Prepared in cooperation with the Indiana Department of Transportation

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Scientific Investigations Report 2017–5140

U.S. Department of the Interior
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Cover: View of the I–64 Bridge looking to the northeast, August 17, 2015. Photograph by Dan Ghere, Federal Highway Administration.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
acre (ac)	0.404686	hectare (ha)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Datums

Vertical coordinate information is referenced to either (1) stage, the height above an arbitrary datum established at a streamgage; or (2) elevation, the height above the North American Vertical Datum of 1988 (NAVD 88).

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

Development of a Hydraulic Model and Flood-Inundation Maps for the Wabash River near the Interstate 64 Bridge near Grayville, Illinois

By Justin A. Boldt

Abstract

A two-dimensional hydraulic model and digital flood-inundation maps were developed for a 30-mile reach of the Wabash River near the Interstate 64 Bridge near Grayville, Illinois. The flood-inundation maps, which can be accessed through the U.S. Geological Survey (USGS) Flood Inundation Mapping Science web site at http://water.usgs.gov/osw/flood_inundation/, depict estimates of the areal extent and depth of flooding corresponding to selected water levels (stages) at the USGS streamgage on the Wabash River at Mount Carmel, Ill (USGS station number 03377500). Near-real-time stages at this streamgage may be obtained on the internet from the USGS National Water Information System at http://waterdata.usgs.gov/ or the National Weather Service (NWS) Advanced Hydrologic Prediction Service (AHPS) at http://water.weather.gov/ahps/, which also forecasts flood hydrographs at this site (NWS AHPS site MCRI2). The NWS AHPS forecasts peak stage information that may be used with the maps developed in this study to show predicted areas of flood inundation.

Flood elevations were computed for the Wabash River reach by means of a two-dimensional, finite-volume numerical modeling application for river hydraulics. The hydraulic model was calibrated by using global positioning system measurements of water-surface elevation and the current stage-discharge relation at both USGS streamgage 03377500, Wabash River at Mount Carmel, Ill., and USGS streamgage 03378500, Wabash River at New Harmony, Indiana. The calibrated hydraulic model was then used to compute 27 water-surface elevations for flood stages at 1-foot (ft) intervals referenced to the streamgage datum and ranging from less than the action stage (9 ft) to the highest stage (35 ft) of the current stage-discharge rating curve. The simulated water-surface elevations were then combined with a geographic information system digital elevation model, derived from light detection and ranging data, to delineate the area flooded at each water level.

The availability of these maps, along with information on the internet regarding current stage from the USGS streamgage at Mount Carmel, Ill., and forecasted stream stages from the NWS AHPS, provides emergency management personnel and residents with information that is critical for flood-response activities such as evacuations and road closures, as well as for postflood recovery efforts.

Introduction

The city of Grayville, Illinois, is located in Edwards and White counties (not shown, fig. 1) and has an estimated population of 1,666 (U.S. Census Bureau, 2010). Grayville is located near the center of the study domain and is near where Interstate 64 (I–64) crosses the Wabash River. Grayville and the surrounding area are subject to flooding from the Wabash River; however, the city of Grayville has been separated from the main channel of the Wabash River ever since a meander cutoff occurred in 1985. The Wabash River floods on a regular basis, often several times in a year. The most recent major flood events were in 2005, 2008, and 2011. Flood plains along the river are composed mostly of agricultural and forested areas. During flood events, there is significant flooding of surrounding agricultural lands, many local roads become impassable, and some evacuations are necessary.

Prior to this study, emergency responders in Grayville and the surrounding area relied on several information sources to make decisions on how to best alert the public and mitigate flood damages. One source is the Federal Emergency Management Agency (FEMA) flood-insurance study (FIS) for each of the counties in the study area: Wabash County, Ill. (FEMA, 2011), White County, Ill. (FEMA, 2012), Gibson County, Indiana (FEMA, 2014a), and Posey County, Ind. (FEMA, 2014b). A second source of information is U.S. Geological Survey (USGS) streamgage 03377500, Wabash River at Mount Carmel, Ill., from which current (USGS, 2016a) and historical (USGS, 2016b) stage and discharges, including annual peak flows, can be obtained. A third source of flood-related information is the National Weather Service (NWS) Advanced Hydrologic Prediction Service (AHPS), which displays the USGS stage data and also issues forecasts of stage for the Wabash River at the USGS streamgage (NWS, 2016a).

