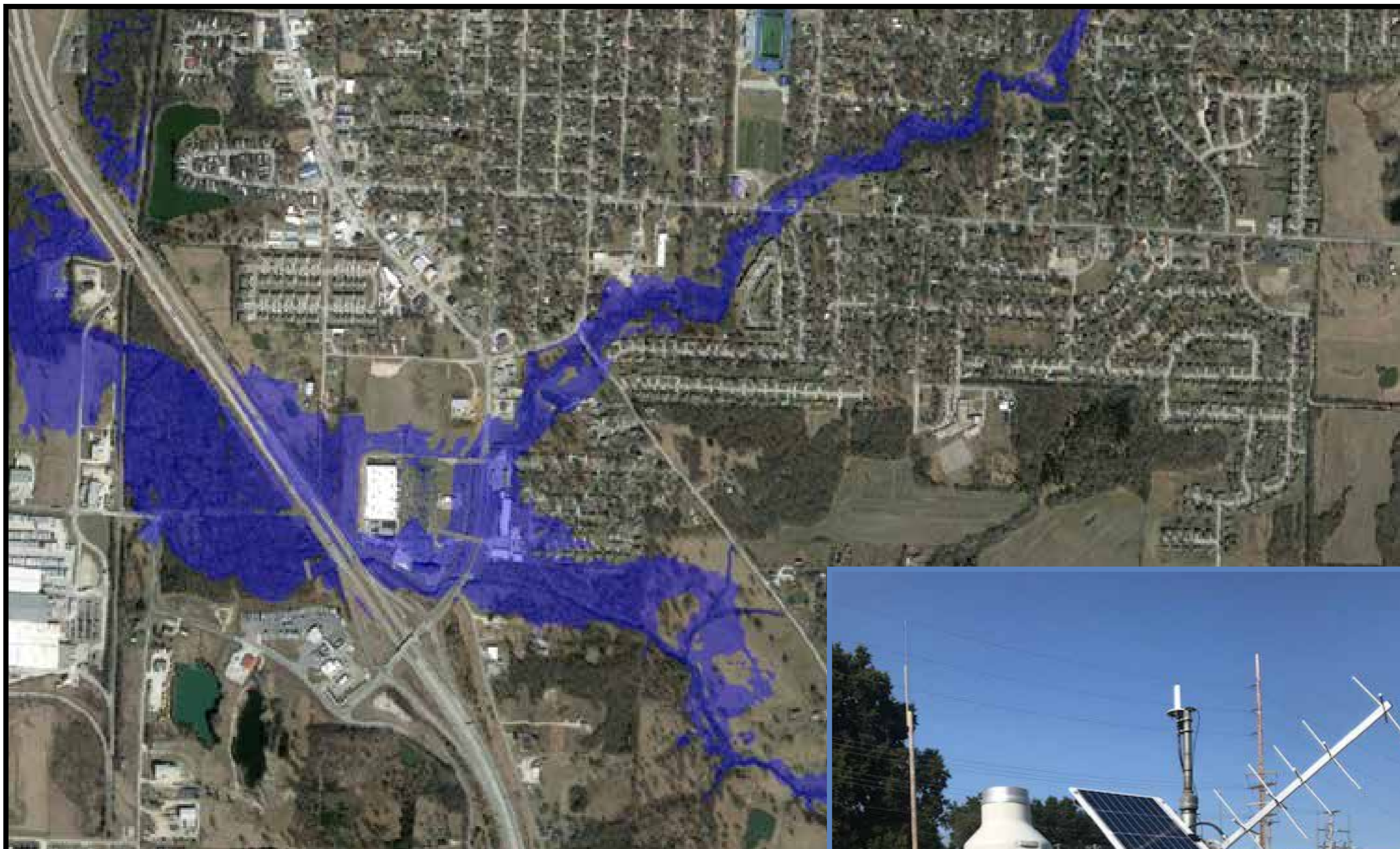
USGS
science for a changing world

Prepared in cooperation with the city of Harrisonville, Missouri

Precipitation-Driven Flood-Inundation Mapping of Muddy Creek at Harrisonville, Missouri



Scientific Investigations Report 2022–5084

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

Map image: Map of the peak simulated flood-inundation extent of Muddy Creek in Harrisonville, Missouri, for a precipitation amount of 6.83 inches in 6 hours.

Photograph of precipitation gage: Photograph showing weighing-bucket precipitation-only gage Harrisonville South (U.S. Geological Survey station 383843094205501) in Harrisonville, Missouri, taken on September 15, 2020, by David Heimann, U.S. Geological Survey.

Precipitation-Driven Flood-Inundation Mapping of Muddy Creek at Harrisonville, Missouri

By David C. Heimann and Paul H. Rydlund

Prepared in cooperation with the city of Harrisonville, Missouri

Scientific Investigations Report 2022–5084

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

U.S. Geological Survey, Reston, Virginia: 2022

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment—visit https://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit https://store.usgs.gov/.

Suggested citation:
Heimann, D.C., and Rydlund, P.H., 2022, Precipitation-driven flood-inundation mapping of Muddy Creek at Harrisonville, Missouri: U.S. Geological Survey Scientific Investigations Report 2022–5084, 18 p., https://doi.org/10.3133/sir20225084.

Associated data for this publication:
City of Harrisonville, 2022, Flood-inundation mapping and model of Muddy Creek: City of Harrisonville web page, https://ci.harrisonville.mo.us/1052/Stormwater-Management.

Heimann, D.C., 2022, Geospatial data and model archives associated with precipitation-driven flood-inundation mapping of Muddy Creek at Harrisonville, Missouri (ver. 2.0, December 2022): U.S. Geological Survey data release, https://doi.org/10.5066/P969ZOLB.

U.S. Geological Survey, 2020, USGS water data for the Nation: U.S. Geological Survey National Water Information System database, https://doi.org/10.5066/F7P55KJN.

ISSN 2328-0328 (online)

Acknowledgments

The authors wish to acknowledge funding provided by the city of Harrisonville, Missouri, for this study along with the continued support from the city of Harrisonville in funding the U.S. Geological Survey precipitation-only gage within the Muddy Creek study basin.

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)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($[ft^3/s]/mi^2$)	0.01093	cubic meter per second per square kilometer ($[m^3/s]/km^2$)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

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

$$°C = (°F - 32) / 1.8.$$

Datum

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).

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

Abbreviations

AEP	annual exceedance probability
CN	Soil Conservation Service runoff curve number
CNI	Soil Conservation Service runoff curve number representing a “dry” antecedent runoff condition
CNII	Soil Conservation Service runoff curve number representing a “normal” antecedent runoff condition
CNIII	Soil Conservation Service runoff curve number representing a “wet” antecedent runoff condition
DEM	digital elevation model
FIS	flood-insurance study
GIS	geographic information system
HEC–HMS	USACE Hydrologic Engineering Center-Hydrologic Modeling System
HEC–RAS	USACE Hydrologic Engineering Center-River Analysis System
lidar	light detection and ranging
n-value	Manning’s roughness coefficient
NSE	Nash-Sutcliffe efficiency
PBIAS	percentage bias
PT	pressure transducer
R	storage coefficient
RMSE	root mean square error
Tc	time of concentration
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
∞	infinity

Precipitation-Driven Flood-Inundation Mapping of Muddy Creek at Harrisonville, Missouri

By David C. Heimann and Paul H. Rydlund

Abstract

The U.S. Geological Survey, in cooperation with the city of Harrisonville, Missouri, assessed flooding of Muddy Creek resulting from varying precipitation magnitudes and durations, antecedent runoff conditions, and channel modifications (cleaned culverts and added detention storage). The precipitation scenarios were used to develop a library of flood-inundation maps that included a 3.8-mile reach of Muddy Creek and tributaries within and adjacent to the city.

Hydrologic and hydraulic models of the upper Muddy Creek study basin were used to assess streamflow magnitudes associated with simulated precipitation amounts and the resulting flood-inundation conditions. The U.S. Army Corps of Engineers Hydrologic Engineering Center-Hydrologic Modeling System (HEC–HMS; version 4.4.1) was used to simulate the amount of streamflow produced from a range of precipitation events. The Hydrologic Engineering Center-River Analysis System (HEC–RAS; version 5.0.7) was then used to route streamflows and map resulting areas of flood inundation.

The hydrologic and hydraulic models were calibrated to the September 28, 2019; May 27, 2021; and June 25, 2021, runoff events representing a range of antecedent runoff conditions and hydrologic responses. The calibrated HEC–HMS model was used to simulate streamflows from design rainfall events of 30-minute to 24-hour durations and ranging from a 100- to 0.1-percent annual exceedance probability. Flood-inundation maps were produced for reference stages of 1.0 foot (ft), or near bankfull, to 4.0 ft, or a stage exceeding the 0.1-percent annual exceedance probability interval precipitation, using the HEC–RAS model. The results of each precipitation duration-frequency value were represented by a 0.5-ft increment inundation map based on the generated peak streamflow from that rainfall event and the corresponding stage at the Muddy Creek reference location.

Seven scenarios were developed with the HEC–HMS hydrologic model with resulting streamflows routed in a HEC–RAS hydraulic model, and these scenarios varied by antecedent runoff condition and potential channel modifications. The same precipitation scenarios were used in each of the seven antecedent runoff and channel conditions, and the simulation results were assigned to a flood-inundation map condition based on the generated peak flow and corresponding stage at the Muddy Creek reference location.

Introduction

The city of Harrisonville, in Cass County in west-central Missouri (fig. 1), had an estimated population of 10,121 in 2020 (U.S. Census Bureau, 2021). The city experienced moderate to major flooding from Muddy Creek in July and August 2017 and again in September 2019. Floodplains along the north tributary of Muddy Creek and the upper main stem of Muddy Creek within the city generally are moderately to highly developed and contain a mix of residential and commercial structures. Before this study, emergency responders in Harrisonville relied on several information sources (all of which are publicly available) to make decisions on how to best alert the public and mitigate flood damages along Muddy Creek. One source is the U.S. Army Corps of Engineers (USACE) Silver Jackets floodplain investigation (U.S. Army Corps of Engineers, 2020a). A second source of information regarding flooding is the Federal Emergency Management Agency flood-insurance study (FIS) for Cass County, dated January 2013 (Federal Emergency Management Agency, 2013). A third source of flood-related information is the National Weather Service issued watches, warnings, and advisories (https://www.weather.gov/).

In 2020, the U.S. Geological Survey (USGS), in cooperation with the city of Harrisonville, Mo., began a project to develop a library of flood-inundation maps for a selected reach of Muddy Creek (fig. 2) and to relate these maps to different rainfall frequencies and durations. As part of this study, a precipitation-only gage, Harrisonville South (USGS station 383843094205501; U.S. Geological Survey, 2020b; fig. 1; table 1) was installed to provide real-time precipitation data within the Muddy Creek study basin. Although the current stage at a particular reference location is useful for residents near the location, it is of limited use to residents farther upstream or downstream because the water-surface elevation is not constant along the stream reach. Knowledge of water levels is difficult to translate into depth and areal extent of flooding at points distant from the reference location.

