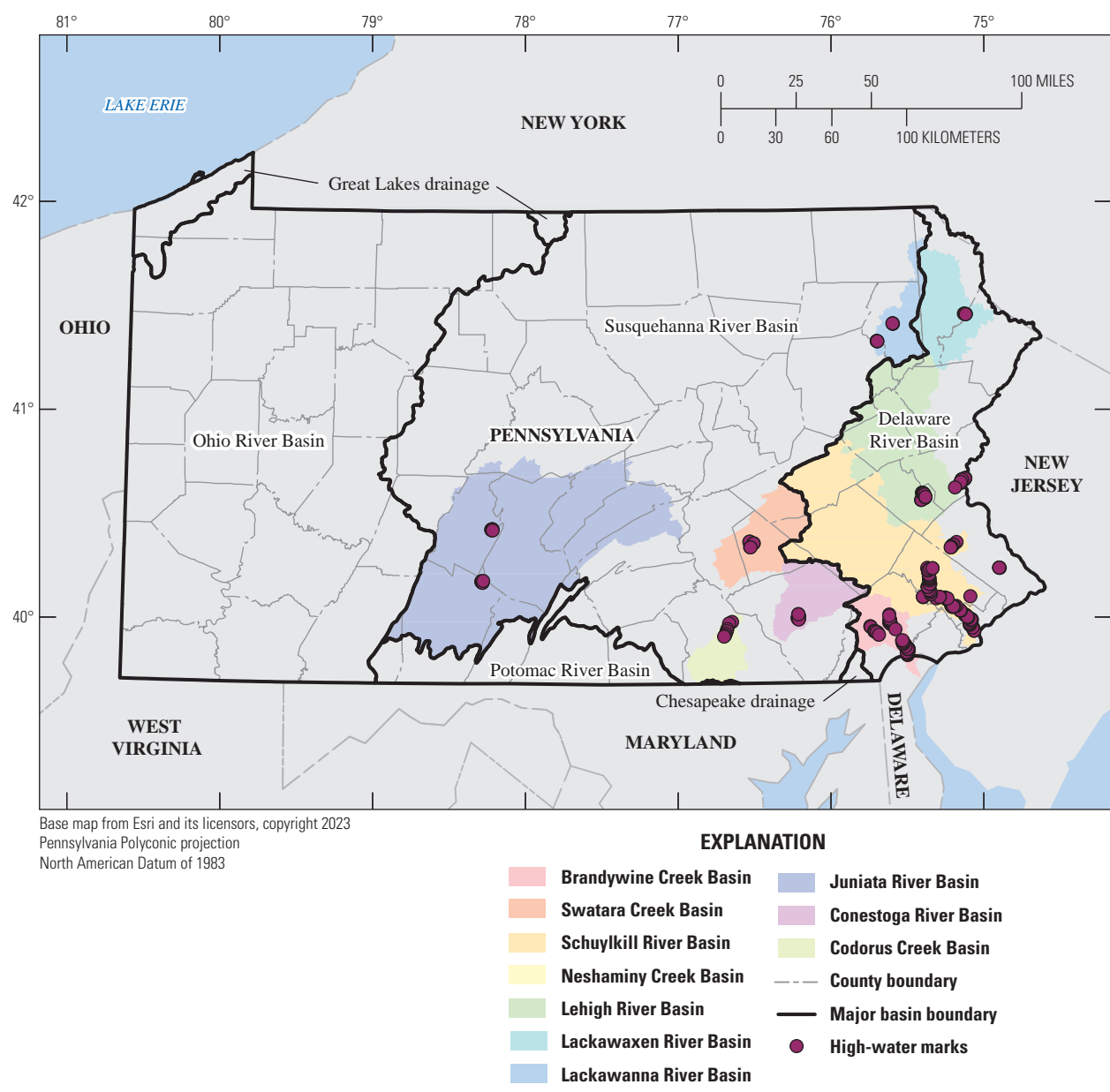
Figure 5.   Map showing the location of identified high-water marks in Pennsylvania from the September 2021 flood.
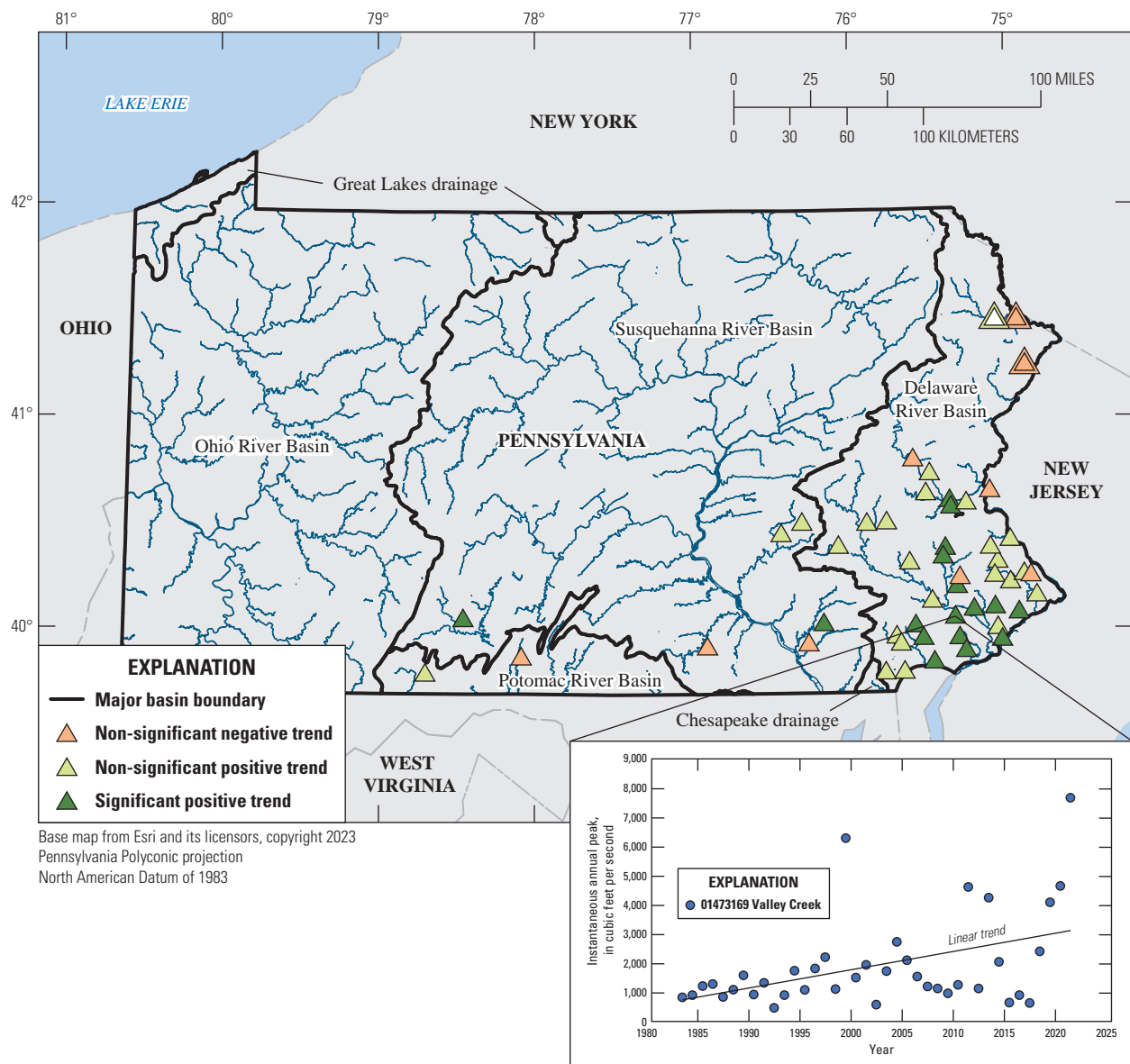
Figure 6. Map showing select U.S. Geological Survey streamgages within Pennsylvania and trends in annual peak flows.

Flood-Probabilities of Peak Streamflow

After a substantial flood, emergency managers and water resource engineers often need to know the expected frequency of peak streamflow for the observed streamflow to provide information on the rarity of the event. The September 1–2, 2021, peak streamflows were analyzed using PeakFQ software version 7.4 (Veilleux and others, 2014) following guidance provided in the USGS Office of Surface Water Technical Memorandum 2013.01 (U.S. Geological Survey, 2012). The AEP for the flood event was estimated through the log-linear interpolation of flood frequencies determined from PeakFQ using the following equation:

$$AEP_{Obs} = AEP_1 + \frac{(AEP_2 - AEP_1) \times (\log_{10}(Q_{Obs}) - \log_{10}(Q_1))}{\log_{10}(Q_2) - \log_{10}(Q_1)} \quad (2)$$

where
- AEP_{Obs} is the AEP of the flood event;
- AEP_1 is the AEP value associated with the lower flow Q_1 bracketing the flood event;
- AEP_2 is the AEP value associated with the upper flow Q_2 bracketing the flood event;
- Q_{Obs} is the flow from the flood event;
- Q_1 is the lower flow bracketing the flood event; and
- Q_2 is the upper flow bracketing the flood event.

Assigning an AEP to an observed flood results in greater uncertainty than determining traditional flood frequencies because the lack of reference data for the extreme flood being assessed. Limits based on the 66.7-percent confidence level were computed for each estimated AEP to convey this uncertainty.