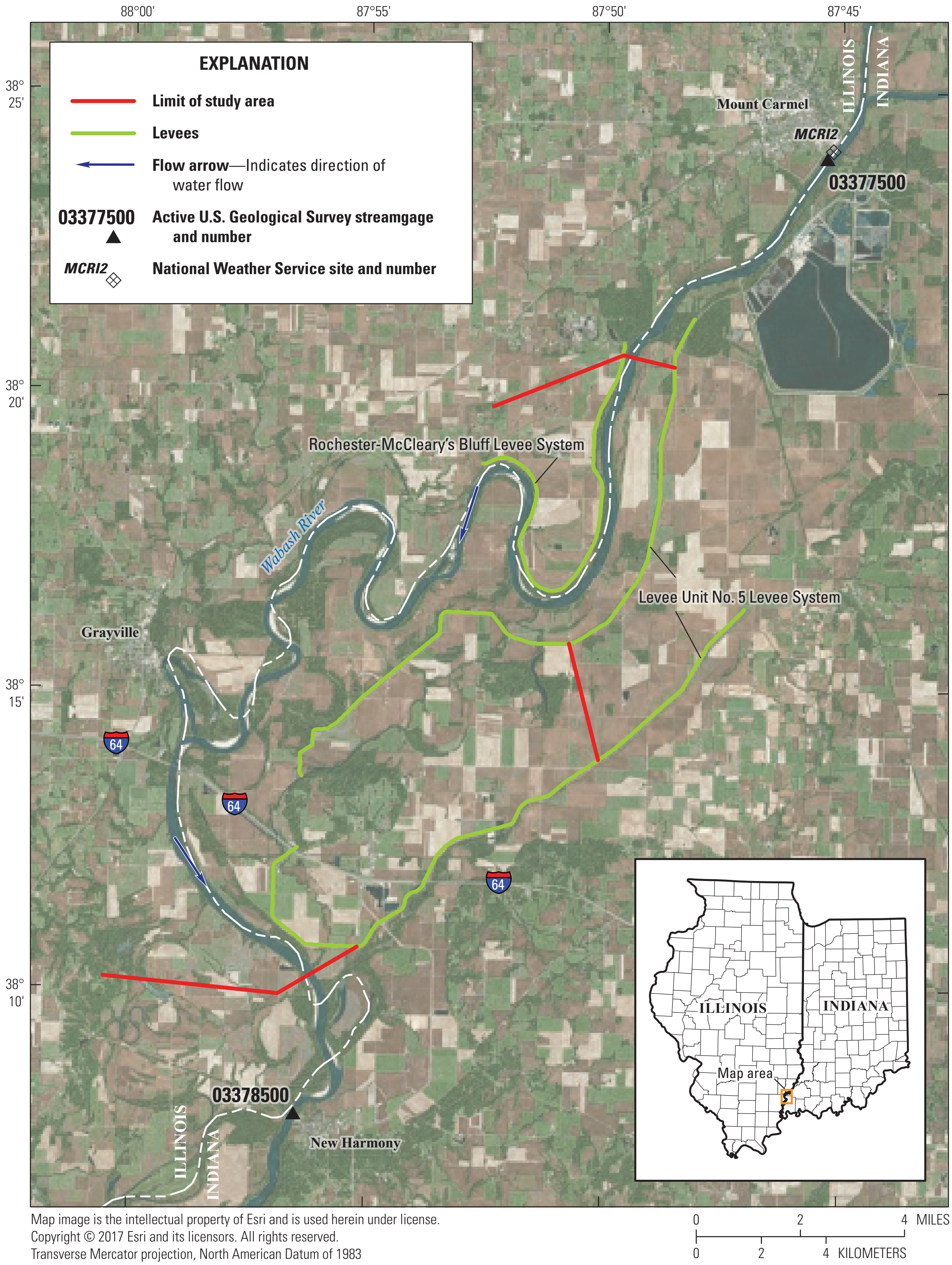


Figure 1. Locations of the study reach for the Wabash River near the I–64 Bridge near Grayville, Illinois, U.S. Geological Survey streamgages 03377500 and 03378500, and the National Weather Service forecast site MCRI2.