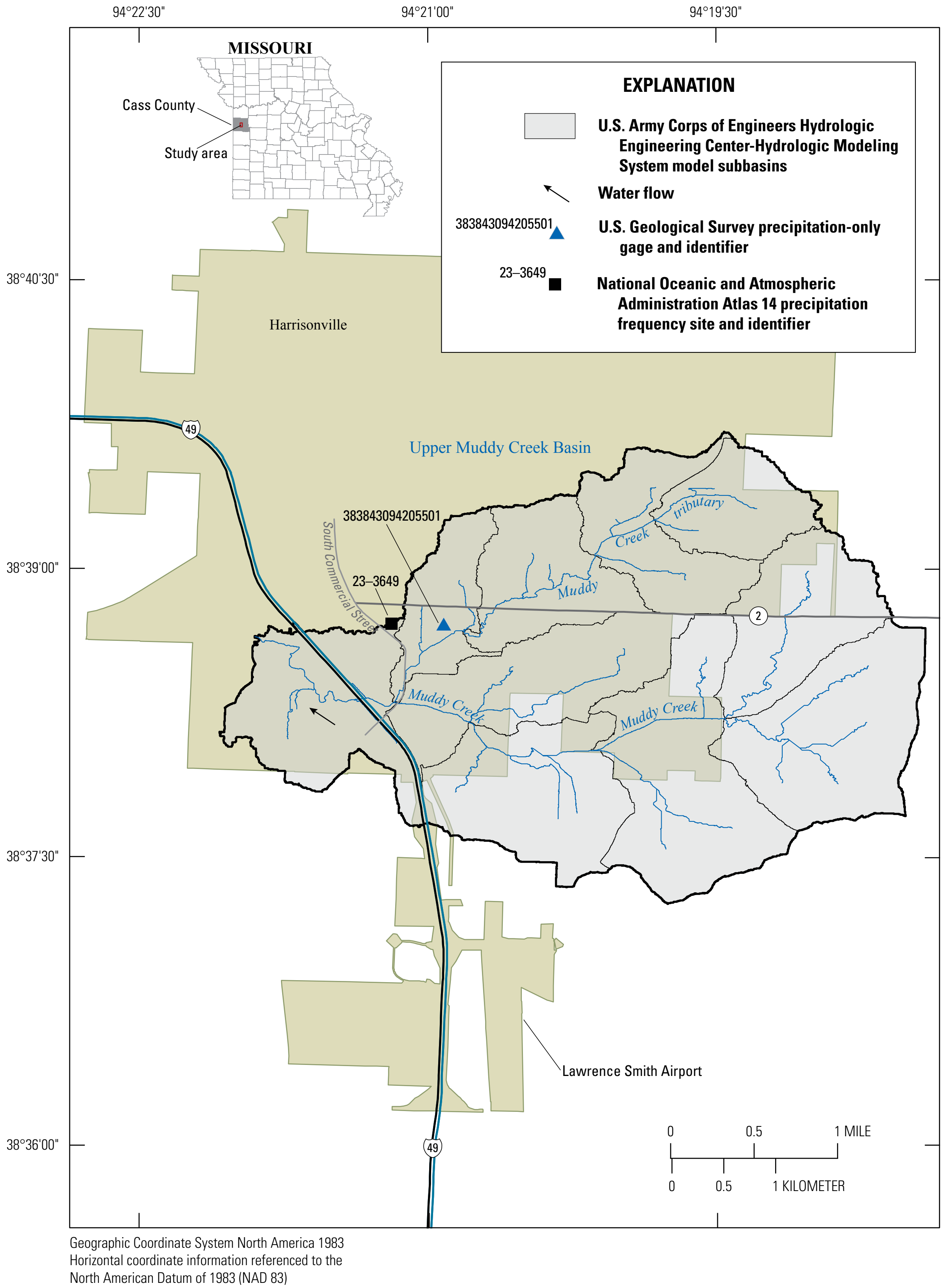


Figure 1. Location of the city of Harrisonville and upper Muddy Creek study basin in Cass County, Missouri.

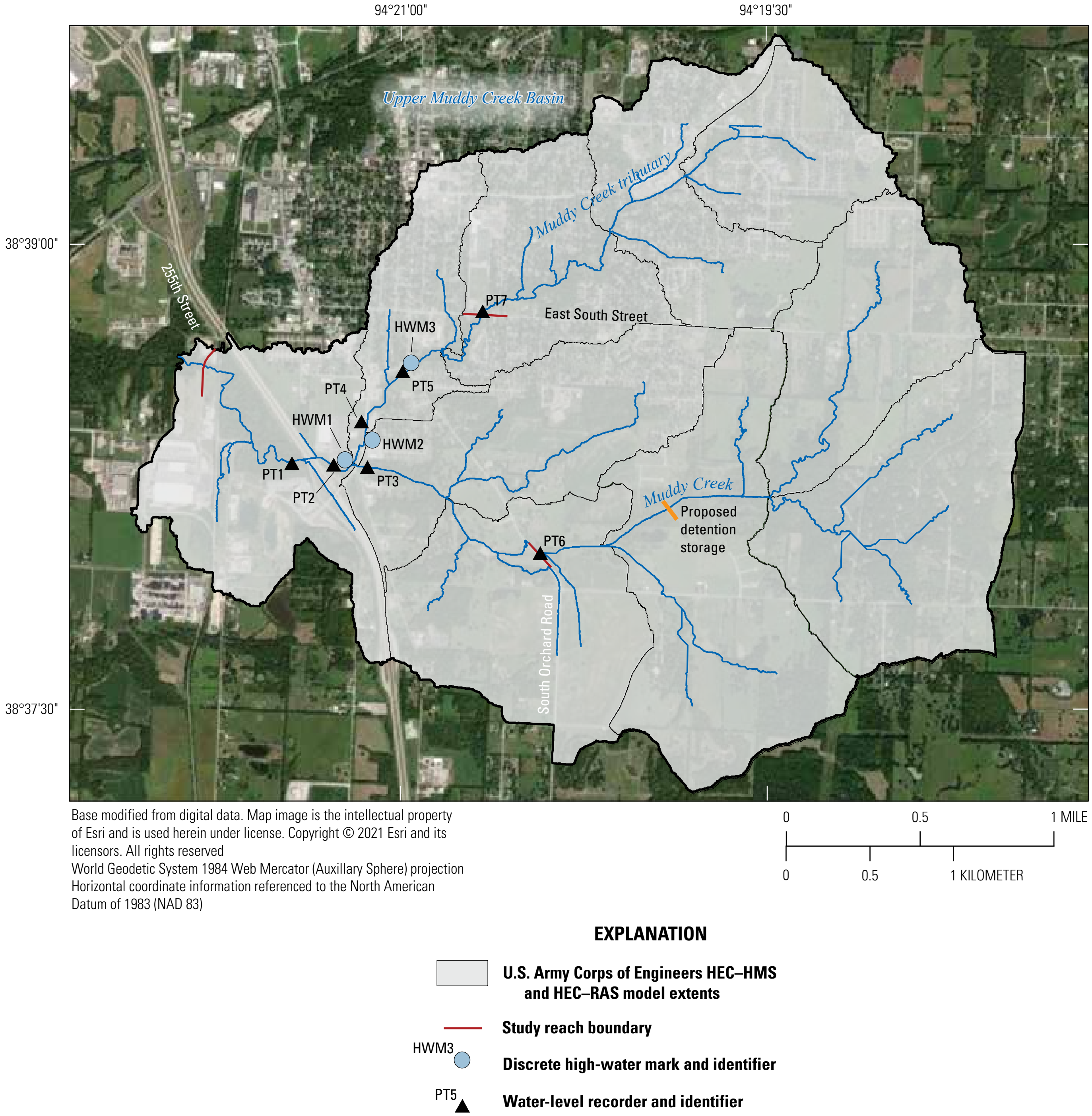


Figure 2. U.S. Army Corps of Engineers Hydrologic Engineering Center-Hydrologic Modeling System (HEC–HMS) and Hydrologic Engineering Center-River Analysis System (HEC–RAS) model extents, water-level monitoring locations, and extent of flood-inundation maps along Muddy Creek, Harrisonville, Missouri.

The small drainage area (5.3 square miles [mi²]) of Muddy Creek at Harrisonville and the small lead time of less than 2 hours (based on observed events) provide limited advance notice to potential flood conditions. One way to address these informational gaps is to produce a library of flood-inundation maps that are based on precipitation amounts and durations and referenced to the stages recorded at a selected reference location. By referring to the appropriate map, emergency responders can discern the severity of flooding (depth of water and areal extent), identify roads that are or will soon be flooded, and make plans for notifying or evacuating residents in harm's way for some distance upstream and

Table 1. Description of U.S. Geological Survey precipitation-only gage in the Muddy Creek study basin.

[Station location is shown in figure 1. Latitude and longitude are given in degrees (°), minutes (′), and seconds (″). USGS, U.S. Geological Survey; NAD 83, North American Datum of 1983; present refers to the time of publication (2022)]

USGS station name	USGS station number	Latitude (NAD 83)	Longitude (NAD 83)	Period of record (water year[a])
Harrisonville South	383843094205501	38°38′43″	94°20′55″	2020–present

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

downstream from a selected location. In addition, the capability to visualize the potential extent of flooding may motivate residents to take precautions and heed warnings that they previously might have disregarded.

Purpose and Scope

This report describes the development of a series of estimated flood-inundation maps for Muddy Creek at Harrisonville and identifies where on the internet the maps can be accessed and ancillary data (geographic information system [GIS] flood polygons and depth grids) can be downloaded. The study extent includes a 3.8-mile reach extending from 255th Street at the downstream end of the reach to East South Street (Highway 2) on the north tributary of Muddy Creek and to South Orchard Road on the upper Muddy Creek main stem (fig. 2). The maps were produced for flood levels using streamflow and reference stage data collected at Muddy Creek near Interstate 49 (pressure transducer [PT] reference location PT1 in fig. 2) and simulated flood peaks from a range of precipitation probabilities and durations. The procedures applied in constructing the hydrologic and hydraulic models used to simulate flood-inundation scenarios with design rainfall events of 30-minute to 24-hour durations ranging from a 100- to a 0.1-percent annual exceedance probability (AEP) are described. Flood levels were referenced to water levels recorded at a reference location along Muddy Creek near Interstate 49 near the downstream end of the study reach.

The flood-inundation maps of Muddy Creek cover stages ranging from 1.0 to 4.0 feet (ft), in 0.5-ft increments referenced to the elevation of the water surface at the Muddy Creek reference location (PT1). The 1.0-ft stage corresponds to a water-surface elevation of 871.0 ft and is near bankfull condition. The 4.0-ft stage, correlating to a water-surface elevation of 874.0 ft, exceeds the stage that corresponds to the estimated 0.1-percent AEP precipitation event.