Flood-Documentation Mapping

Flood-documentation maps were created using a geographic information system (GIS) approach to show the extent of inundation from the September 1–2, 2021, flooding along five selected river reaches in southeastern Pennsylvania that contained HWMs in sufficient number and density (fig. 7). These flood-documentation maps are intended to be estimates of the areal extent and the maximum depth of flooding that correspond to the HWMs identified and surveyed by USGS field crews after the flood event. The community, county, waterbodies, reach lengths, and number of HWMs used to generate the flood-documentation maps are listed in table 4.

A flood-elevation raster surface was created in GIS to generate the flood-documentation maps. GIS surfaces documenting the areal extent of the maximum depth of flooding were created independently for each area that was mapped using the point elevations of the HWMs and streamgages by using a GIS interpolation technique—the ArcGIS Topo

to Raster tool (Esri, 2021) described by Musser and others (2016). A geographic areal boundary limit was placed on the generated surface because of the distribution of HWMs and an understanding of the natural hydrologic flow in each area that was mapped.

The flood-elevation raster surface that was created using GIS interpolation was then combined with 1-meter digital elevation model (DEM) data with a 10-meter cell size. The DEM was derived from light detection and ranging (lidar) data that had a 10-centimeter vertical root-mean-square-error and a nominal point spacing of 2 points per square meter or better (U.S. Geological Survey, 2023a). A DEM is a digital point representation of a surface; in this instance, the DEM is a topographical representation of the earth's surface in the study area. An inundated area was depicted where the flood-elevation surface was higher than the DEM land surface. The maximum depth of flooding was calculated as the difference between the flood-elevation surface and the DEM land surface. Because of the many bridges in the mapped reaches (common in Pennsylvania), the inundation surfaces were not modified to show any bridges that were not inundated.

The flood-elevation interpolation method was used to develop the water-surface elevation layer from points represented by the HWM dataset and the USGS streamgage peak stage water-surface elevation values (where available). Interpolation was conducted between these elevations to generate the water-surface elevation using the ArcGIS Topo to Raster tool with the point interpolation procedure (Esri, 2021).

Uncertainties in the mapped extent and calculated depth of flooding within the maps result from the interpolation methods described above and the number and spatial distribution of HWMs within each mapped reach. Hydraulic models were not used to determine the extent or depth of flooding. Without hydraulic models, factors that can affect the extent or depth of flooding are not accounted for using this GIS interpolation methodology. Factors such as land-surface features, changes in flood plains, as well as the timing of the flooding event in the smaller inflow tributaries versus the larger main-stem tributaries and intermingling flows from adjacent streams, likely contribute to the extent and impact of flooding. In locations where HWMs are at a comparably greater distance of separation, spatial interpretations of the extent and depth of flooding may be less accurate. Within a given mapped area, some extrapolation was used beyond the most upstream and downstream HWMs. Often, the mapping boundary was extended to some anthropogenic structure, such as a road or bridge crossing.

The flood-documentation maps as described and shown in this report should not be used for navigation or 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 the maps. The maps shown in figs. 8–12 only depict the September 2021 remnant Hurricane Ida flood event on select stream reaches in southeastern Pennsylvania and may not be representative of other flooding conditions.

Table 3. Site descriptions, summary statistics, equivalent recurrence intervals, and exceedance probabilities, for select streamgages associated with September 2021 flooding in Pennsylvania.

[Dates shown as month/day/year. USGS, U.S. Geological Survey; mi², square miles; AEP, annual exceedance probability; ft, foot; ft³/s, cubic feet per second; PA, Pennsylvania; %, percent; <, less than; >, greater than]

USGS station number	USGS station name	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (mi²)	Number of annual peaks in analysis	September 2021 flood data				AEP for observed September 2021 flood			
						Date of peak streamflow	Peak gage height (ft)	Peak streamflow (ft³/s)	Period of record rank for peak streamflow	Estimate	Equivalent recurrence interval (years)	Upper 66.7-percent confidence interval[1]	Lower 66.7-percent confidence interval[1]
01431500	Lackawaxen River at Hawley, PA	41.476200	−75.172119	290	62	9/2/2021	14.31	17,300	4	3.9%	26	9.2%	3.5%
01432110	Lackawaxen River at Rowland, PA	41.475923	−75.036281	589	14	9/2/2021	13.39	25,100	1	3.2%	31	12.0%	1.3%
01449000	Lehigh River at Lehighton, PA	40.829259	−75.705189	591	40	9/2/2020	14.11	27,100	1	3.2%	32	4.4%	0.5%
01451000	Lehigh River at Walnutport, PA	40.757040	−75.602964	889	61	9/2/2021	13.19	45,300	3	3.2%	31	7.3%	2.3%
01451650	Little Lehigh Creek at Tenth Street Bridge at Allentown	40.596486	−75.474071	98.2	35	9/1/2021	9.6	7,610	5	8.4%	12	19.3%	8.4%
01451800	Jordan Creek near Schnecksville, PA	40.661762	−75.626854	53	55	9/1/2021	11.28	5,880	4	6.4%	16	10.3%	3.9%
01452000	Jordan Creek at Allentown, PA	40.623153	−75.482405	75.8	77	9/2/2021	10.71	13,300	4	1.7%	59	7.4%	2.8%
01453000	Lehigh River at Bethlehem, PA	40.615376	−75.378791	1,279	61	9/2/2021	19.53	56,000	5	3.8%	26	11.3%	4.8%
01454700	Lehigh River at Glendon, PA	40.669266	−75.236288	1,359	55	9/2/2021	24.11	58,100	3	3.7%	27	8.1%	2.6%
01459500	Tohickon Creek near Pipersville, PA	40.433715	−75.116561	97.4	48	9/1/2021	11.18	15,600	4	5.3%	19	11.8%	4.5%
01464645	North Branch Neshaminy Creek below Lake Galena near New Britain, PA	40.312328	−75.206563	16.2	36	9/1/2021	5.4	2,350	1	2.5%	40	4.9%	0.5%
01464720	North Branch Neshaminy Creek at Chalfont, PA	40.288162	−75.203785	31.5	31	9/1/2021	11.58	7,290	1	5.2%	19	5.6%	0.6%
01464750	Neshaminy Creek near Rushland, PA	40.260385	−75.034892	91	26	9/2/2021	21.83	13,300	1	2.8%	36	6.7%	0.7%
01464907	Little Neshaminy Creek at Valley Road nr Neshaminy PA	40.229275	−75.119616	26.8	23	9/1/2021	12.78	8,740	3	3.3%	30	18.7%	6.2%

Table 3. Site descriptions, summary statistics, equivalent recurrence intervals, and exceedance probabilities, for select streamgages associated with September 2021 flooding in Pennsylvania.—Continued

[Dates shown as month/day/year. USGS, U.S. Geological Survey; mi², square miles; AEP, annual exceedance probability; ft, foot; ft³/s, cubic feet per second; PA, Pennsylvania; %, percent; <, less than; >, greater than]

USGS station number	USGS station name	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (mi²)	Number of annual peaks in analysis	September 2021 flood data				AEP for observed September 2021 flood			
						Date of peak streamflow	Peak gage height (ft)	Peak streamflow (ft³/s)	Period of record rank for peak streamflow	Estimate	Equivalent recurrence interval (years)	Upper 66.7-percent confidence interval[1]	Lower 66.7-percent confidence interval[1]
01465200	Neshaminy Creek near Penns Park, PA	40.251842	−75.008708	157	20	9/2/2021	24.46	26,400	1	1.7%	59	8.6%	0.9%
01465500	Neshaminy Creek near Langhorne, PA	40.173998	−74.956834	210	88	9/2/2021	20.81	27,000	5	4.6%	22	7.9%	3.3%
01467042	Pennypack Creek at Pine Road, at Philadelphia, PA	40.089833	−75.069061	37.9	31	9/2/2021	14.6	14,600	1	0.4%[2]	245	5.6%	0.6%
01470500	Schuylkill River at Berne, PA	40.522593	−75.998268	355	75	9/2/2021	15.67	26,000	5	7.3%	14	9.2%	3.9%
01470755	Maiden Creek near Virginville, PA[3]	40.525372	−75.874925	157	33	9/2/2021	--	14,400	3	3.8%	26	13.3%	4.3%
01470779	Tulpehocken Creek near Bernville, PA	40.413426	−76.171613	70.4	48	9/1/2021	10.37	5,360	5	8.9%	11	14.3%	6.1%
01471875	Manatawny Creek near Spangsville, PA	40.339538	−75.742136	56.9	28	9/1/2021	8.54	4,970	4	9.6%	10	19.8%	7.7%
01472157	French Creek near Phoenixville, PA	40.151491	−75.601305	59.1	53	9/1/2021	12.32	7,660	4	7.0%	14	10.7%	4.1%
01472198	Perkiomen Creek at East Greenville, PA	40.393988	−75.515459	38	40	9/1/2021	9.24	8,850	2	3.4%	30	7.9%	1.8%
01472199	West Branch Perkiomen Creek at Hillegass, PA	40.373988	−75.522403	23	40	9/1/2021	6.42	3,400	4	7.3%	14	14.1%	5.4%
01472620	East Branch Perkiomen Creek near Dublin, PA	40.403993	−75.234342	4.05	38	9/1/2021	10.66	2,890	1	2.2%	46	4.6%	0.5%
01472810	East Branch Perkiomen Creek near Schwenksville, PA	40.258714	−75.428787	58.7	30	9/2/2021	16.88	18,000	1	1.4%	72	5.8%	0.6%
01473000	Perkiomen Creek at Graterford, PA	40.229547	−75.451567	279	107	9/2/2021	24.23	64,400	1	<0.2%[2]	>500	1.7%	0.2%
01473169	Valley Creek at PA Turnpike Bridge near Valley Forge	40.079274	−75.460748	20.8	39	9/1/2021	16.44	7,930	1	0.7%[2]	141	4.5%	0.5%