Although the current stage at a USGS streamgage and the NWS AHPS flood-forecast information are particularly useful for residents in the immediate vicinity of a streamgage, it is generally of limited use to residents farther upstream or downstream because the water-surface elevation is not constant along the entire stream reach. In addition, knowledge of a water level at a streamgage is difficult to translate into the depth and the areal extent of flooding at points distant from the streamgage. One way to address these informational gaps is to produce a library of flood-inundation maps that are referenced to the stages recorded at the USGS streamgage. 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 notification or evacuation of residents in harm's way for some distance upstream and downstream from the streamgage. In addition, the capability to visualize the potential extent of flooding has been shown to motivate residents to take precautions and heed warnings that they might have previously disregarded. The USGS, in cooperation with the Indiana Department of Transportation, led a study to develop a two-dimensional (2-D) model and produce a library of flood-inundation maps for the Wabash River near the I–64 Bridge near Grayville, Ill.

Purpose and Scope

The purpose of the study was to better understand the hydrodynamics of the Wabash River in the vicinity of the I–64 Bridge. Additional background information can be found in a related report (Lant and Boldt, 2018), which focused on the development and results of a river meander model for the same study area. The current report describes the two-dimensional simulation of flow and the development of a series of estimated flood-inundation maps for the Wabash River near the I–64 Bridge near Grayville, Ill., 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. Internet users can select estimated inundation maps that correspond to (1) flood stages at USGS streamgage 03377500 and (2) the NWS forecasted peak stage at the NWS AHPS site MCRI2. The scope of the study was limited to the Wabash River reach beginning approximately 5 miles (mi) downstream of Mount Carmel, Ill., and ending approximately 3 mi upstream of New Harmony, Ind. (fig. 1).

The flood-inundation maps were produced for flood levels referenced to the stage recorded at the USGS streamgage (03377500) on the Wabash River at Mount Carmel, Ill. (table 1). The maps cover a range in stage from 9 to 35 foot (ft), gage datum. The 9-ft stage is 2 feet less than what is defined by the National Weather Service (2016b) as the "action stage" or that stage which, when reached by a rising stream, requires the NWS or a partner to take some type of mitigation action in preparation for possible significant hydrologic activity. The 19-ft, 25-ft, and 32-ft stages are defined by the NWS (2016a) as flood stage, moderate flood stage, and major flood stage, respectively. The 35-ft stage is the highest stage of the current stage-discharge rating curve (USGS, 2016a) and exceeds the major flood stage as defined by the NWS (NWS, 2016b). Since 1875, there have been five flood events with crests over 32 ft (1913, 2002, 2005, 2008, and 2011), with the record crest being 34.02 ft on May 3, 2011 (USGS, 2016c).

Table 1. U.S. Geological Survey streamgage information for the Wabash River at Mount Carmel, Illinois, and New Harmony, Indiana.

[mi², square miles; NAD 83, North American Datum of 1983; °, degree; ′, minute; ″, second; NAVD 88, North American Vertical Datum of 1988; ft, feet; ft³/s, cubic feet per second]

Streamgage name	Streamgage number	Drainage area (mi²)	Latitude (NAD 83)	Longitude (NAD 83)	Datum of streamgage (ft, NAVD 88)	Period of record	Maximum recorded flood elevation (NAVD 88) and date	Maximum discharge (ft³/s) and date
Wabash River at Mount Carmel, Illinois	03377500	28,635	38°23′54″	87°45′23″	368.98	October 1927 to present[1]	403.00 ft on May 3, 2011 (corresponds to a gage height of 34.02 ft)	270,000 on May 3, 2011
Wabash River at New Harmony, Indiana	03378500	29,234	38°07′55″	87°56′25″	352.67	October 1938 to September 1947, October 2009 to present[2]	376.51 ft on May 26, 1943 (corresponds to a gage height of 23.84 ft)	327,000[3] on May 26, 1943

[1]Dates are for times when daily data were published. Peak streamflow records go back to 1875.

[2]Dates are for times when discharge and gage height were published. During 1988–2009, only gage height values were published.

[3]Estimated discharge based on rating 2.0.