Study Area Description

Muddy Creek is in west-central Missouri in the Wooded Osage Plains subdivision (U.S. Environmental Protection Agency, 2020) of the Central Irregular Plains ecoregion (Omernik, 1987). The study basin is characterized by gently rolling to moderately hilly topography with about 170 ft of relief (determined using the Cass County digital elevation model [DEM]; U.S. Geological Survey, 2021b). The headwaters originate in Cass County, Mo., and the stream flows generally westward before joining Town Creek (not shown on fig. 1) and the East Branch of the Grand River (not shown on fig. 1). The drainage area at the stage reference location near Interstate 49 is 5.3 mi^2, as calculated using StreamStats (U.S. Geological Survey, 2021a). Based on the DEM derived from light detection and ranging (lidar) data (U.S. Geological Survey, 2021b), Muddy Creek within Harrisonville has an average top-of-bank channel width of about 58 ft and an average channel slope of about 21 feet per mile. The greatest commercial and residential property damage from flooding along Muddy Creek has been along South Commercial Street near the intersection with Interstate 49 (fig. 1).

Based on the 2019 National Land Cover Database (Dewitz, 2021), about 45.4 percent of the land cover in the Muddy Creek study basin upstream from Interstate 49 was classified as developed; 38.9 percent was classified as cropland, grasslands, and pasture; and 14.8 percent was classified as forest. In the hydraulic model of the upper Muddy Creek study area, 12 channel structures (bridges and culverts) were included.

Previous Studies

Probabilistic flood-inundation maps showing the extent of flood inundation previously were generated as part of the latest FIS for Muddy Creek and the city of Harrisonville (Federal Emergency Management Agency, 2013) completed by AMEC Earth and Environmental in March 2010. The FIS provides estimates of peak streamflows of 10-, 4-, 2-, 1-, and 0.2-percent AEPs and their associated water-surface elevations for Muddy Creek and selected tributaries.

Creation of Flood-Inundation-Map Library

The USGS has standardized the procedures for creating flood-inundation maps for flood-prone communities (U.S. Geological Survey, 2020a) so that the process followed and products produced are similar regardless of which USGS office is responsible for the work. Tasks specific to the development of the flood-inundation maps for this study included (1) developing and acquiring hydrologic and hydraulic models for the upper Muddy Creek study basin, (2) collecting streamflow measurements and high-water marks for high-flow events during the study period, (3) calibrating parameters associated with the hydrologic model, (4) calibrating energy-loss factors (roughness coefficients) in the stream channel and floodplain associated with the hydraulic model, (5) determining unsteady-state flow data using the calibrated USACE Hydrologic Engineering Center-Hydrologic Modeling System (HEC–HMS) computer program (U.S. Army Corps of Engineers, 2020c) and probabilistic precipitation events, (6) computing water-surface profiles using the USACE Hydrologic Engineering Center-River Analysis System (HEC–RAS) computer program (U.S. Army Corps of Engineers, 2019), (7) producing estimated flood-inundation maps for the selected study reach using HEC–RAS and a GIS, and (8) preparing the maps as shapefile polygons that depict the areal extent of flood inundation at various stages and as depth grids that provide the depth of floodwaters shown on a USGS flood-inundation mapping application.

Precipitation-Derived Streamflow

Given the lack of an established streamgage on Muddy Creek, a theoretical rating was developed using existing streamflow measurements and the calibrated HEC–RAS model. Muddy Creek at Harrisonville is not a National Weather Service forecast point because of the lack of an established streamgage, the small drainage area (5.3 mi^2), and the flashy hydrologic response of this basin. Flood stages at this location were, therefore, predicted from varying rainfall magnitudes and durations and the generated flood hydrographs from a calibrated hydrologic model (HEC–HMS).

Hydrologic Data

This study uses hydrologic data from discrete streamflow measurements and discrete and continuous stage measurements including those collected at a reference location (PT1) on Muddy Creek near Interstate 49 (fig. 2). Discrete streamflow measurements during high-flow events were collected in accordance with techniques provided in Turnipseed and Sauer (2010). Stage at PT locations (fig. 2) was measured every 5 minutes using a submersible data logger, and data were corrected for atmospheric pressure changes using continuous (5-minute increments) barometric pressure data. The stage data at the reference location (PT1) were converted to water-surface elevations referenced to the North American Vertical Datum of 1988 by adding the vertical datum of 865.20 ft. The time-series data for this and other PTs used in this study are available in a USGS data release (Heimann, 2022). A level IV survey (Rydlund and Densmore, 2012) procedure was used in acquiring reference elevations for PT locations in the study reach with a resulting vertical accuracy of reference points within 0.32 ft.

Hydrologic Model Development

A hydrologic model was used to simulate the peak streamflow for Muddy Creek using design rainfall events covering a range of magnitudes and probabilities of exceedance. The hydrologic model was constructed using the USACE modeling system HEC–HMS (version 4.4.1; U.S. Army Corps of Engineers, 2020c). The HEC–HMS model was calibrated to a stage-discharge rating developed for the PT1 reference location using discrete streamflow measurements and continuous stage measurements during the May 27, 2021, and June 25, 2021, events. The calibrated HEC–HMS model was then used to simulate precipitation runoff from Atlas 14 rainfall amounts (National Oceanic and Atmospheric Administration, 2020) at site 23–3649 (fig. 1) covering a range of 30 minutes to 24 hours in duration and AEPs of 100 to 0.1 percent (Heimann, 2022). Output peak flow time series from the HEC–HMS model were then used as inputs to the hydraulic model (see “Hydraulic Model” section).

The HEC–HMS model was developed with the USACE Hydrologic Engineering Center-Geospatial Hydrologic Modeling System tool (version 10.2; U.S. Army Corps of Engineers, 2020b) and ArcHydro toolbox (version 10.7.1; Esri, 2021), which are GIS extensions. With the extensions, a 4-ft DEM and stream centerline were used to delineate the 5.3-mi^2 drainage basin, define 10 subbasins (fig. 2), and define initial model parameters. The HEC–HMS model was run for single rainfall events (rather than as a continuous simulation), and subbasin components were defined for transformation, loss, and recession components in the model. The HEC–HMS model was then used to estimate streamflow time series at subbasin outlet locations that were used to represent inflow boundary locations in the hydraulic model.

Model Scenarios

Seven hydrologic and hydraulic model scenarios were developed for this study (table 2) and included “dry,” “normal,” and “wet” antecedent runoff conditions and potential future modifications to channel conditions including the addition of detention storage and clean culverts (the default simulation conditions include about 1 ft of sediment in selected culverts). The potential future detention storage was included on the upper main stem of Muddy Creek (fig. 2), is designed to pass base flow and low-risk floods (U.S. Army Corps of Engineers, 2020a), and includes about 115 acre-feet of storage.

Precipitation Data

Accurate precipitation data are needed as inputs to the hydrologic model to simulate the resulting runoff and streamflow. A precipitation-only gage (Harrisonville South, USGS station 383843094205501) was installed on

September 14, 2020, within the Muddy Creek study basin (fig. 1). Precipitation totals at the precipitation-only gage are logged every 5 minutes and transmitted every 15 minutes by satellite radio, and the gage has been in operation since September 2020 (U.S. Geological Survey, 2020b). The historical September 2019 precipitation values (20-minute data) were obtained from the National Weather Service for the Lawrence Smith Airport, Harrisonville, Mo. (Iowa State University, 2021). The observed precipitation for the September 28, 2019; May 27, 2021; and June 25, 2021, high-flow events were used in calibrating the HEC–HMS model. In the future, observed precipitation data from the Harrisonville South precipitation-only gage can serve as an indicator of potential flooding. Precipitation totals corresponding to 1-, 2-, 3-, 4-, 6-, 12-, and 24-hour durations can be set in the USGS WaterAlert system (U.S. Geological Survey, 2021c) to notify users when target conditions have been met. The HEC–HMS simulations corresponding to selected precipitation event durations and magnitudes indicate the hydrologic response of the rainfall event and the appropriate flood-inundation map to reference.

Common precipitation events used as input to the hydrologic model for seven modeled scenarios (table 2) were developed from the National Oceanic and Atmospheric Administration Atlas 14 point-precipitation frequency estimates (National Oceanic and Atmospheric Administration, 2020) using the Harrisonville, Mo., precipitation station (site identifier 23–3649, fig. 1). The Atlas 14 event duration values were refined to include additional 4- and 8-hour duration events for this small study basin. The values for the 4- and 8-hour precipitation magnitudes were interpolated by fitting a logarithmic trend line to the 1-, 2-, 3-, 6-, 12-, and 24-hour duration values for each recurrence interval (fig. 3). The values represent a total amount for the specified duration. Time series of precipitation based on these totals were developed by distributing the precipitation in 5-minute increments over the specified duration using an alternating block distribution approach (Chow and others, 1988).

Transformation Method

Precipitation exceeding soil infiltration and storage is transformed into runoff in the developed HEC–HMS model using the Clark (1945) unit-hydrograph method. Two parameters needed to define this unit-hydrograph method are time of concentration (*Tc*) and a storage coefficient (*R*). The *Tc* is the time of travel (in hours) it takes for precipitation runoff to travel from the most distant point in a subbasin to the subbasin outlet. *R* is a storage coefficient (in hours) used to account for storage within the floodplain such as wetlands, reservoirs, and bridges that can produce flood-wave attenuation. Initial estimates of *Tc* were calculated using the TR–55 methodology (Soil Conservation Service, 1986). The *R* values were set to the initial *Tc* values for the subbasins such that $R/(Tc+R)=0.5$ corresponding to the approximate mean value for this relation in rural basins in Illinois (Straub and others, 2000) and these parameters were adjusted during model calibration.

Loss Method

The Soil Conservation Service runoff curve number (CN) method was used to simulate precipitation losses (Soil Conservation Service, 1986; Natural Resources Conservation Service, 2004). The CN values were applied to each subbasin according to the TR–55 methodology (Soil Conservation Service, 1986), and represent hydrologic soil types, land uses and treatments, and antecedent runoff conditions. Composite CNs for each subbasin were determined through the Hydrologic Engineering Center-Geospatial Hydrologic Modeling System by developing a CN grid using soil spatial data from the Soil Survey Geographic Database (Natural Resources Conservation Service, 2020), land-cover information from the 2019 National Land Cover Database (Dewitz, 2021), and a lookup table of CN values corresponding to soil hydrologic classes and land use (Soil Conservation Service, 1986).

Table 2. Description of U.S. Army Corps of Engineers Hydrologic Engineering Center-Hydrologic Modeling System and Hydrologic Engineering Center-River Analysis System model scenarios developed in the study.