[Dates shown as month/day/year. USGS, U.S. Geological Survey; mi², square miles; AEP, annual exceedance probability; ft, foot; ft³/s, cubic feet per second; PA, Pennsylvania; %, percent; <, less than; >, greater than]

USGS station number	USGS station name	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (mi²)	Number of annual peaks in analysis	September 2021 flood data				AEP for observed September 2021 flood			
						Date of peak streamflow	Peak gage height (ft)	Peak streamflow (ft³/s)	Period of record rank for peak streamflow	Estimate	Equivalent recurrence interval (years)	Upper 66.7-percent confidence interval[1]	Lower 66.7-percent confidence interval[1]
01473500	Schuylkill River at Norristown, PA	40.111219	−75.346850	1,760	36	9/2/2021	26.88	119,000	1	1.2%	81	4.9%	0.5%
01473900	Wissahickon Creek at Fort Washington, PA	40.123999	−75.219899	40.8	41	9/1/2021	17.74	13,700	2	1.0%[2]	104	7.7%	1.8%
01474000	Wissahickon Creek at Mouth, Philadelphia, PA	40.015390	−75.206846	64	56	9/2/2021	11.05	17,800	2	0.9%[2]	117	5.7%	1.3%
01474500	Schuylkill River at Philadelphia, PA	39.967891	−75.188512	1,893	43	9/2/2021	16.35	125,000	1	0.9%[2]	106	4.1%	0.4%
01475850	Crum Creek near Newtown Square, PA	39.976499	−75.436586	15.8	45	9/1/2021	12.33	4,030	3	5.5%	18	9.8%	3.1%
01476480	Ridley Creek at Media, PA	39.916222	−75.403250	30.5	34	9/2/2021	11.61	4,940	5	9.4%	11	19.9%	8.7%
01478120	East Branch White Clay Creek at Avondale, PA	39.828443	−75.780773	11.3	14	9/1/2021	9.75	2,600	1	5.4%	19	12.0%	1.3%
01480500	West Branch Brandywine Creek at Coatesville, PA	39.985661	−75.827447	45.8	61	9/1/2021	9.62	7,120	4	4.9%	21	9.3%	3.5%
01480617	West Branch Brandywine Creek at Modena, PA	39.961773	−75.801334	55	52	9/1/2021	13.36	12,300	1	1.3%	75	3.4%	0.4%
01480700	East Branch Brandywine Creek near Downingtown, PA	40.034828	−75.708549	60.6	48	9/1/2021	13.6	16,100	1	<0.2%[2]	>500	3.7%	0.4%
01480870	East Branch Brandywine Creek below Downingtown, PA	39.968719	−75.673272	89.9	48	9/1/2021	19.31	21,000	1	0.2%[2]	432	3.7%	0.4%
01481000	Brandywine Creek at Chadds Ford, PA	39.869833	−75.593262	287	102	9/2/2021	21.04	49,000	1	<0.2%[2]	>500	1.7%	0.2%

Table 3. Site descriptions, summary statistics, equivalent recurrence intervals, and exceedance probabilities, for select streamgages associated with September 2021 flooding in Pennsylvania.—Continued

[Dates shown as month/day/year. USGS, U.S. Geological Survey; mi², square miles; AEP, annual exceedance probability; ft, foot; ft³/s, cubic feet per second; PA, Pennsylvania; %, percent; <, less than; >, greater than]

USGS station number	USGS station name	Latitude (decimal degrees)	Longitude (decimal degrees)	Drainage area (mi²)	Number of annual peaks in analysis	September 2021 flood data				AEP for observed September 2021 flood			
						Date of peak streamflow	Peak gage height (ft)	Peak streamflow (ft³/s)	Period of record rank for peak streamflow	Estimate	Equivalent recurrence interval (years)	Upper 66.7-percent confidence interval[1]	Lower 66.7-percent confidence interval[1]
01494850	East Branch Big Elk Creek at Forestville, PA	39.822331	−75.896888	9.69	14	unknown	15.26	3,030	1	6.2%	17	12.0%	1.3%
01560000	Dunning Creek at Belden, PA	40.071747	−78.492517	172	83	9/2/2021	13.51	14,800	4	2.4%	42	6.9%	2.6%
01564512	Aughwick Creek near Shirleysburg, PA	40.28202	−77.890553	301	32	9/2/2021	15.51	18,500	3	9.2%	11	13.7%	4.4%
01572025	Swatara Creek near Pine Grove, PA	40.53259	−76.402179	116	33	9/1/2021	15.31	11,300	4	6.3%	16	16.9%	6.5%
01572190	Swatara Creek near Inwood, PA	40.479256	−76.530797	167	33	9/2/2021	17.35	12,500	4	9.4%	11	16.9%	6.5%
01573695	Conewago Creek near Bellaire, PA	40.195278	−76.567778	20.5	10	9/1/2021	8.81	2,490	2	8.3%	12	28.9%	7.4%
01573710	Conewago Creek near Falmouth, PA	40.149306	−76.687750	47.5	11	9/1/2021	14.71	6,000	2	9.3%	11	26.6%	6.7%
01573825	West Conewago Creek at East Berlin, PA	39.941222	−76.990000	218	18	9/1/2021	17.96	13,500	3	8.6%	12	23.6%	7.9%
01576500	Conestoga River at Lancaster, PA	40.050097	−76.277180	324	93	9/2/2021	18.5	23,000	4	3.9%	25	6.2%	2.3%
01576754	Conestoga River at Conestoga, PA	39.946489	−76.367739	470	37	9/2/2021	16.27	22,300	2	7.6%	13	8.5%	2.0%
01601000	Wills Creek below Hyndman, PA	39.812029	−78.716407	146	54	9/1/2021	13.02	15,500	2	1.5%	67	5.9%	1.4%
01613050	Tonoloway Creek near Needmore, PA	39.898421	−78.132229	10.7	59	9/1/2021	8.53	1,130	4	8.1%	12	9.6%	3.6%

[1]The AEP 66.7-percent confidence interval is a nonparametric estimate based on a flood of a given rank within a specified period of record. These confidence intervals are not centered about the interpolated AEP estimate. Consequently, the range of the confidence interval may exclude the AEP estimate.

[2]Streamgages with AEP estimates less than 1-percent, also highlighted in gray.

[3]Peaks include those from sites 01470756 (not listed) and 01470755.
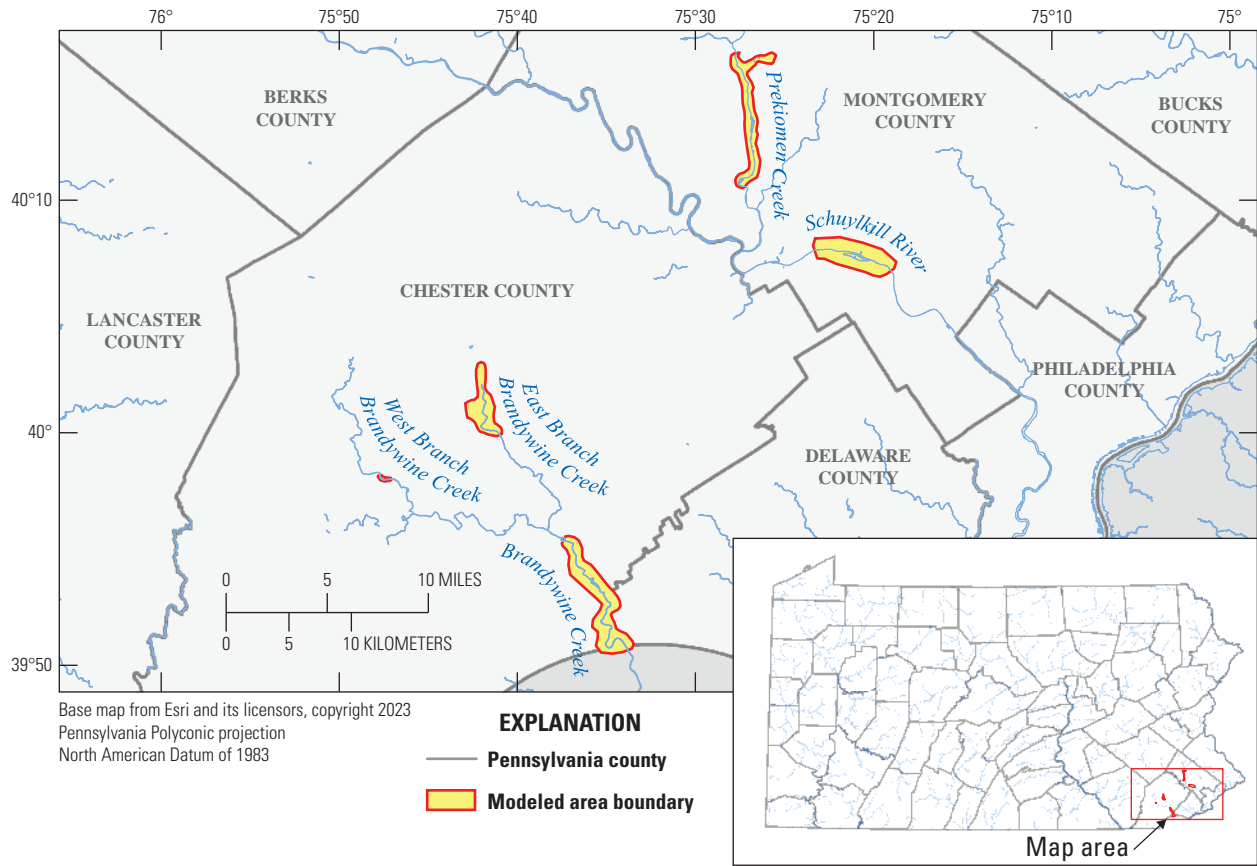
Figure 7.   Map showing the locations of the flood-documentation maps created to show the extent of flooding caused by the remnants of Hurricane Ida on September 1–2, 2021.