Study Area Description

The Wabash River, near the city of Grayville, Ill., is in southwest Indiana and southeast Illinois in the Wabash Lowland physiographic section of the Southern Hills and Lowlands Region (Gray, 2000). The drainage area is 28,635 square miles (mi^2) at USGS streamgage 03377500, Wabash River at Mount Carmel, Ill., and 29,060 mi^2 at the I–64 Bridge (USGS, 2016b, 2016d). The headwaters originate in western Ohio (not shown), and the river flows west and southwest across Indiana until it nears the eastern border of Illinois. The river then turns south and approximately follows the state boundary between Indiana and Illinois for roughly 200 mi until it drains into the Ohio River at the southwest corner of Indiana. The Wabash River is the longest free-flowing river in the Nation east of the Mississippi River (Indiana Department of Natural Resources, n.d.). There are no significant tributaries to the Wabash River as it flows through the study reach. Minor tributaries within the study reach include (from upstream to downstream) Scott Ditch, Bonpas Creek, French Creek, and Big Bayou River (not shown in figures). The Wabash River meanders freely in its own alluvium except in a few places where it is impeded by bedrock (Jackson, 1976; Shaver, 1979). The study reach is approximately 30 mi long and has an average top-of-bank channel width of about 980 ft and an average channel slope of 0.0001 (0.5 feet per mile). Most of the land contiguous to the study reach is either agricultural or forested with scattered houses and oil and gas wells. The main channel and adjacent flood plain within the study reach has one major road crossing (I–64), which consists of two parallel bridges, and one partially collapsed railroad crossing. There are two separate leveed areas within the study area flood plain: the Rochester-McCleary’s Bluff Levee System and the Levee Unit No. 5 Levee System. These levee systems are included in the U.S. Army Corps of Engineers’ (USACE) National Levee Database (USACE, 2016). The Rochester-McCleary’s Bluff Levee System protects 4,823 acres, and the Levee Unit No. 5 Levee System protects 50,584 acres. Both levee systems were inspected by the USACE in August 2016, and the inspection resulted in a rating of minimally acceptable.

Previous Studies

The most recent FIS that provides information for the streamgage at the Wabash River at Mount Carmel is the FIS for Wabash County, Ill. (FEMA, 2011). However, because of the large extent of the study reach and because the Wabash River runs along county boundaries, there are three additional FIS reports that provide information for the surrounding area (FEMA, 2012, 2014a, 2014b). These FIS reports include redelineation of the previously effective flood-hazard information and updates to the format of the Flood Insurance Rate Maps. No new hydrologic or hydraulic analyses for the Wabash River were in the countywide FIS for Wabash County, Ill., dated December 16, 2011 (FEMA, 2011). The FIS for Wabash County, Ill., provided water-surface elevations for peak discharges with 10-, 2-, 1-, and 0.2-percent annual exceedance probabilities for the Wabash River at the USGS streamgage (03377500) at Mount Carmel, Ill. The FIS was a Special Flood Hazard study of the Wabash River prepared by the USACE Louisville District (USACE, n.d.).

The Indiana Department of Natural Resources, the USGS, the Natural Resources Conservation Service, and the USACE have agreed to the discharge-frequency values for sites along many rivers in Indiana; the values are termed “coordinated discharges” and assure consistency among the State and Federal agencies that undertake streamflow studies (Indiana Department of Natural Resources, 1976). The coordinated discharges for the Wabash River at Mount Carmel were obtained from the Coordinated Discharge Graph for the Wabash River below J. E. Roush Reservoir (not shown; Indiana Department of Natural Resources, 2015) and are listed in table 2.

Table 2. Coordinated discharges for selected annual exceedance probabilities for the Wabash River at Mount Carmel, Illinois.

[**Coordinated discharges:** Data from Indiana Department of Natural Resources (2015). mi^2, square miles; ft^3/s, cubic feet per second; USGS, U.S. Geological Survey]

Location on Wabash River	Drainage area (mi^2)	Coordinated discharges (ft^3/s) for indicated annual exceedance probabilities (in percent)			
		10	4	2	1
At USGS streamgage number 03377500	28,635	224,500	258,900	283,700	306,300

An investigation just downstream of the river reach in the study area produced flood-inundation maps for the Wabash River at New Harmony, Ind. (Fowler, 2016). These maps cover a 3.7-mi reach of the Wabash River extending 1.8 mi upstream and 1.9 mi downstream from the USGS streamgage (03378500) at New Harmony, Ind., which is located on the now-closed New Harmony Toll Bridge across the Wabash River (fig. 1). Flood profiles were computed for the river reach by means of a one-dimensional step-backwater model.