[CNI, Soil Conservation Service runoff curve number representing a “dry” antecedent runoff condition; CNII, Soil Conservation Service runoff curve number representing a “normal” antecedent runoff condition; CNIII, Soil Conservation Service runoff curve number representing a “wet” antecedent runoff condition]

Model scenario	Terrain	Antecedent runoff condition
1	Existing	CNI, dry
2	Existing, with detention	CNI, dry
3	Existing	CNII, normal
4	Existing, with clean culverts	CNII, normal
5	Existing, with detention	CNII, normal
6	Existing	CNIII, wet
7	Existing, with detention	CNIII, wet

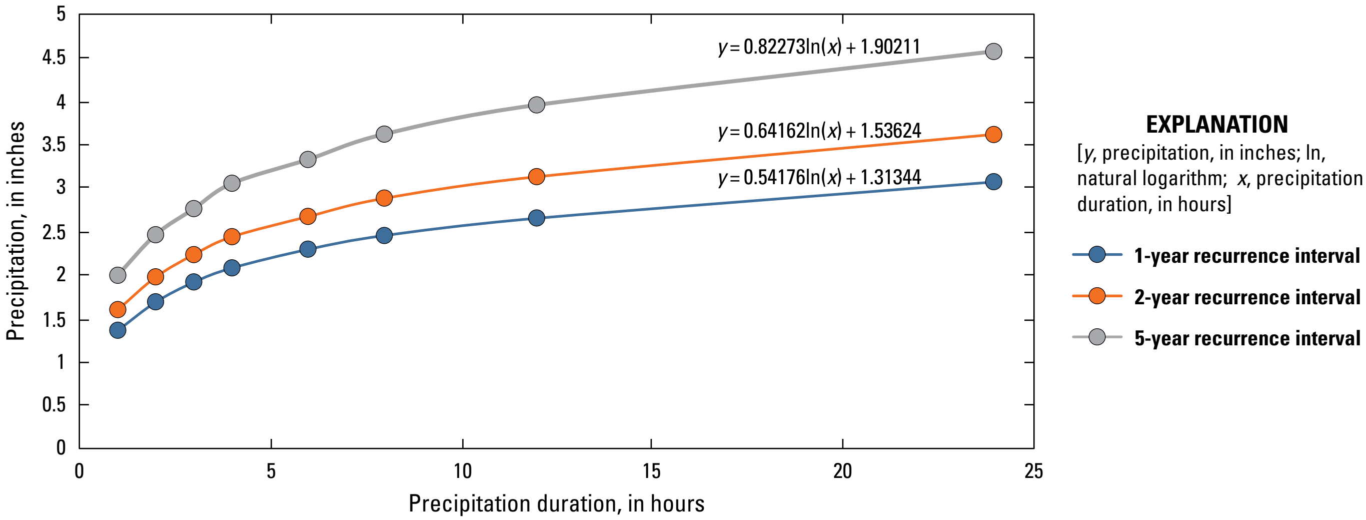


Figure 3. Examples of the interpolation of 4- and 8-hour precipitation totals for 1-, 2-, and 5-year recurrence interval frequencies (100-, 50-, and 20-percent annual exceedance probabilities) using provided 1-, 2-, 3-, 6-, 12-, and 24-hour precipitation values from the National Oceanic and Atmospheric Administration Atlas 14 precipitation frequency estimates (National Oceanic and Atmospheric Administration, 2020).

Using the Soil Conservation Service CN approach, antecedent runoff conditions are divided into three classes: *CN*(I) for “dry,” *CN*(II) for “normal,” and *CN*(III) for “wet” antecedent runoff conditions (Natural Resources Conservation Service, 2004). All three antecedent runoff conditions were simulated in this study. The initial average runoff condition *CN*(II) values used in the model were converted to initial estimates of dry conditions (*CN*[I]) and wet conditions (*CN*[III]) using the following equations from Chow and others (1988):

$$CN(\mathrm{I}) = \frac{4.2CN(\mathrm{II})}{10 - 0.058CN(\mathrm{II})} \quad (1)$$

and

$$CN(\mathrm{III}) = \frac{23CN(\mathrm{II})}{10 + 0.13CN(\mathrm{II})}. \quad (2)$$

Base-Flow Method

The recession base-flow method (Chow and others, 1988) was used to simulate base flow within the basin. For this method, the HEC–HMS model requires three parameters: initial streamflow, a recession constant, and a ratio-to-peak constant. The initial streamflow was applied to each subbasin based on the ratio of the subbasin area to the total drainage area. The recession constant represents the rate at which base flow recedes after a rainfall event. The ratio-to-peak constant is a threshold that indicates when to begin base flow on the recession limb of a hydrograph. These parameters were estimated and adjusted during the HEC–HMS model calibration.

Streamflow Routing Method

No streamflow routing method was selected within HEC–HMS; rather, simulated HEC–HMS streamflows were routed through an unsteady-state HEC–RAS model. This method was selected to accurately represent floodplain storage and potential backwater conditions at the tributary and main-stem junctions. The HEC–HMS and HEC–RAS models were run consecutively and iteratively for calibration.

Hydrologic Model Calibration

The hydrologic model was manually (no automatic functions used) calibrated to observed streamflow data for the May 27, 2021, and June 25, 2021, high-flow events and to high-water marks for the September 28, 2019, event. The parameters *CN*, *Tc*, *R*, and base-flow recession were the primary parameters used in calibrating the simulated hydrograph peak and shape. Initial estimates of *Tc* and *R* were determined using the TR–55 methodology (Soil Conservation Service, 1986). The parameters initially were set to the same value and adjusted to match hydrograph shape, magnitude, and timing. Final calibration results indicated similarity in simulated and observed hydrographs (fig. 4), noting that an emphasis during the HEC–HMS calibration was on the magnitude and timing of peak flows because these factors were most directly related to the objective of developing flood-inundation mapping products. The Nash-Sutcliffe efficiency (NSE) coefficient (Nash and Sutcliffe, 1970) and percentage bias (PBIAS; Gupta and others, 1999) statistics were used to assess model fit. Values of NSE can vary from negative infinity (∞) to 1. Values of 1 correspond to a perfect match between simulated and observed time series, whereas values less than 0 indicate the observed average is a better predictor than the simulated

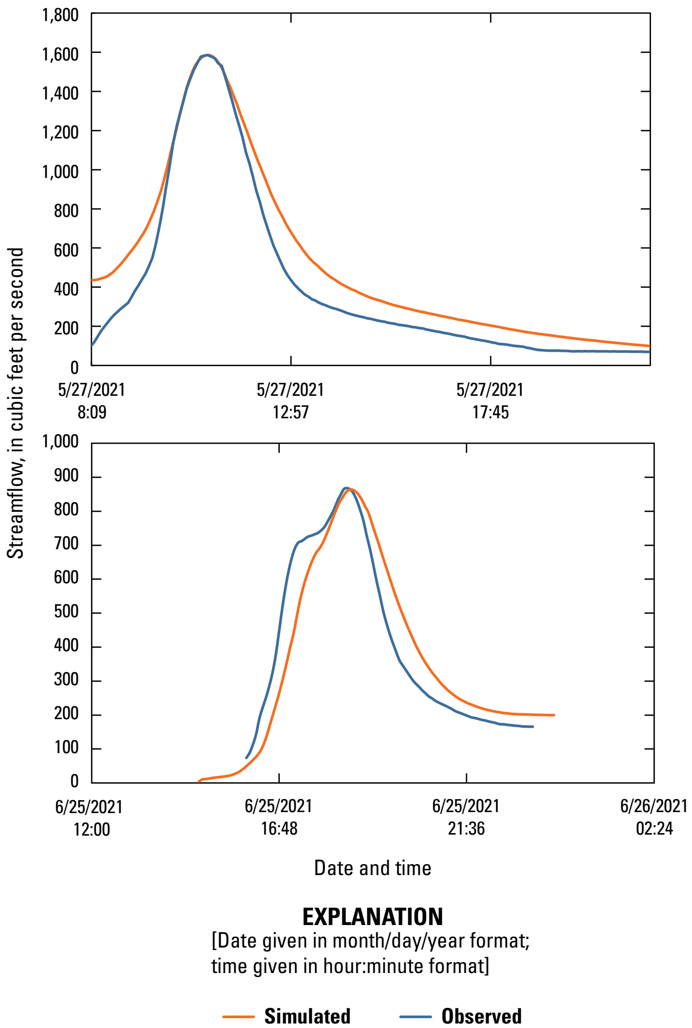


Figure 4. Simulated and observed streamflow hydrographs from the May 27, 2021, and June 25, 2021, high-flow events at Muddy Creek at Harrisonville, Missouri, at reference location PT1.

values. The NSE of the calibrated May 27, 2021, and June 25, 2021, models were 0.909 and 0.947, respectively, indicating that the simulated values were a good predictor of the observed hydrograph. The September 28, 2019, event did not have observed streamflows available for calibration with HEC–HMS, and only observed high-water marks were available. Peak flows for this event were simulated using observed rainfall and routed using HEC–RAS, and the simulated water-surface elevations were compared to the observed high-water marks and flow parameters adjusted in a quasi-calibration of the Hydrologic Modeling System. The event is considered a quasi-calibration of the Hydrologic Modeling System because simulated results from HEC–HMS were not compared to observed streamflows directly; rather, the results were compared to water-surface elevations after routing HEC–HMS streamflows through HEC–RAS (see “Hydraulic Model Calibration” section). The PBIAS is a measure of average tendency of the simulated data to be larger or smaller than observed values. Values of PBIAS can vary from −∞ to ∞ with an optimum value of 0. The calibrated model yielded PBIAS values of −1.8 (May 27) and −27.7 (June 25), indicating a good to fair model fit. A comparison of relevant hydrograph characteristics also indicates similarities, in general, between simulated and observed peak streamflow, time of peak, and runoff volume (table 3).

Hydrologic Model Validation

An additional observed wet antecedent condition event on April 28, 2021, was used to validate the Soil Conservation Service runoff curve number representing a “wet” antecedent runoff condition (CNIII) model. The NSE value of the validation events of the Muddy Creek CNIII model was 0.736, indicating that the simulated values were a good predictor of the observed hydrograph. The PBIAS value of the validation run was −43.5, which indicated an overestimation of the simulated hydrograph volume but the simulated and observed peak streamflows were similar (table 4).

Table 3. Model performance metrics of the U.S. Army Corps of Engineers Hydrologic Engineering Center-Hydrologic Modeling System models developed for Muddy Creek at Harrisonville, Missouri.

[HEC–HMS, U.S. Army Corps of Engineers Hydrologic Engineering Center-Hydrologic Modeling System; NSE, Nash-Sutcliffe model efficiency; PBIAS, percentage bias; CNIII, Soil Conservation Service runoff curve number representing a “wet” antecedent runoff condition; CNII, Soil Conservation Service runoff curve number representing a “normal” antecedent runoff condition; NA, not available; CNI, Soil Conservation Service runoff curve number representing a “dry” antecedent runoff condition]

HEC–HMS calibration/validation event	NSE	PBIAS, in percent
CNIII, May 27, 2021, calibration	0.909	−27.7
CNII, September 28, 2019, calibration[a]	NA[a]	NA[a]
CNI, June 25, 2021, calibration	0.947	−1.8
CNIII, April 28, 2021, validation	0.736	−43.5

[a]Observed peak streamflows were not collected during this event, and only high-water marks (provided in table 7) were available.