Table 4.   Site descriptions of high-water marks in southeastern Pennsylvania used to generate flood-documentation maps for the September 1–2, 2021, flood.

Community or communities	Associated waterbody	County or counties	Approximate reach length (miles)	Number of high-water marks used to generate flood-documentation map
East Bradford, East Brandywine, East Caln, Uwchlan, and West Bradford Townships and Downingtown Borough	East Branch Brandywine Creek	Chester	5	43
Modena Borough	West Branch Brandywine Creek	Chester	0.5	40
Birmingham, Chadds Ford, Pennsbury, and Pocopson Townships	Brandywine Creek	Chester, Delaware	9	22
Lower Providence, Lower Salford, Perkiomen, Skippack Townships, and Upper Providence Townships and Collegeville and Schwenksville Boroughs	Perkiomen Creek	Montgomery	8	23
Upper Merion and West Norriton Townships and Bridgeport and Morrisville Boroughs	Schuylkill River	Montgomery	4	26
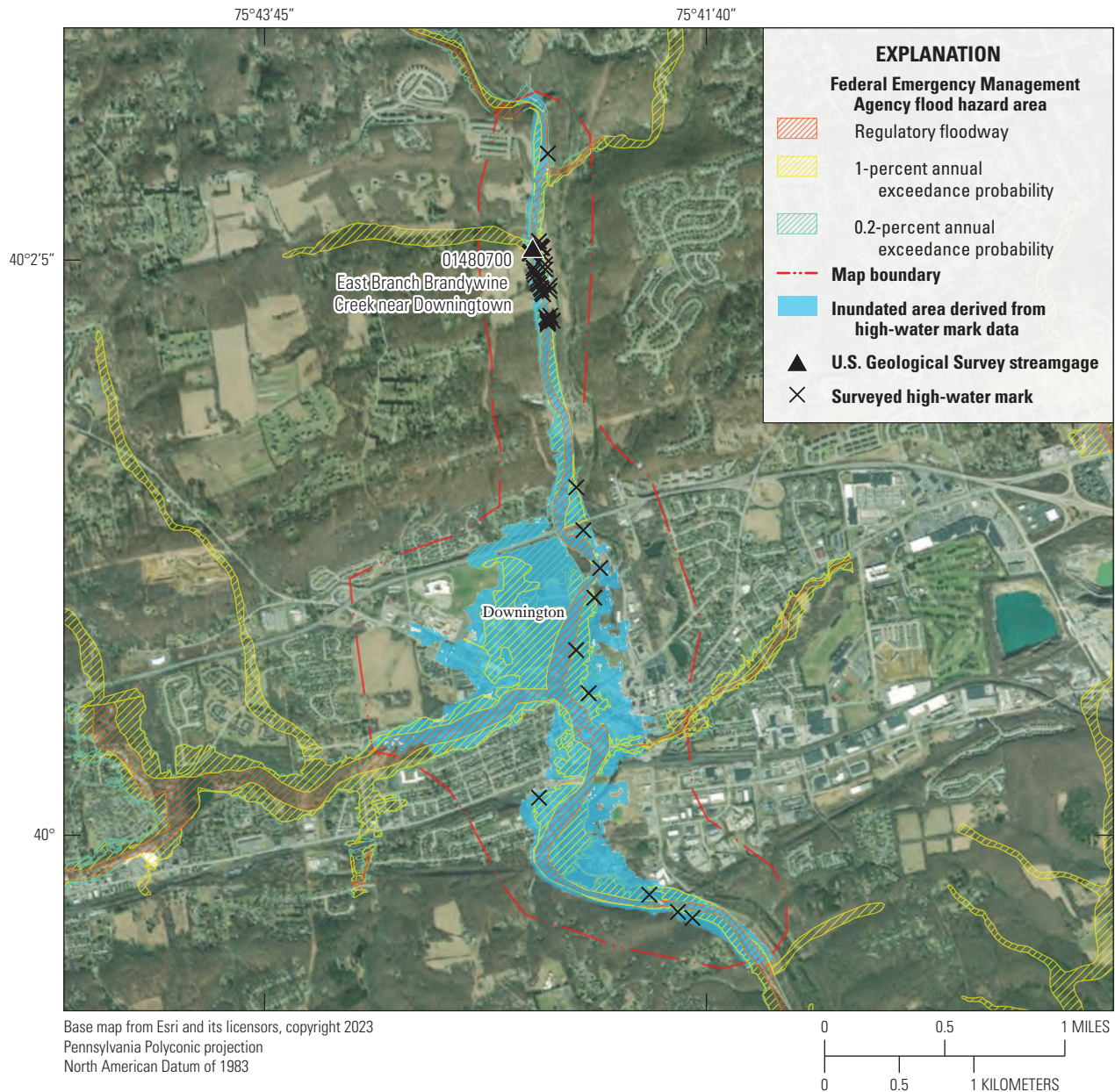
Figure 8.   Map showing the inundated area along the East Branch Brandywine Creek in Downingtown, Pennsylvania, September 1–2, 2021.

Estimated Magnitudes and Exceedance Probabilities for Peak Streamflows

Peak gage-height data, streamflow data, and associated AEPs with 66.7-percent confidence intervals determined for the September 2021 flood event from the 52 USGS streamgages analyzed are listed in table 3. Streamgages had