Hydrologic Model Scenarios

Seven antecedent runoff condition and channel condition scenarios were simulated using the hydrologic model (table 2). Each precipitation event provided in the "Precipitation Data" section was simulated using each of the seven condition scenarios. The resulting peak flows from each scenario that fell within the defined range of flows from bankfull to the stage exceeding the 0.1-percent AEP precipitation event were assigned to a 0.5-ft increment flood-inundation map (Heimann, 2022). The development of the flood-inundation maps is described in the following sections. The total range of stages produced from the precipitation scenarios was 1.0 to 4.0 ft, as referenced to Muddy Creek at PT1 water levels near Interstate 49 (fig. 1). Flood-inundation maps were produced for 0.5-ft increments in stage ranging from near bankfull (1.0 ft) to the stage exceeding the estimated 0.1-percent AEP precipitation event (4.0 ft). Each precipitation scenario with a resulting stage between 1.0 and 4.0 ft was then assigned to one of the 0.5-ft increment flood maps. Model reach input flows were obtained from HEC–HMS runs that produced resulting peak flows (Heimann, 2022), and scenarios at or near the corresponding 0.5-ft stage increments (table 5) are represented in the flood-inundation maps.

Hydrologic Model Sensitivity

The primary hydrologic model parameter that was modified to simulate the variable antecedent runoff conditions (Soil Conservation Service runoff curve number representing a "dry" antecedent runoff condition [CNI], Soil Conservation Service runoff curve number representing a "normal" antecedent runoff condition [CNII], and CNIII) in the Muddy Creek study basin was the CN used in the precipitation loss method.

Table 4. Simulated and observed hydrograph characteristics of the April 28, 2021; May 27, 2021; and June 25, 2021, high-flow events at Muddy Creek at Harrisonville, Missouri, at reference location PT1.

[ft^3/s, cubic foot per second; hh:mm, hour and minute; acre-ft, acre foot; CNI, Soil Conservation Service runoff curve number representing a "dry" antecedent runoff condition; CNIII, Soil Conservation Service runoff curve number representing a "wet" antecedent runoff condition]

Peak streamflow (ft^3/s)			Time of peak (hh:mm)			Runoff volume (acre-ft)		
Simulated	Observed	Percentage difference	Simulated	Observed	Difference	Simulated	Observed	Percentage difference
June 25, 2021, CNI calibration event								
864	868	0.44	18:40	18:30	00:10	257.1	252.6	1.8
May 27, 2021, CNIII calibration event								
1,585	1,585	0.0	11:00	11:00	0:00	592.4	464.3	24.3
April 28, 2021, CNIII validation event								
1,276	1,011	23.1	19:15	19:15	0:00	353.8	246.6	35.7

Table 5. Selected scenarios used to represent flood-inundation map stage conditions of 1.0 to 4.0 feet at Muddy Creek at Harrisonville, Missouri.

[ft, foot; NAVD 88, North American Vertical Datum of 1988; ft^3/s, cubic foot per second; CNI, Soil Conservation Service runoff curve number representing a "dry" antecedent runoff condition; CNIII, Soil Conservation Service runoff curve number representing a "wet" antecedent runoff condition]

Precipitation scenario (summary table in Heimann [2022])[a]	Stage of water-surface profile (ft)	Water-surface elevation (ft, NAVD 88)	Simulated peak streamflow (ft^3/s)
5 year, 6 hour, CNI	1.0	871.00	769
5 year, 24 hour, CNI	1.5	871.53	1,050
1 year, 4 hour, CNIII	2.0[b]	872.03	1,490
50 year, 30 minute, CNIII	2.5	872.52	2,020
10 year, 12 hour, CNIII	3.0	873.02	2,590
25 year, 24 hour, CNIII	3.5	873.50	3,260
1,000 year, 24 hour, CNIII	4.0	873.98	3,760

[a]See "MuddyCreek_summary_tables" in Heimann (2022).

[b]The highest streamflow measurement corresponds to a stage of about 2.0 ft.

The response of the calibrated CNI, CNII, and CNIII models to a consistent precipitation event of a 25-year recurrence interval, 30-minute duration (2.12 inches [in.]) indicates the large variability in the hydrologic response of the basin (fig. 5) from below bankfull to moderate flooding. A 45-percent change in the curve number results in a 262-percent change in streamflow (from 502 to 1,820 cubic feet per second), representing a difference of 2.34 ft in peak water-surface elevation in these simulations as determined from the HEC–RAS routed streamflows. Factors affecting the hydrologic response that are represented by the changes in the runoff curve number and in the three antecedent condition models include the amount and intensity of precipitation, vegetation cover density, stage of vegetation growth, and temperature (Natural Resources Conservation Service, 2004). The antecedent runoff condition also can be described in terms of a range in response probabilities. The CNI curve number condition can be considered the 10th-percentile value, the CNII curve number can be considered the 50th-percentile value, and the CNIII curve number can be considered the 90th-percentile value in the range of possible values and responses (Natural Resources Conservation Service, 2004).

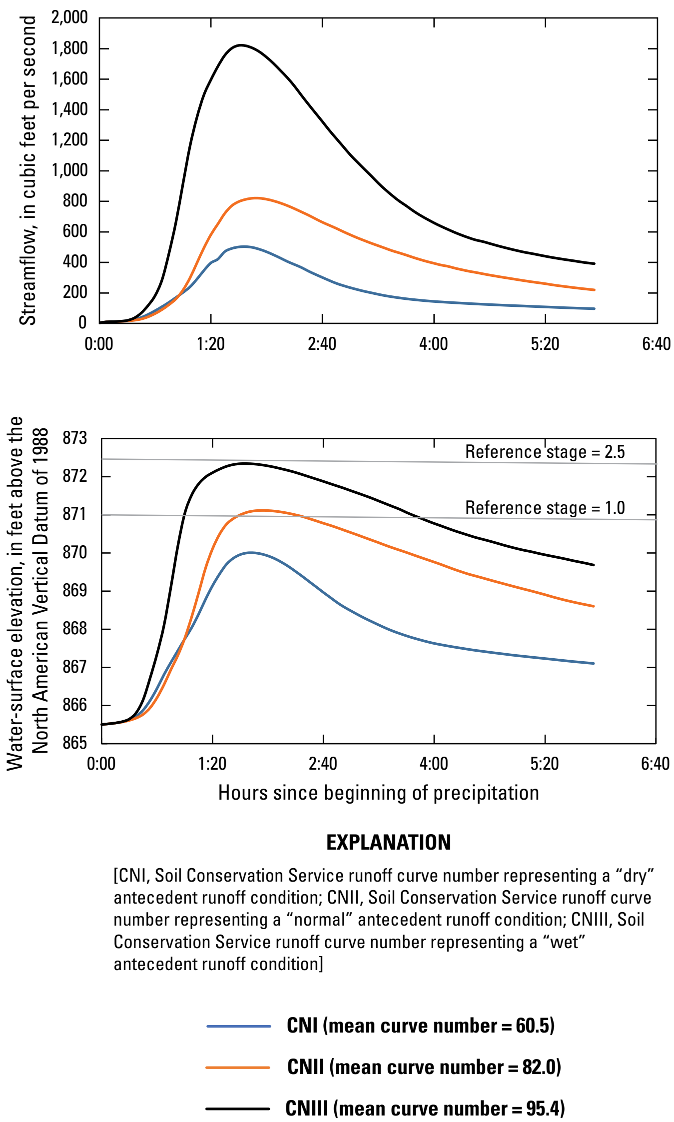


Figure 5. Simulated hydrologic response of Muddy Creek at Harrisonville, Missouri, at the reference location PT1 (see fig. 2) to a 25-year recurrence interval, 30-minute duration rainfall under varying antecedent runoff and curve number conditions indicating the range of streamflows, water-surface elevations, and reference stages for corresponding flood-inundation maps.

Computation of Water-Surface Profiles

The HEC–RAS hydraulic model used in this study was developed by the USACE (Allen Chestnut, U.S. Army Corps of Engineers, written commun., 2020) using version 5.0.7 (U.S. Army Corps of Engineers, 2019). HEC–RAS is a one- or two-dimensional model for simulating water-surface profiles with steady-state (gradually varied) or unsteady-state flow computation options. A two-dimensional HEC–RAS model with an unsteady-state flow computation option was used in this study.

Topographic and Bathymetric Data

The elevation data used in the HEC–HMS model were obtained from a 1-meter DEM that was derived from lidar data collected between December 2019 and February 2020 (U.S. Geological Survey, 2021b). As per USGS quality level 2 data-accuracy specifications (version 1.2; Heidemann, 2018), the lidar data required a nonvegetated vertical accuracy of a maximum 10-centimeter root mean square error (RMSE), and a vegetated vertical accuracy of a maximum of 30 centimeters at the 95th percentile. The HEC–RAS model uses 2006 lidar data from Cass County, available through the Missouri lidar DEM download tool (Missouri Spatial Data Information Service, 2020). Hydraulic structures (bridges, culverts) in the 2006 lidar were updated to 2019 conditions. The 2006 lidar collection specifications included a vertical RMSE of less than 0.607 ft at the 95-percent confidence level and a horizontal RMSE of less than 3.28 ft at the 95-percent confidence level. The vertical RMSE of the elevation data obtained from the topographic mapping data was 0.314 ft. The horizontal RMSE was 2.46 ft or less. Lidar data obtained for Cass County were collected by Sanborn Mapping Co. in April 2006, and post-processing was completed in August 2006. The horizontal resolution of the combined lidar dataset was 4.0 ft. The accuracy specifications for all lidar datasets met or exceeded the U.S. National Map Accuracy Standards for vertical and horizontal accuracy guidelines for 2-ft contours (American Society for Photogrammetry and Remote Sensing, 1990, 2004).

Hydraulic Structures

A total of 12 hydraulic structures are represented in the hydraulic model of Muddy Creek and its tributaries. These structures have the potential to affect water-surface elevations during flooding along the stream. These 12 structures include 1 major four-lane highway and 11 two-lane road culverts. In the "clean culverts" scenario the 1 foot of assumed sediment was removed from the I–49 bridge and South Commercial Street bridge culverts on Muddy Creek (see fig. 1 for selected Muddy Creek road crossings). For the "with detention" scenario an in-line detention basin with about 115 acre-feet of storage (U.S. Army Corps of Engineers, 2020a) was added to Muddy Creek (fig. 2). All bridge-geometry information is contained in the hydraulic models used for analyses and provided in Heimann (2022).

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) *n*-values were selected on the basis of field observations, high-resolution aerial photographs collected through the U.S. Department of Agriculture National Agriculture Imagery Program and available through the Missouri Spatial Data Information Service (2019), and tabulated (Chow, 1959) and photographic estimates of *n*-values (Barnes, 1967).

As part of the calibration process, the initial *n*-values were varied by flow and adjusted until the differences between simulated and observed water-surface elevations at the continuous water-level monitoring locations and documented high-water marks (fig. 2) along the study reach from the high-flow calibration events were minimized. The final *n*-values ranged from 0.03 to 0.05 for the main channel and from 0.0125 to 0.12 for the overbank areas simulated in this analysis. The lowest channel coefficients were placed in straight, downstream sections of the model reach, and the highest were placed in coarse-material reaches with vegetated banks. The lowest roughness coefficients on the floodplain were placed in open parking lot areas and the highest in densely forested areas.

Hydraulic Model

The HEC–RAS analysis for this study was completed using the two-dimensional unsteady-state flow computation option. Input flow data consisted of flow regimes, boundary conditions, and peak flows that produced water-surface elevations at the continuous water-level monitoring locations (fig. 2) that matched target water-surface elevations. These target elevations coincided with 0.5-ft increments of stage, referenced to the local streamgage datum. Subcritical (tranquil) flow regime was assumed for the simulations. Normal depth, based on an estimated average water-surface slope of 0.003, was used as the downstream boundary condition. The input hydrographs for the HEC–RAS model scenarios were generated using a range of precipitation frequency-duration events in HEC–HMS, as detailed in the "Hydrologic Data" section.

Hydraulic Model Calibration

The HEC–RAS model was calibrated primarily to observed streamflow-stage measurements collected during the May 27, 2021, high-flow event. Model calibration was completed by adjusting *n*-values until the results of the hydraulic computations closely agreed with the observed water-surface elevations for given flows at the PT1 reference location and water-level readings from other continuous loggers in the reach (fig. 2). The differences between surveyed and simulated elevations of seven high-water marks in the study reach for the May 27, 2021, event were less than or equal to 0.46 ft (table 6). The results demonstrate that the model is capable of simulating accurate water levels throughout the reach.

Hydraulic Model Validation

The dissected Muddy Creek study basin upstream from PT2 (fig. 2) limited the application of the measured streamflows collected near location PT1 to locations upstream. To quasi-calibrate and validate the streamflows from the hydrologic model and the corresponding water-surface elevations derived from the hydraulic model, the water-surface elevations from the simulated inflows were compared to observed peak elevations within the study reach (table 7). Simulated water-surface elevations generally were within 0.58 ft, except at monitoring locations at the upstream extent of the study reach arms (PT6, PT7) and during the April 28, 2021, HEC–HMS validation event.

Development of Water-Surface Profiles

The calibrated hydraulic model was used to generate water-surface profiles for a total of seven stages at 0.5-ft intervals from 1.0 to 4.0 ft, as referenced to the Muddy Creek reference location near Interstate 49. These stages correspond to elevations of 871.0 and 874.0 ft above the North American Vertical Datum of 1988, respectively. A rating developed using streamflow measurements was extended using HEC–RAS model results to cover the full range of simulated flows and select scenario results corresponding to the target 0.5-ft stage increments.

Development of Flood-Inundation Maps

Flood-inundation maps were created for the Muddy Creek study reach and referenced to a reference location PT1 (fig. 2) on Muddy Creek near Interstate 49. The DEM data were derived from the same lidar data described in the "Topographic and Bathymetric Data" section and, therefore, have an estimated vertical accuracy of 2 ft (that is, plus or minus 1 ft). Estimated flood-inundation boundaries and depth

Table 6. Comparison of measured water-surface elevations with simulated water-surface elevations at corresponding streamflows for the May 27, 2021, high-flow event at the Muddy Creek reference location PT1.

[hh:mm, hour and minute; ft^3/s, cubic foot per second; ft, foot; NAVD 88, North American Vertical Datum of 1988]

Measurement time (hh:mm)	Streamflow (ft^3/s)	Target water-surface elevation (ft, NAVD 88)	Simulated water-surface elevation (ft, NAVD 88)	Difference in elevation (ft)
09:55	944	871.08	871.35	0.27
10:05	1,050	871.63	871.54	−0.09
10:20	1,380	872.09	871.90	−0.19
10:33	1,600	872.30	872.15	−0.15
10:40	1,420	872.43	871.97	−0.46
11:05	1,620	872.48	872.17	−0.31
11:28	1,360	872.20	871.88	−0.32

grids for each simulated profile were developed with the HEC–RAS mapper and exported from HEC–RAS (Heimann, 2022). Shapefile polygons and depth grids of the inundated areas for each profile were modified, as needed, in the ArcMap (version 10.7.1) application of ArcGIS Pro (Esri, 2021) to ensure a hydraulically reasonable transition of the flood boundaries between modeled cross sections.

Any inundated areas that were detached from the main channel were examined to identify subsurface connections with the main river, such as through culverts under roadways. Where such connections existed, the mapped inundated areas were retained in their respective flood maps; otherwise, the erroneously delineated parts of the flood extent were deleted. The flood-inundation areas are overlaid on high-resolution, georeferenced, aerial photographs of the study area. Bridge surfaces are shown as not inundated until the lowest flood stage exceeds the elevation of the bridge deck, in which case, the bridge surface is depicted as being inundated. Estimates of water depth can be obtained from the depth-grid data that are included with the presentation of the flood maps on an interactive mapping application described in the "Flood-Inundation Map Delivery" section. Only the "existing conditions" scenario maps are displayed on the interactive flood-inundation map application and the effects of "clean culverts" or "with-detention" potential channel modification scenarios are displayed as an "existing conditions" map with the net effects of the alternate scenarios shown based on the net change in stage at the reference location. Any localized effects of the "clean culverts" or "with-detention" scenario, therefore, are not displayed in the flood maps. For example, a precipitation condition that resulted in a stage of 2.5 ft at the reference location for the "existing conditions" scenario may only result in a stage of 2.0 ft at the reference location for the potential "with detention" scenario and, therefore, the 2.0 ft "existing conditions" map will be displayed. The net differences in the resulting stages and corresponding flood-inundation maps for the various scenarios in table 2 are provided in the "MuddyCreek_summary_tables" in Heimann (2022). The "existing conditions" scenario flood map corresponding to the highest simulated water-surface profile, a stage of 4.0 ft, is shown in figure 6.

Flood-Inundation Map Delivery

The developed flood-inundation polygons and corresponding depth grids are available in Heimann (2022). Also, a flood-inundation mapping interface (City of Harrisonville, 2022) has been established to make fully processed USGS flood-inundation study information available to the public. The website links to a mapping application that provides map libraries and detailed information on flood extents and depths for modeled sites.

The determination of the appropriate flood-inundation map to reference for a particular event begins with the monitoring of rainfall (fig. 7). The user can sign up for USGS WaterAlert (U.S. Geological Survey, 2021c) notifications for rainfall durations of 1, 2, 3, 4, 6, 12, and 24 hours using the link provided with the USGS station 383843094205501 in the USGS National Water Information System database (U.S. Geological Survey, 2020b). The WaterAlert application notifies the user when a user-specified rainfall threshold (the magnitude, duration, and hydrologic response of various precipitation events can be determined using data from the "MuddyCreek_summary_tables" in Heimann [2022]) has been exceeded. For example, when observed rainfall exceeds a set threshold of 1.0 in. in 1 hour or a second threshold of 2.0 in. in 2 hours, then the user will be notified by phone or email. The total precipitation and duration selected with the flood-inundation mapping interface (City of Harrisonville, 2022) and the corresponding flood-inundation map provides the minimum expected response as a result of the current accumulated precipitation. If precipitation continues, then the user can note the accumulated total and duration using additional WaterAlert notifications, totals from station updates tabulated on the flood-inundation interface, or from the National Water Information System (U.S. Geological Survey, 2020b). By

Table 7. U.S. Army Corps of Engineers Hydrologic Engineering Center-River Analysis System validation of selected Hydrologic Engineering Center-Hydrologic Modeling System calibrated and validated high-flow events of September 28, 2019; May 27, 2021; June 25, 2021; and April 28,2021.

[ft, foot; NAVD 88, North American Vertical Datum of 1988; HWM, high-water mark; PT, pressure transducer]

Water-level recording location (fig. 2)	Target water-surface elevation (ft, NAVD 88)	Simulated water-surface elevation (ft, NAVD 88)	Difference in elevation (ft)
September 28, 2019			
HWM1	884.59	884.57	−0.02
HWM2	879.80	880.14	0.34
HWM3	878.00	873.53	−0.47
May 27, 2021			
PT1	872.50	872.13	−0.37
PT2	874.60	874.56	−0.04
PT3	876.14	876.12	−0.02
PT4	876.30	875.73	−0.57
PT5	881.01	880.97	−0.04
PT6	889.86	888.56	−1.30
PT7	892.38	891.79	−0.59
June 25, 2021			
PT1	870.96	871.21	0.25
PT2	872.28	872.05	−0.23
PT3	873.46	873.35	−0.11
PT4	874.21	874.45	0.24
PT5	878.82	879.39	0.58
PT6	886.17	886.57	0.40
PT7	890.40	891.36	0.95
April 28, 2021			
PT1	872.17	871.99	−0.18
PT2	869.38	870.52	1.14
PT3	871.09	871.54	0.45
PT4	868.47	869.45	0.98
PT5	884.92	885.98	1.06
PT6	876.91	877.57	0.61
PT7	888.75	889.88	1.13

tracking the 15-minute rainfall updates and WaterAlert notifications, the user can continue updating the expected response and the corresponding flood-inundation map in effect.

The hydrologic response, as represented by the selected flood-inundation map, associated with a precipitation magnitude and duration also will vary depending on the antecedent runoff condition that is selected (dry, normal, wet). The antecedent runoff condition is determined from an awareness of hydroclimatic conditions in the basin preceding an event and is selected as a display option on the flood-inundation mapping interface (City of Harrisonville, 2022). As an example, in calibrating the models for this study, the dry antecedent runoff condition was observed in the summer (June 25, 2021, event) with full vegetation cover, antecedent 7-day rainfall of 0.09 in., and the maximum daily air temperatures, in degrees Fahrenheit, in the 90s for several weeks preceding the event. The normal condition event was in September under full vegetation, antecedent 7-day rainfall of 1.08 in., and the maximum daily temperatures, in degrees Fahrenheit, in the weeks preceding the event were in the 70s to 90s. The wet antecedent runoff conditions were observed for the spring (March, April, May) events with sparse vegetation cover, antecedent 7-day rainfalls of 0.56 to 1.85 in., and the maximum daily temperatures, in degrees Fahrenheit, during the period varied from the 40s to the 70s.