10 to 107 years of peak streamflow records; and the mean was 45 years. New peak streamflows of record (peak of record) were observed at 19 of the 52 USGS streamgages (table 3; Stuckey and Conlon, 2023). Peak streamflows ranked second or third among the highest peaks of record at another 14 streamgages. At the 19 remaining streamgages, peak streamflows ranked fourth or fifth among the highest peaks of record measured at these stations. The AEP estimates for the analyzed streamgages during the September 2021 flood ranged from less than 0.2 to 10 percent (greater than a 500-year
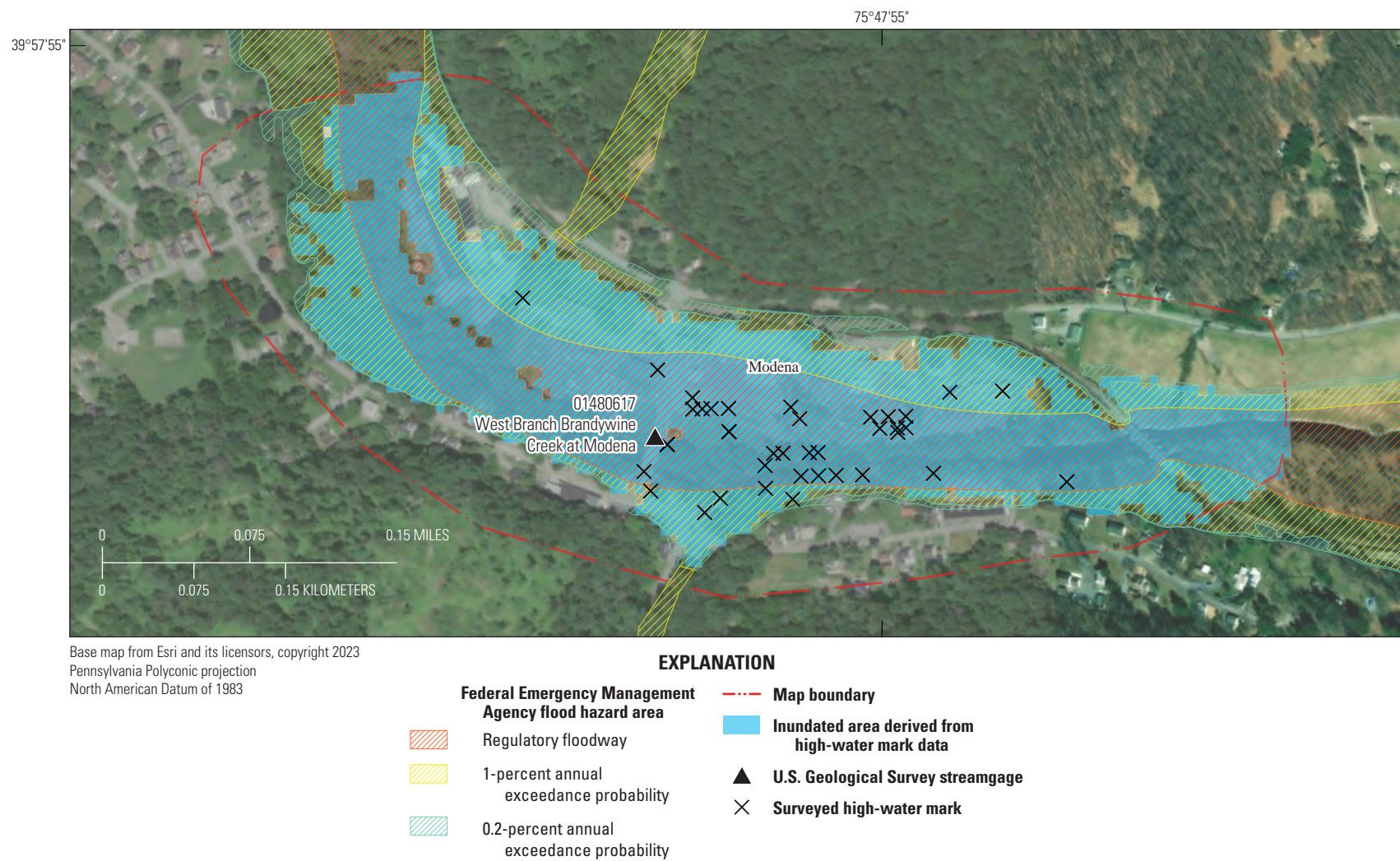
Figure 9. Map showing the inundated area along the West Branch Brandywine Creek in Modena, Pennsylvania, September 1–2, 2021.
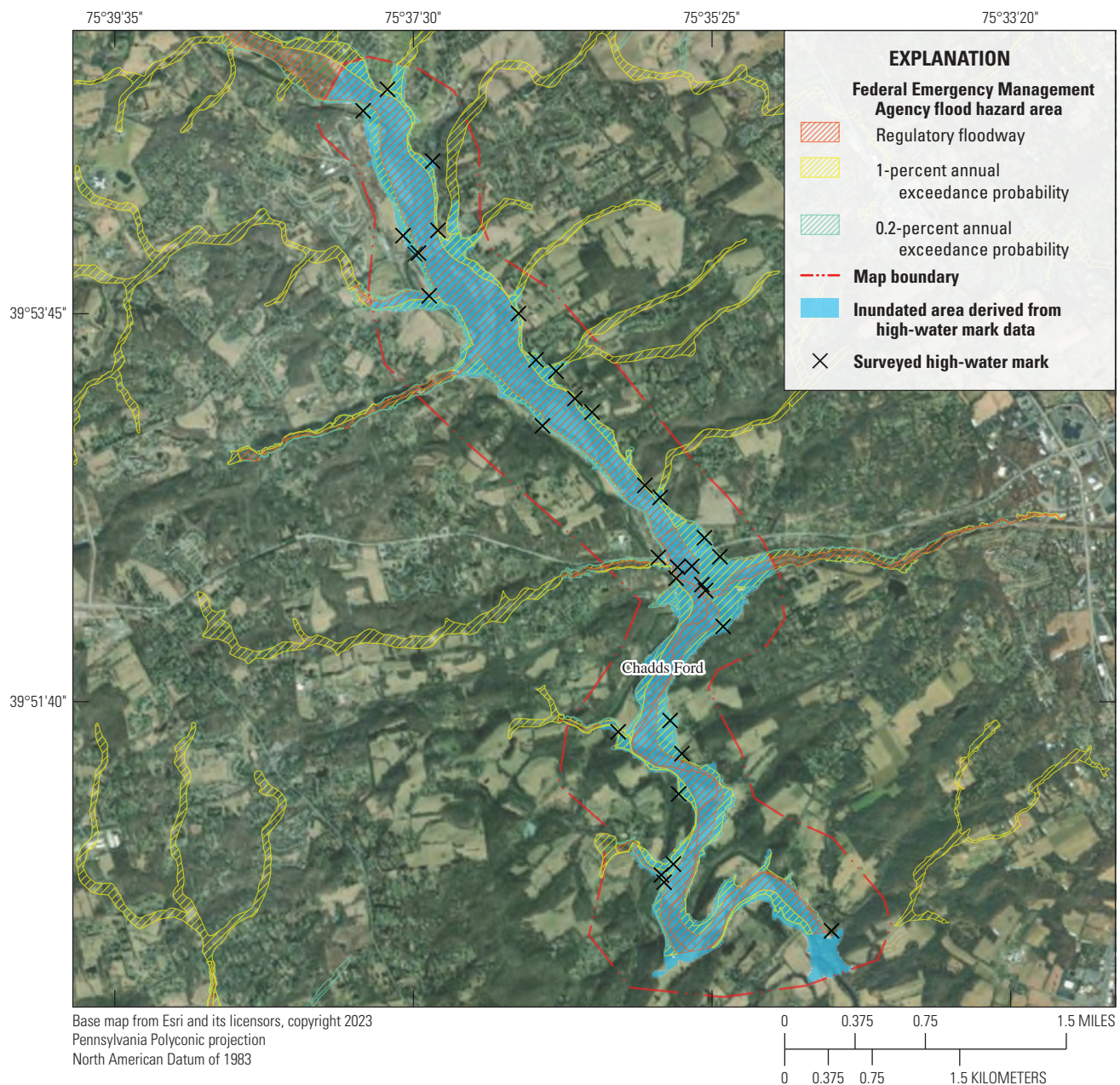
Figure 10.   Map showing the inundated area along the Brandywine Creek near Chadds Ford, Pennsylvania, September 1–2, 2021.

recurrence interval [RI] to a 10-year RI). The September 2021 AEP at nine streamgages is estimated to be less than or equal to the 1 percent (at least a 100-year RI); these nine streamgages are in Pennypack Creek, the Schuylkill River, and the Brandywine Creek Basins. Two streamgages with over 100 years of record have less than a 0.2-percent AEP or greater than a 500-year RI for the September 2021 flood (01473000 Perkiomen Creek at Graterford and 01481000 Brandywine Creek at Chadds Ford).

Flood frequencies associated with the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs were determined for 52 streamgages in Pennsylvania using EMA methods and are available in Stuckey and Conlon (2023). Comparisons of AEP results were made using these updated flood frequencies and flood frequencies using data through 2015 published by Roland and Stuckey (2020) to determine the percentage change since the flood frequencies were last published. Percentage changes in the 1-percent AEP flood frequencies

Figure 11. Map showing the inundated area along the Perkiomen Creek near Graterford and Collegeville, Pennsylvania, September 1–2, 2021.

(100-year RI) for 45 streamgages included in both analyses ranged from −2 percent to 57 percent, with a mean change of 9 percent (table 5). Of the 45 streamgages, 5 had a negative percentage change in the 1-percent AEP (100-year RI), indicating the 1-percent AEP estimate has decreased since last computed, and 36 had a positive percentage change, indicating the 1-percent AEP is larger than previously computed.

Flood-Documentation Maps

Five flood-documentation maps were created for communities in southeastern Pennsylvania (figs. 8–12). Each map shows the areal extent of the floodwaters along affected reaches. The HWMs used to create the flood-documentation maps and derive the associated information are provided in Stuckey and Conlon (2023) Digital datasets of the inundation

Base map from Esri and its licensors, copyright 2023
Pennsylvania Polyconic projection
North American Datum of 1983