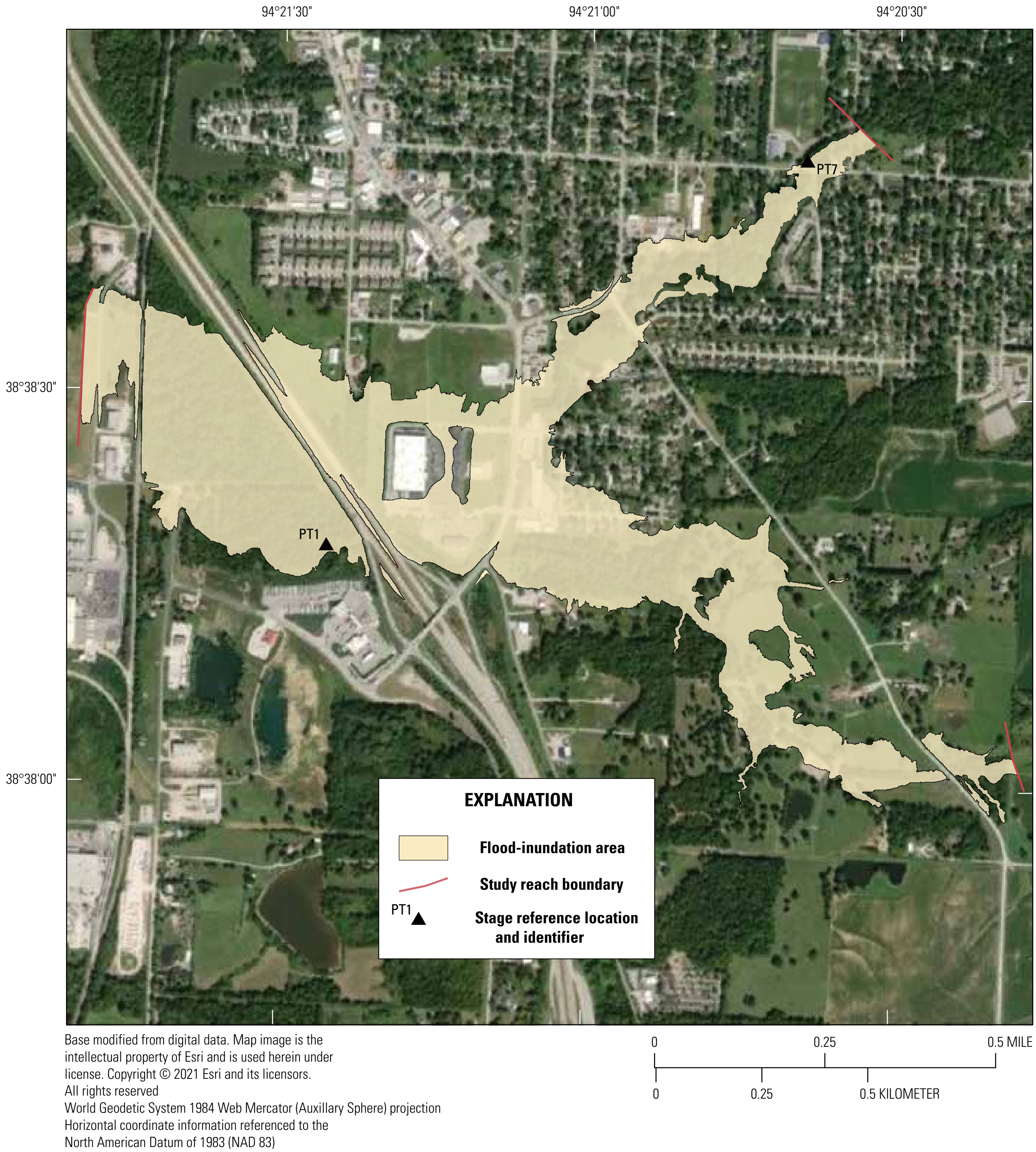


Figure 6. Flood-inundation map for the Muddy Creek at Harrisonville, Missouri, study reach corresponding to a stage of 4.0 feet at reference location PT1.

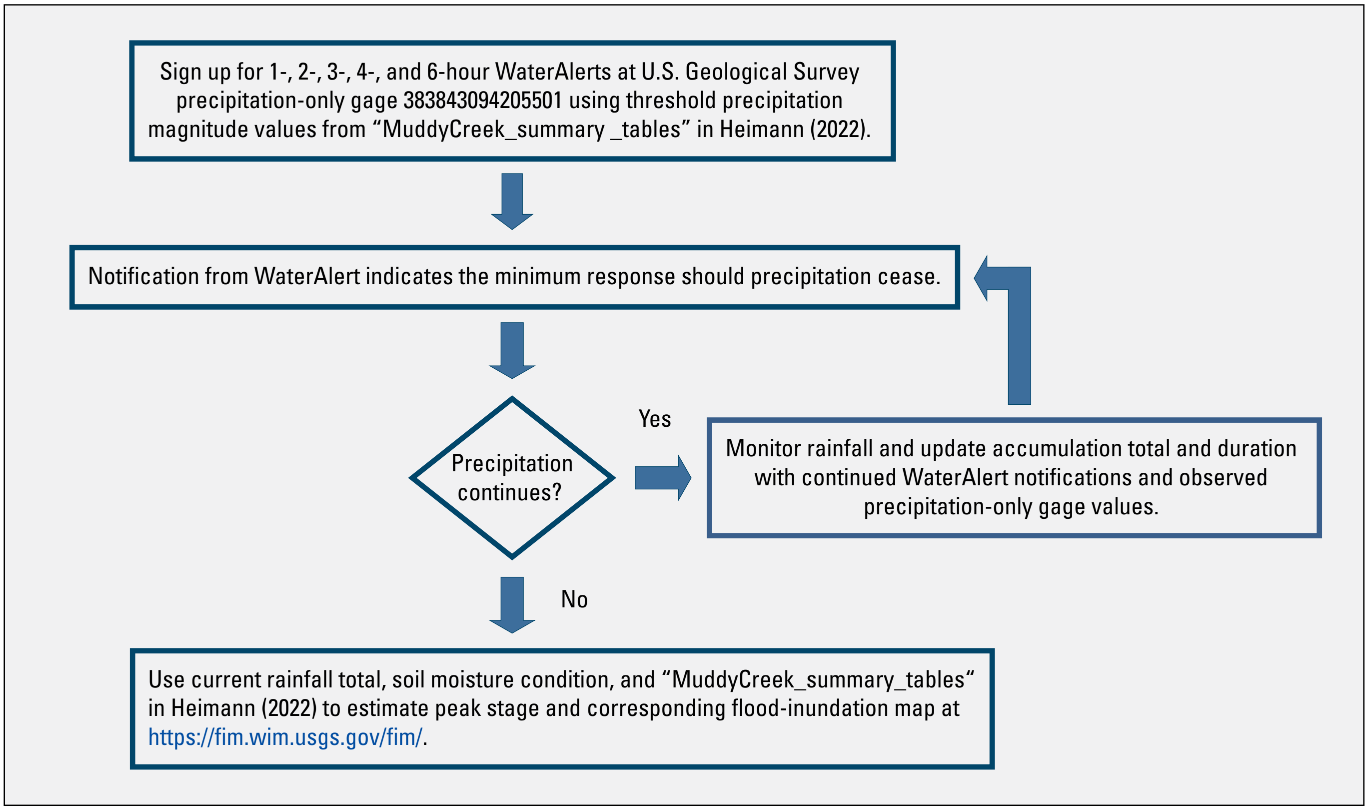


Figure 7. Decision process in determining the hydrologic response, including estimated stage and corresponding flood-inundation map, from observed accumulated precipitation.

The estimated flood-inundation maps are shown in sufficient detail so that preparations for flooding and decisions for emergency response could be completed 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. Bridges are shaded—that is, shown as inundated—when the flood stage exceeds the elevation of the bridge deck. A shaded building should not be interpreted to mean that the structure is completely submerged; rather, bare earth surfaces near the building are inundated. In these instances, the water depth (as indicated in the mapping application by holding the cursor over an inundated area) near the building would be an estimate of the water level inside the structure, unless elevating or flood-proofing measures had 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 and general risk communication 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 based on water stages at a selected reference location based on the hydrologic response from selected precipitation magnitudes and durations. Water-surface elevations along the stream reach were estimated by unsteady-state hydraulic modeling, assuming unobstructed flow, and used streamflows and hydrologic conditions anticipated at the Muddy Creek main stem and tributary. The hydraulic model reflects the land-cover characteristics and any bridge, dam, levee, or other hydraulic structures existing as of September 2019. 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 in the water-surface elevations and inundation boundaries shown. Additional areas may be flooded because of unanticipated conditions such as changes in the streambed elevation or roughness, backwater into major tributaries along a river main-stem, 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 DEM used to simulate the land surface. Of the seven flood-inundation model scenarios, four exceed the largest streamflow measurement made at the Muddy Creek reference location corresponding to a stage of about 2.0 ft; therefore, additional uncertainty for flood-inundation maps exists at stages greater than 2.0 ft.

The user also should be aware of additional uncertainties that may be inherent or factored into the simulation of flood peaks using rainfall-runoff simulations. A hydrologic model was used to simulate flood peaks associated with various probabilistic precipitation amounts. The precipitation was assumed to follow a defined temporal distribution over the duration of the event and an even spatial distribution over the basin. The actual temporal and spatial distribution of precipitation may vary, thereby affecting the timing and magnitude of the predicted flood peak in the main stem or tributary. A single "simple" storm was simulated with a near-base-flow starting condition. For multiple compounding precipitation events, the user should take into consideration that the starting streamflow condition may be considerably higher than base flow and, therefore, the peak condition also will be higher than simulated conditions. Other sources of uncertainty will arise from the selection of the appropriate antecedent runoff condition and the occurrence of atypical precipitation events including rainfall on frozen ground or on a substantial existing snowpack, all of which may affect the timing and magnitude of the predicted flood peak.

Summary

A series of seven digital flood-inundation maps were developed by the U.S. Geological Survey, in cooperation with the city of Harrisonville, Missouri, for a 3.8-mile reach of Muddy Creek and tributaries within and adjacent to the city. The maps were developed using input streamflows derived from precipitation values of 30-minute to 24-hour durations and ranging from 1- to 1,000-year recurrence intervals (100- to 0.1-percent annual exceedance probability) and the Hydrologic Engineering Center-Hydrologic Modeling System (version 4.4.1). Water-surface profiles from the input streamflows were computed using the U.S. Army Corps of Engineers Hydrologic Engineering Center-River Analysis System (version 5.0.7) and used to estimate flood-inundation areas and depths of flooding. The hydrologic and hydraulic models were calibrated to the September 28, 2019; May 27, 2021; and June 25, 2021, runoff events representing a range of antecedent runoff conditions and hydrologic responses and to discrete streamflow measurements from a reference location on Muddy Creek. The hydrologic and hydraulic models encompassing the study reach were used to simulate runoff, route streamflows and map the resulting seven water-surface profiles for flood stages at 0.5-foot (ft) intervals referenced to the local streamgage datum and ranging from 1.0 ft, or near bankfull, to 4.0 ft, which exceeds the stage corresponding to the estimated 0.1-percent annual exceedance probability precipitation (1,000-year recurrence interval). A total of 7 scenarios were developed with the Hydrologic Engineering Center-Hydrologic Modeling System hydrologic model that include 3 antecedent runoff conditions and potential channel modifications including cleaned culverts and added detention storage. All precipitation scenarios were input into each of the seven land-cover antecedent runoff conditions and then assigned to a resulting flood-inundation map based on the generated peak flow and corresponding stage at the Muddy Creek reference location.

The simulated water-surface profiles were then combined with a geographic information system digital elevation model derived from light detection and ranging data to delineate estimated flood-inundation areas as shapefile polygons and depth grids for each profile. These flood-inundation polygons were overlaid on high-resolution, georeferenced aerial photographs of the study area. The flood maps are available through a mapping application that can be accessed on the U.S. Geological Survey "Flood Inundation Mapping (FIM) Program" website (https://www.usgs.gov/mission-areas/water-resources/science/flood-inundation-mapping-fim-program).

Interactive use of the maps on this mapping application can give users a general indication of the depth of water at any point by using the mouse cursor to click within the shaded areas. The joint products could help guide the public in taking individual safety precautions and provide emergency-management personnel with a tool to mitigate and prepare for flood-related emergencies, efficiently manage emergency flood operations, and effectively complete postflood recovery efforts.

References Cited

American Society for Photogrammetry and Remote Sensing, 1990, ASPRS accuracy standards for large-scale maps: American Society for Photogrammetry and Remote Sensing, 3 p., accessed December 17, 2018, at http://www.asprs.org/a/society/committees/standards/1990_jul_1068-1070.pdf.

American Society for Photogrammetry and Remote Sensing, 2004, ASPRS guidelines—Vertical accuracy reporting for lidar data: American Society for Photogrammetry and Remote Sensing, 20 p., accessed December 17, 2018, at https://www.asprs.org/a/society/committees/standards/Vertical_Accuracy_Reporting_for_Lidar_Data.pdf.

Barnes, H.H., Jr., 1967, Roughness characteristics of natural channels: U.S. Geological Survey Water-Supply Paper 1849, 219 p. [Also available at https://doi.org/10.3133/wsp1849.]

Chow, V.T., 1959, Open-channel hydraulics: New York, McGraw-Hill, 680 p.

Chow, V.T., Maidment, D.R., and Mays, L.W., Jr., 1988, Applied hydrology: New York, McGraw-Hill Book Company, 572 p.

City of Harrisonville, 2022, Flood-inundation mapping and model of Muddy Creek: City of Harrisonville web page, accessed November 17, 2022, at https://ci.harrisonville.mo.us/1052/Stormwater-Management.

Clark, C.O., 1945, Storage and the unit hydrograph: Transactions of the American Society of Civil Engineers, v. 110, no. 1, p. 1419–1446. [Also available at https://doi.org/10.1061/TACEAT.0005800.]

Dewitz, J., 2021, National Land Cover Database (NLCD) 2019 Products (ver. 2.0, June 2021): U.S. Geological Survey data release, accessed August 5, 2021, at https://doi.org/10.5066/P9KZCM54.

Esri, 2021, Arc Hydro (version 10.7.1): Esri software release, accessed February 12, 2020, at https://community.esri.com/t5/water-resources-questions/arc-hydro-installation-versions-and-documentation/m-p/269522.

Federal Emergency Management Agency, 2013, Mapping information platform: Federal Emergency Management Agency web page, accessed June 8, 2020, at https://hazards.fema.gov/femaportal/wps/portal.

Gupta, H.V., Sorooshian, S., and Yapo, P.O., 1999, Status of automatic calibration for hydrologic models—Comparison with multilevel expert calibration: Journal of Hydrologic Engineering, v. 4, no. 2, p. 135–143. [Also available at https://doi.org/10.1061/(ASCE)1084-0699(1999)4:2(135).]

Heidemann, H.K., 2018, Lidar base specification (ver. 1.3, February 2018): U.S. Geological Survey Techniques and Methods, book 11, chap. B4, 101 p., accessed February 7, 2020, at https://doi.org/10.3133/tm11B4.

Heimann, D.C., 2022, Geospatial data and model archives associated with precipitation-driven flood-inundation mapping of Muddy Creek at Harrisonville, Missouri (ver. 2.0, December 2022): U.S. Geological Survey data release, https://doi.org/10.5066/P969ZOLB.

Iowa State University, 2021, Iowa Environmental Mesonet—Missouri ASOS Network, LRY Harrisonville: Iowa State University digital data, accessed January 19, 2021, at https://mesonet.agron.iastate.edu/sites/obhistory.php?station=LRY&network=MO_ASOS.

Missouri Spatial Data Information Service, 2019, Missouri imagery data: Missouri Spatial Data Information Service digital data, accessed September 14, 2019, at https://www.msdis.missouri.edu/data/imagery/index.html. [National Agriculture Imagery Program 2018 data directly accessible at https://msdis-archive.missouri.edu/archive/Missouri_Imagery/naip2018/.]

Missouri Spatial Data Information Service, 2020, Missouri LiDAR DEM download tool: Missouri Spatial Data Information Service digital data, accessed January 4, 2020, at https://msdis.maps.arcgis.com/apps/View/index.html?appid=350bcb69dfb74ca58aae74a32728f58b.

Nash, J.E., and Sutcliffe, J.V., 1970, River flow forecasting through conceptual models part 1—A discussion of principles: Journal of Hydrology, v. 10, no. 3, p. 282–290. [Also available at https://doi.org/10.1016/0022-1694(70)90255-6.]

National Oceanic and Atmospheric Administration, 2020 NOAA Atlas 14—Point precipitation frequency estimates—MO: National Oceanic and Atmospheric Administration digital data, accessed March 2020 at https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_map_cont.html?bkmrk=mo.

Natural Resources Conservation Service, 2004, Estimation of direct runoff from storm rainfall—Part 630 hydrology—National engineering handbook: Washington, D.C., U.S. Department of Agriculture, [variously paged]. [Also available at https://directives.sc.egov.usda.gov/17752.wba.]

Natural Resources Conservation Service, 2020, Geospatial Data Gateway: Natural Resources Conservation Service web page, accessed March 8, 2020, at https://datagateway.nrcs.usda.gov/.

Omernik, J.M., 1987, Ecoregions of the conterminous United States: Annals of the Association of American Geographers, v. 77, no. 1, p. 118–125. [Also available at https://doi.org/10.1111/j.1467-8306.1987.tb00149.x.]

Rydlund, P.H., Jr., and Densmore, B.K., 2012, Methods of practice and guidelines for using survey-grade global navigation satellite systems (GNSS) to establish vertical datum in the United States Geological Survey: U.S. Geological Survey Techniques and Methods, book 11, chap. D1, 102 p. with appendixes. [Also available at https://doi.org/10.3133/tm11D1.]

Soil Conservation Service, 1986, Urban hydrology for small watersheds—TR–55: Washington, D.C., U.S. Department of Agriculture, 98 p. [Also available at https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044171.pdf.]

Straub, T.D., Melching, C.S., and Kocher, K.E., 2000, Equations for estimating Clark unit-hydrograph parameters for small rural watersheds in Illinois: U.S. Geological Survey Water-Resources Investigations Report 00–4184, 30 p. [Also available at https://doi.org/10.3133/wri004184.]

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://doi.org/10.3133/tm3A8.]

U.S. Army Corps of Engineers, 2019, HEC–RAS—River analysis system—Hydraulic reference manual (ver. 5.0.7, March 2019): U.S. Army Corps of Engineers, [variously paged], accessed May 15, 2019, at https://www.hec.usace.army.mil/software/hec-ras/download.aspx.

U.S. Army Corps of Engineers, 2020a, Harrisonville, Missouri—Silver Jackets Floodplain Investigation: U.S. Army Corps of Engineers, 63 p., accessed December 2021 at https://usace.contentdm.oclc.org/utils/getfile/collection/p266001coll1/id/9744.

U.S. Army Corps of Engineers, 2020b, Hydrologic Engineering Center (HEC–GeoHMS 10.2): U.S. Army Corps of Engineers software release, accessed February 22, 2020, at https://www.hec.usace.army.mil/software/hec-geohms/downloads.aspx.

U.S. Army Corps of Engineers, 2020c, Hydrologic Engineering Center (HEC–HMS 4.4.1): U.S. Army Corps of Engineers software release, accessed February 22, 2020, at https://www.hec.usace.army.mil/software/hec-hms/downloads.aspx.

U.S. Census Bureau, 2021, Decennial census—Harrisonville, Missouri: U.S. Census Bureau digital data, accessed December 2021 at https://data.census.gov/cedsci/table?g=1600000US2930610&tid=DECENNIALPL2020.P1.

U.S. Environmental Protection Agency, 2020, Level III and IV ecoregions by EPA region: U.S. Environmental Protection Agency digital data, accessed December 2020 at https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-epa-region.

U.S. Geological Survey, 2020a, Flood Inundation Mapping (FIM) Program: U.S. Geological Survey web page, accessed January 7, 2020, at https://www.usgs.gov/mission-areas/water-resources/science/flood-inundation-mapping-fim-program?qt-science_center_objects=0#qt-science_center_objects.

U.S. Geological Survey, 2020b, USGS 383843094205501 Harrisonville South, *in* USGS water data for the Nation: U.S. Geological Survey National Water Information System database, accessed October 4, 2020, at https://doi.org/10.5066/F7P55KJN. [Site information directly accessible at https://waterdata.usgs.gov/nwis/uv?site_no=383843094205501.]

U.S. Geological Survey, 2021a, StreamStats, version 4.40, Missouri: U.S. Geological Survey digital data, accessed June 2021 at https://streamstats.usgs.gov/ss/.

U.S. Geological Survey, 2021b, 3DEP LidarExplorer: U.S. Geological Survey digital data, accessed January 4, 2021, at https://prd-tnm.s3.amazonaws.com/LidarExplorer/index.html#/.

U.S. Geological Survey, 2021c, WaterAlert: U.S. Geological Survey digital data, accessed January 20, 2021, at https://maps.waterdata.usgs.gov/mapper/wateralert/.

For more information about this publication, contact:
Director, USGS Central Midwest Water Science Center
1400 Independence Road
Rolla, MO 65401
573–308–3667

For additional information, visit: https://www.usgs.gov/centers/cm-water

Publishing support provided by the
Rolla and Lafayette Publishing Service Centers

Heimann and Rydlund—**Precipitation-Driven Flood-Inundation Mapping of Muddy Creek at Harrisonville, Missouri**—SIR 2022–5084

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20225084