EXPLANATION

Federal Emergency Management Agency flood hazard area

Regulatory floodway

1-percent annual exceedance probability

0.2-percent annual exceedance probability

Map boundary

Inundated area derived from high-water mark data

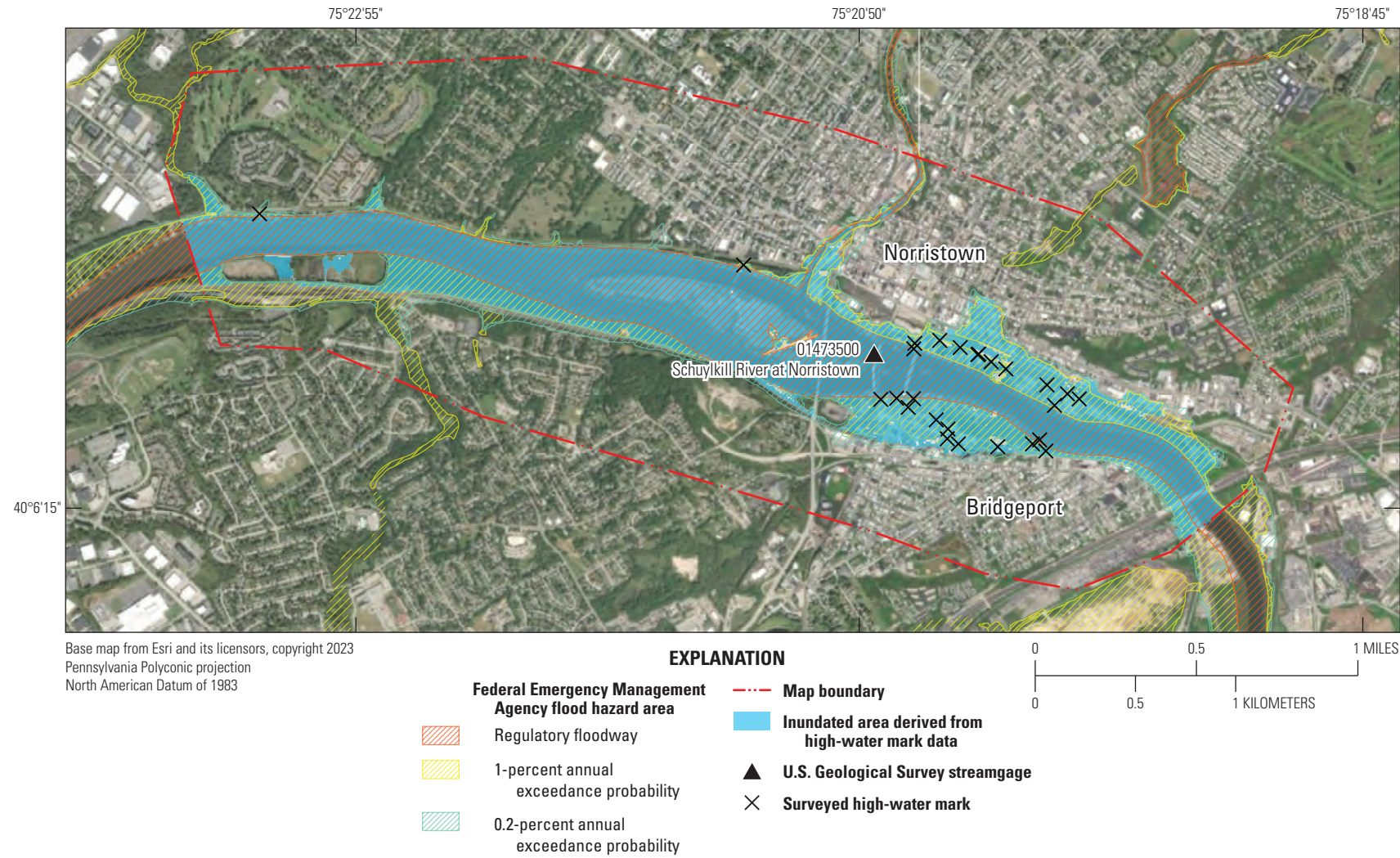▲   U.S. Geological Survey streamgage

✕   Surveyed high-water mark

Figure 12.   Map showing the inundated area along the Schuylkill River near Norristown and Bridgeport, Pennsylvania, September 1–2, 2021.

Table 5. Summary of percentage changes from previously published peak-flow annual exceedance probabilities for select streamgages associated with September 1–2, 2021, flooding in Pennsylvania.

[Previously published flood frequencies from Roland and Stuckey (2020) using data through 2015. Flood-frequency method determined from weighted estimates (WTD) or the at-site expected moments algorithm (EMA). USGS, U.S. Geological Survey; PA, Pennsylvania; %, percent; ---, not included in Roland and Stuckey (2020)]

USGS station number	USGS station name	Number of peaks used in current analysis	Flood-frequency method	Change of peak-flow exceedance values from previously published values (percent)							
				Exceedance probability							
				0.5	0.2	0.1	0.04	0.02	0.01	0.005	0.002
01431500	Lackawaxen River at Hawley, PA	62	EMA	0%	0%	0%	0%	1%	1%	---	---
01432110	Lackawaxen River at Rowland, PA	14	---	---	---	---	---	---	---	---	---
01449000	Lehigh River at Lehighton, PA	40	EMA	−3%	−2%	0%	1%	3%	5%	---	---
01451000	Lehigh River at Walnutport, PA	61	EMA	−2%	−1%	0%	1%	3%	4%	---	---
01451650	Little Lehigh Creek at Tenth Street Bridge at Allentown	35	WTD	12%	14%	14%	13%	12%	11%	11%	10%
01451800	Jordan Creek near Schnecksville, PA	55	WTD	3%	4%	4%	5%	5%	5%	5%	6%
01452000	Jordan Creek at Allentown, PA	77	EMA	2%	6%	8%	10%	12%	13%	14%	15%
01453000	Lehigh River at Bethlehem, PA	61	EMA	2%	2%	1%	1%	2%	1%	---	---
01454700	Lehigh River at Glendon, PA	55	EMA	2%	2%	2%	2%	2%	2%	---	---
01459500	Tohickon Creek near Pipersville, PA	48	EMA	0%	0%	1%	1%	2%	3%	---	---
01464645	North Branch Neshaminy Creek below Lake Galena near New Britain, PA	36	EMA	−3%	0%	3%	7%	10%	14%	---	---
01464720	North Branch Neshaminy Creek at Chalfont, PA	31	EMA	−9%	−4%	3%	16%	27%	39%	---	---
01464750	Neshaminy Creek near Rushland, PA	26	WTD	2%	3%	4%	5%	5%	6%	6%	6%
01464907	Little Neshaminy Creek at Valley Road near Neshaminy PA	23	WTD	−1%	−1%	0%	1%	2%	1%	2%	2%
01465200	Neshaminy Creek near Penns Park, PA	20	WTD	−2%	0%	1%	3%	4%	4%	5%	6%
01465500	Neshaminy Creek near Langhorne, PA	88	WTD	−1%	−1%	−1%	0%	0%	0%	1%	1%
01467042	Pennypack Creek at Pine Road, at Philadelphia, PA	31	WTD	4%	8%	9%	11%	11%	11%	11%	12%
01470500	Schuylkill River at Berne, PA	75	WTD	1%	0%	0%	−1%	−1%	−1%	−2%	−2%
01470755	Maiden Creek near Virginville, PA	33	---	---	---	---	---	---	---	---	---
01470779	Tulpehocken Creek near Bernville, PA	48	WTD	5%	3%	2%	1%	0%	0%	−1%	−1%
01471875	Manatawny Creek near Spangsville, PA	28	WTD	2%	8%	13%	15%	17%	20%	22%	25%
01472157	French Creek near Phoenixville, PA	53	WTD	3%	2%	1%	0%	0%	−1%	−1%	−2%
01472198	Perkiomen Creek at East Greenville, PA	40	WTD	8%	14%	16%	17%	17%	17%	16%	16%
01472199	West Branch Perkiomen Creek at Hillegass, PA	40	WTD	5%	14%	18%	21%	44%	24%	25%	26%

Table 5.   Summary of percentage changes from previously published peak-flow annual exceedance probabilities for select streamgages associated with September 1–2, 2021, flooding in Pennsylvania.—Continued

[Previously published flood frequencies from Roland and Stuckey (2020) using data through 2015. Flood-frequency method determined from weighted estimates (WTD) or the at-site expected moments algorithm (EMA). USGS, U.S. Geological Survey; PA, Pennsylvania; %, percent; ---, not included in Roland and Stuckey (2020)]

USGS station number	USGS station name	Number of peaks used in current analysis	Flood-frequency method	Change of peak-flow exceedance values from previously published values (percent)							
				Exceedance probability							
				0.5	0.2	0.1	0.04	0.02	0.01	0.005	0.002
01472620	East Branch Perkiomen Creek near Dublin, PA	38	WTD	3%	5%	7%	7%	8%	8%	8%	8%
01472810	East Branch Perkiomen Creek near Schwenksville, PA	30	WTD	0%	4%	5%	7%	8%	8%	9%	9%
01473000	Perkiomen Creek at Graterford, PA	107	WTD	1%	7%	8%	8%	7%	5%	3%	1%
01473169	Valley Creek at PA Turnpike Bridge near Valley Forge, PA	39	WTD	8%	15%	17%	18%	18%	18%	17%	17%
01473500	Schuylkill River at Norristown, PA	36	---	---	---	---	---	---	---	---	---
01473900	Wissahickon Creek at Fort Washington, PA	41	WTD	3%	5%	6%	7%	7%	7%	−4%	7%
01474000	Wissahickon Creek at Mouth, Philadelphia, PA	56	WTD	2%	5%	6%	6%	6%	7%	7%	6%
01474500	Schuylkill River at Philadelphia, PA	43	EMA	2%	4%	6%	9%	11%	13%	---	---
01475850	Crum Creek near Newtown Square, PA	45	WTD	5%	8%	9%	9%	9%	8%	8%	8%
01476480	Ridley Creek at Media, PA	34	WTD	3%	2%	2%	1%	1%	1%	2%	1%
01478120	East Branch White Clay Creek at Avondale, PA	14	---	---	---	---	---	---	---	---	---
01480500	West Branch Brandywine Creek at Coatesville, PA	61	WTD	4%	4%	4%	3%	2%	1%	0%	1%
01480617	West Branch Brandywine Creek at Modena, PA	52	WTD	3%	6%	7%	7%	8%	8%	8%	8%
01480700	East Branch Brandywine Creek near Downingtown, PA	48	EMA	−1%	8%	18%	32%	44%	57%	---	---
01480870	East Branch Brandywine Creek below Downingtown, PA	48	EMA	0%	9%	18%	31%	42%	55%	---	---
01481000	Brandywine Creek at Chadds Ford, PA	102	WTD	0%	4%	6%	9%	11%	13%	15%	17%
01494850	East Branch Big Elk Creek at Forestville, PA	14	---	---	---	---	---	---	---	---	---
01560000	Dunning Creek at Belden, PA	83	WTD	−1%	1%	2%	3%	4%	5%	5%	6%
01564512	Aughwick Creek near Shirleysburg, PA	32	WTD	−2%	−3%	−3%	−2%	−2%	−2%	−2%	−1%
01572025	Swatara Creek near Pine Grove, PA	33	WTD	8%	6%	5%	4%	4%	3%	3%	2%
01572190	Swatara Creek near Inwood, PA	33	WTD	7%	4%	3%	1%	1%	0%	0%	0%
01573695	Conewago Creek near Bellaire, PA	10	---	---	---	---	---	---	---	---	---
01573710	Conewago Creek near Falmouth, PA	11	---	---	---	---	---	---	---	---	---
01573825	West Conewago Creek at East Berlin, PA	18	WTD	−5%	−3%	−2%	−2%	−1%	−1%	−1%	−1%

Table 5. Summary of percentage changes from previously published peak-flow annual exceedance probabilities for select streamgages associated with September 1–2, 2021, flooding in Pennsylvania.—Continued

[Previously published flood frequencies from Roland and Stuckey (2020) using data through 2015. Flood-frequency method determined from weighted estimates (WTD) or the at-site expected moments algorithm (EMA). USGS, U.S. Geological Survey; PA, Pennsylvania; %, percent; ---, not included in Roland and Stuckey (2020)]

USGS station number	USGS station name	Number of peaks used in current analysis	Flood-frequency method	Change of peak-flow exceedance values from previously published values (percent)							
				Exceedance probability							
				0.5	0.2	0.1	0.04	0.02	0.01	0.005	0.002
01576500	Conestoga River at Lancaster, PA	93	WTD	0%	1%	0%	1%	1%	1%	1%	1%
01576754	Conestoga River at Conestoga, PA	37	WTD	-3%	-1%	0%	0%	0%	0%	0%	0%
01601000	Wills Creek below Hyndman, PA	54	WTD	0%	2%	4%	6%	7%	7%	8%	9%
01613050	Tonoloway Creek near Needmore, PA	59	WTD	-1%	-1%	-2%	-1%	-1%	-1%	-1%	-1%

area, modeling boundary, and water-depth are available for download at Stuckey and Conlon (2023). The areas covered by the specific flood-documentation maps are described in the following sections. All reported peak-stage data obtained from USGS streamgages (U.S. Geological Survey, 2023c) in this report represent final approved data unless explicitly stated as provisional data. All elevations are referenced to NAVD 88 unless otherwise noted.

Brandywine Creek

Brandywine Creek generally flows southeast through Chester County in southeastern Pennsylvania to its confluence with the Christina River in Delaware. Brandywine Creek's two main branches, the East Branch Brandywine Creek and the West Branch Brandywine Creek, both begin in northern Chester County. Separate flood-documentation maps for the East Branch Brandywine Creek, West Branch Brandywine Creek, and the main stem Brandywine Creek were created to show the areal extent of flooding in the Brandywine Creek Basin (figs. 8–10). The map extent for the East Branch Brandywine Creek includes 5 miles (mi) through several municipalities, including the borough of Downingtown, Pennsylvania. (fig. 8). The map extent for the West Branch Brandywine Creek includes a short distance (about 0.5 mi) as it flows through the borough of Modena (fig. 9). The main-stem Brandywine Creek includes 9 mi as it flows through several municipalities, including Chadds Ford Township (fig. 10). A total of 105 HWMs surveyed along the Brandywine Creek were used to create flood-documentation maps: 43 in the East Branch Brandywine Creek, 40 in the West Branch Brandywine Creek, and 22 in the main stem Brandywine Creek. The measured height above ground surface at the HWMs ranged from 0 to 7.5 ft, and the peak water-surface elevations ranged from 47.8 to 84.5 ft above NAVD 88. The USGS operates two streamgages on the Brandywine Creek that were also used in the creation of the flood-documentation maps:

1. 01480700 East Branch Brandywine Creek near Downingtown—a peak stage of 13.60 ft above streamgage datum (approximate water-surface elevation of 268 ft above NGVD 88) was recorded at 19:30 on September 1, 2021; and

2. 01480617 West Branch Brandywine Creek at Modena—a peak stage of 13.36 ft above streamgage datum (water-surface elevation of 275.9 ft above NAVD 88) was recorded at 19:00 on September 1, 2021.

The USGS operates four precipitation gages in the Brandywine Creek Basin, only three of the four undergo review and approval of the data. Approved rainfall totals from the USGS precipitation gages ranged from 6.68 inches (01480399) to 8.18 inches (01480617) on September 1, 2021 (U.S. Geological Survey, 2023c). The NWS reported

rainfall totals in Chester County to be from 10.1 inches in Downingtown to 1.68 inches in Octoraro Creek Nottingham during the event (National Weather Service, 2023b).

Perkiomen Creek

Perkiomen Creek generally flows southeast through Berks, Bucks, Lehigh, and Montgomery Counties in south-eastern Pennsylvania to its confluence with the Schuylkill River. Perkiomen Creek consists of two main branches: the Perkiomen Creek, which begins in Berks County, and East Branch Perkiomen Creek, which begins in Bucks County. A flood-documentation map was created to show the areal extent of flooding in the Perkiomen Creek Basin near Graterford and Collegeville, Pennsylvania, which is downstream from the confluence of the two branches at Schwenksville, Pennsylvania (fig. 11). The map extent includes 8 mi of the Perkiomen Creek, flowing through the boroughs of Graterford and Collegeville, Pennsylvania. (fig.11). A total of 23 HWMs surveyed along the Perkiomen Creek were used to create the flood-documentation map. The measured height above ground surface at the HWMs ranged from 0 to 9.7 ft, and the peak water-surface elevations ranged from 35.6 to 49.7 ft above NAVD 88. The USGS operates two streamgages on the Perkiomen Creek that were also used to create the flood-documentation map:

1. 01472810 East Branch Perkiomen Creek near Schwenksville—A peak stage of 16.88 ft above streamgage datum (approximate water-surface elevation of 167 ft above NGVD 29) was recorded at 01:30 on September 2, 2021.

2. 01473000 Perkiomen Creek at Graterford—The equipment at the streamgage was inundated; therefore, an exact peak stage is unknown. An estimated peak stage of 24.23 ft above streamgage datum (water-surface elevation of 136.89 ft above NGVD 29) was determined for September 2, 2021.

The NWS reported rainfall totals in Montgomery County to be 8.4 inches in Hatfield to 3.48 inches in Glenside during the event (National Weather Service, 2023b).

Schuylkill River

The Schuylkill River generally flows southeast through the Schuylkill, Berks, and Montgomery Counties of southeastern Pennsylvania to its confluence with the Delaware River near Philadelphia, Pennsylvania. The Schuylkill River flows for 135 mi from the confluence of the East and West Branch Schuylkill River to Philadelphia and is joined by several major tributaries. One flood-documentation map was created to show the areal extent of flooding in the Schuylkill River Basin near Norristown and Bridgeport, Pennsylvania, which is downstream from the confluence of the Schuylkill River and Perkiomen Creek at Phoenixville, Pennsylvania (fig. 12). The

reach includes 4 mi of the Schuylkill River, flowing through the boroughs of Norristown and Bridgeport, Pennsylvania (fig. 12). A total of 26 HWMs surveyed along the Schuylkill River were used to create flood-documentation maps. The measured height above ground surface at the HWMs ranged from 0 to 9.1 ft above ground, and the peak water-surface elevations ranged from 22.3 to 24.0 ft above NAVD 88. The USGS operates one streamflow-gaging station on the Schuylkill River that was used in the creation of the flood-documentation maps:

1. 01473500 Schuylkill River at Norristown—A peak stage of 26.88 ft above streamgage datum (approximate water-surface elevation of 78 ft above NGVD 29) was recorded at 06:15 on September 2, 2021.

The USGS operates a precipitation gage at 01473500 Schuylkill River at Norristown. These precipitation data are not reviewed and approved and offered as provisional data for 120 days only (U.S. Geological Survey, 2023c). The provisional rainfall total recorded at 01473500 during the event was 7.00 inches. The NWS reported rainfall totals in Montgomery County to be 8.41 inches in Hatfield to 3.48 inches in Glenside during the event (National Weather Service, 2023b).

Flood Damages

The remnants of Hurricane Ida in September of 2021 that moved through the mid-Atlantic area caused historic flooding in many streams and rivers and the loss of many lives. Of the 96 fatalities caused by the storm along its entire path from Louisiana to New England, 22 were in the mid-Atlantic area (National Weather Service, 2023b). Many roads and bridges were damaged or destroyed. Estimates of monetary losses from damage to many homes, businesses, and infrastructure are estimated to be over 70 billion dollars; Pennsylvania alone had 117 million dollars' worth of damage (National Centers for Environmental Information, 2023a).

Summary

In September 2021, rainfall from the remnants of Hurricane Ida caused flooding in many streams and rivers in eastern and south-central Pennsylvania. Rainfall totals of 5 to 10 inches were widespread throughout the area, and most of the rain fell in little more than 6 hours. At least 22 fatalities were reported and damages were estimated to be in the millions of dollars for the mid-Atlantic area. In the aftermath of the flooding, the U.S. Geological Survey (USGS) and the Federal Emergency Management Agency initiated a cooperative study to flag and survey high-water marks and evaluate the flood's magnitude, extent, and probability of occurrence at select USGS streamgages in Pennsylvania.

Fifty-two USGS streamgages in Pennsylvania with at least 10 years of record had a 2021 annual peak streamflow related to Hurricane Ida that ranked in the top five of all annual peaks for a given station and a recurrence interval estimated to be at least 10-percent annual exceedance probability (AEP). The 52 analyzed streamgages had 10 to 107 years of peak streamflow data with a mean of 45 years of peak streamflow data. New peak streamflow records were recorded at 19 of the 52 USGS streamgages. The AEP estimates for the September 2021 event ranged from less than 0.2 to 10 percent (greater than a 500-year recurrence interval to a 10-year recurrence interval). Flood frequencies were also computed for the 52 streamgages using annual peak streamflow data through 2021 and compared with flood frequencies previously published in 2020 (using data through 2015). On average, the 1-percent AEP flood frequency statistic increased by 9 percent using the additional 6 years of data at streamgages used in both analyses.

USGS hydrographers identified and documented 338 high-water marks, 154 of which were used along with geographic information system methods to create 5 flood-documentation maps that document the depth and extent of flooding. Flood-documentation maps were created for communities along the West Branch Brandywine Creek near Modena, the East Branch Brandywine Creek near Downingtown, the main stem Brandywine Creek near Chadds Ford, the Perkiomen Creek near Graterford and Collegeville, and the main stem Schuylkill River near Norristown and Bridgeport. Digital datasets of the inundation area, modeling boundary, and water-depth are available for download.

References Cited

Austin, S.H., Watson, K.M., Lotspeich, R.R., Cauller, S.J., White, J.S., and Wicklein, S.M., 2018, Characteristics of peak streamflows and extent of inundation in areas of West Virginia and southwestern Virginia affected by flooding, June 2016 (ver. 1.1, September 2018): U.S. Geological Survey Open-File Report 2017–1140, 35 p., https://doi.org/10.3133/ofr20171140.

Benson, M.A., and Dalrymple, T., 1967, General field and office procedures for indirect discharge measurements: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. Al, 30 p. [Also available at https://pubs.er.usgs.gov/publication/twri03A1.]

Cohn, T.A., Lane, W.L., and Baier, W.G., 1997, An algorithm for computing moments-based flood quantile estimates when historical flood information is available: Water Resources Research, v. 33, no. 9, p. 2089–2096. [Also available at https://doi.org/10.1029/97WR01640.]

Cohn, T.A., England, J.F., Berenbrock, C.E., Mason, R.R., Stedinger, J.R., and Lamontagne, J.R., 2013, A generalized Grubbs-Beck test statistic for detecting multiple potentially influential low outliers in flood series: Water Resources Research, v. 49, no. 8, p. 5047–5058. [Also available at https://doi.org/10.1002/wrcr.20392.]

England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2018, Guidelines for determining flood flow frequency—Bulletin 17C: U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., accessed April 2, 2018, at https://doi.org/10.3133/tm4B5.

Esri, 2021, Topo to raster: Esri web page, accessed January 21, 2022, at https://desktop.arcgis.com/en/arcmap/latest/tools/3d-analyst-toolbox/topo-to-raster.htm.

Federal Emergency Management Agency, 2023, One month later—By the numbers: Federal Emergency Management Agency press release, accessed August 8, 2023, at https://www.fema.gov/press-release/20211019/one-month-later-numbers#:~:text=A%20major%20federal%20disaster%20was%20declared%20for%20the,Bedford%20and%20Northampton%2C%20were%20added%20on%20September%2024.

Holmes, R.R., Jr., and Dinicola, K., 2010, 100-Year flood—It's all about chance: U.S. Geological Survey General Information Product 106, 1 p. [Also available at https://pubs.usgs.gov/gip/106/.]

Interagency Advisory Committee on Water Data, 1982, Guidelines for determining flood flow frequency: Reston, Va., U.S. Geological Survey, Office of Water Data Coordination, Hydrology Subcommittee Bulletin 17B [variously paged].

Koenig, T.A., Bruce, J.L., O'Connor, J.E., McGee, B.D., and Holmes, R.R., Jr., Hollins, R., Forbes, B.T., Kohn, M.S., Schellekens, M.F., Martin, Z.W., and Peppler, M.C., 2016, Identifying and preserving high-water mark data: U.S. Geological Survey Techniques and Methods, book 3, chap. A24, 47 p. [Also available at https://doi.org/10.3133/tm3A24.]

Musser, J.W., Watson, K.M., Painter, J.A., and Gotvald, A.J., 2016, Flood-inundation maps of selected areas affected by the flood of October 2015 in central and coastal South Carolina: U.S. Geological Survey Open-File Report 2016–1019, 81 p. [Also available at https://doi.org/10.3133/ofr20161019.]

National Centers for Environmental Information, 2023a, September 2021 national climate report: National Centers for Environmental Information web page, accessed June 20, 2023, at https://www.ncei.noaa.gov/access/monitoring/monthly-report/national/202109.

National Centers for Environmental Information, 2023b, U.S. climate normals quick access: National Centers for Environmental Information web page, accessed June 20, 2023, at https://www.ncei.noaa.gov/access/us-climate-normals/.

National Weather Service, 2019, National Weather Service manual 10-950—Definitions and general terminology: Water Resources Services Program, accessed June 17, 2023, at pd01009050curr.pdf (noaa.gov).

National Weather Service, 2023a, Advanced Hydrologic Prediction Service: National Weather Service web page, accessed June 20, 2023, at https://water.weather.gov/precip/.

National Weather Service, 2023b, September 1—Remnants of Ida: National Weather Service web page, accessed June 20, 2023, at https://www.weather.gov/phi/eventreview20210901.

Pennsylvania Bureau of Topographic and Geologic Survey, 1998, Preliminary landform subdivisions of Pennsylvania, 1998: Harrisburg, Pa., Pennsylvania Bureau of Topographic and Geologic Survey, Department of Conservation and Natural Resources digital geographic information systems dataset, accessed June 21, 2023, at https://www.pasda.psu.edu/uci/DataSummary.aspx?dataset=295.

Pennsylvania Department of Conservation and Natural Resources, 2023, Landforms: Pennsylvania Department of Conservation and Natural Resources web page, accessed August 7, 2023, at https://www.dcnr.pa.gov/Geology/GeologyOfPA/Landforms/Pages/default.aspx.

Rantz, S.E., 1982, Measurement and computation of streamflow: U.S. Geological Survey Water-Supply Paper 2175, v. 1, 284 p. (Also available at https://doi.org/10.3133/wsp2175.)

Roland, M.A., and Stuckey, M.H., 2020, Development of regression equations for the estimation of flood flows at ungaged streams in Pennsylvania (ver. 1.1, December 2020): U.S. Geological Survey Scientific Investigations Report 2019–5094, 36 p. [Supersedes USGS Scientific Investigations Report 2008–5102]. [Also available at https://doi.org/10.3133/sir20195094.]

Stuckey, M.H., and Conlon, M.D., 2023, Data in support of peak streamflows and flooding in select areas of Pennsylvania from the remnants of Hurricane Ida, September 1–2, 2021: U.S. Geological Survey data release, https://doi.org/10.5066/P9GR6FPU.

Turnipseed, D.P., and Sauer, V.B., 2010, Discharge measurements at gaging stations: U.S. Geological Survey Techniques and Methods book 3, chap. A8, 87 p. [Also available at https://pubs.usgs.gov/tm/tm3-a8/.]

U.S. Geological Survey, 2012, Computation of annual exceedance probability (AEP) for characterization of observed flood peaks: Office of Surface Water Technical Memorandum 2013.01, accessed December 16, 2022, at https://water.usgs.gov/admin/memo/SW/sw13.01.pdf.

U.S. Geological Survey, 2021, USGS flood event viewer: U.S. Geological Survey web page, accessed July 5, 2023, at https://www.usgs.gov/tools/usgs-flood-event-viewer.

U.S. Geological Survey, 2023a, 1 meter digital elevation models (DEMs)—USGS National Map 3DEP downloadable data collection: U.S. Geological Survey data release, accessed October 26, 2022, at https://data.usgs.gov/datacatalog/data/USGS:77ae0551-c61e-4979-aedd-d797abdcde0e.

U.S. Geological Survey, 2023b, PeakFQ software user notice: U.S. Geological Survey web page, accessed June 20, 2023, at https://www.usgs.gov/mission-areas/water-resources/peakfq-software-user-notice.

U.S. Geological Survey, 2023c, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed July 5, 2023, at https://doi.org/10.5066/F7P55KJN.

Veilleux, A.G., Cohn, T.A., Flynn, K.M., Mason, R.R., Jr., and Hummel, P.R., 2014, Estimating magnitude and frequency of floods using the PeakFQ 7.0 program: U.S. Geological Survey Fact Sheet 2013–3108, 2 p., [Also available at https://doi.org/10.3133/fs20133108.]

Watson, K.M., Storm, J.B., Breaker, B.K., and Rose, C.E., 2017, Characterization of peak streamflows and flood inundation of selected areas in Louisiana from the August 2016 flood: U.S. Geological Survey Scientific Investigations Report 2017–5005, 26 p., accessed March 2018 at https://pubs.er.usgs.gov/publication/sir20175005.

Watson, K.M., Harwell, G.R., Wallace, D.S., Welborn, T.L., Stengel, V.G., and McDowell, J.S., 2018, Characterization of peak streamflows and flood inundation of selected areas in southeastern Texas and southwestern Louisiana from the August and September 2017 flood resulting from Hurricane Harvey: U.S. Geological Survey Scientific Investigations Report 2018–5070, 44 p., accessed June 21, 2023, at https://doi.org/10.3133/sir20185070.