Development of a Hydraulic Model and Creation of the Flood-Inundation-Map Library

The USGS has standardized the procedures for creating flood-inundation maps for flood-prone communities so that the process followed and products produced are similar regardless of which USGS office is responsible for the work (USGS, 2016e). Tasks specific to the development of the flood-inundation maps for the Wabash River were:

1. Compilation of flow data from USGS streamgage 03377500,
2. Collection of topographic and bathymetric data for selected cross sections and geometric data for structures and bridges along the study reach,
3. Estimation of energy-loss factors (roughness coefficients) in the stream channel and flood plain,
4. Computation of water-surface elevations by use of the SRH–2D river flow model (U.S. Bureau of Reclamation, 2008),
5. Production of estimated flood-inundation maps at various stream stages by use of a GIS computer program called ArcGIS (Esri, 2016), and
6. Preparation of the maps, both as shapefile polygons that depict the areal extent of flood inundation and as depth grids that provide the depth of floodwaters, for display on a USGS floodinundation mapping application. The USGS provided quality-control reviews of the hydraulic model and its related datasets and resulting flood-inundation maps.

Methods used are generally cited from previously published reports (Bales and others, 2007; Whitehead and Ostheimer, 2009). Techniques that varied from previously documented methods in response to local hydrologic conditions or availability of data are described in detail in this report. Twenty-seven maps were produced for water levels referenced to the stage at USGS streamgage 03377500, Wabash River at Mount Carmel, Ill., and range from less than the action stage (9 ft) to the highest stage (35 ft) of the current stage-discharge rating curve.

Computation of Water-Surface Elevations

The water-surface elevations used to produce the 27 flood-inundation maps in this study were simulated by using SRH–2D, version 2 (U.S. Bureau of Reclamation, 2008). SRH–2D is a two-dimensional, finite-volume numerical model for simulation of flow hydraulics. It is capable of using an unstructured, arbitrarily shaped mesh, has a robust and seamless wetting-drying algorithm, and can simulate steady or unsteady flows in all flow regimes. A graphical user interface called Surface-water Modeling System (SMS), version 12.1.3 (Aquaveo, 2016), was used in full-interface mode to develop the computational mesh, assign model parameters and boundary conditions, run the SRH–2D model, and evaluate the model output, along with other pre and post-processing options.

Hydrologic Data

The study area hydrologic network consists of two streamgages (fig. 1; table 1). USGS streamgage 03377500 has been in operation since 1875 and is collocated with the NWS AHPS site MCRI2. The USGS streamgage has a continuous record of measured water level (stage) and computed streamflow. Stage is measured every 15 minutes, transmitted hourly by a satellite radio in the streamgage, and made available on the internet through the USGS National Water Information System (USGS, 2016b). Stage data from this streamgage are referenced to a local datum but can be converted to water-surface elevations referenced to the North American Vertical Datum of 1988 (NAVD 88) by adding 368.98 ft. Information about USGS streamgage 03378500 is available in Fowler (2016). Data from both streamgages were used for calibration of the model and comparison of model results.

The steady-flow data necessary for the hydraulic model consisted of boundary conditions (normal depth) and peak-discharge information. The peak flows used in the model simulations (table 3) were obtained from the current stage-discharge relation for streamgage 03377500 and corresponded with the target stages. The current stage-discharge relation for this investigation is USGS rating no. 18, effective March 19, 2015. All computations used discharge values with known stages from actual streamflow measurements or the stage-discharge relation at the gage. No major tributaries join the Wabash River within the 30-mi study reach; therefore, the gage-derived discharges were not adjusted for tributary inflows but were held constant throughout the study reach for a given profile.

Table 3. Estimated discharges for corresponding stages and water-surface elevations at U.S. Geological Survey streamgage 03377500 used in the hydraulic model of the Wabash River near the I–64 Bridge near Grayville, Illinois.

[**Stage:** Above gage reference datum. ft, feet; NAVD 88, North American Vertical Datum of 1988; ft^3/s, cubic feet per second]

Stage (ft)	Water-surface elevation (ft, NAVD 88)	Estimated discharge at USGS streamgage number 03377500 (ft^3/s)
9.00	377.98	28,400
10.00	378.98	32,500
11.00	379.98	36,700
12.00	380.98	40,900
13.00	381.98	45,200
14.00	382.98	49,600
15.00	383.98	54,000
16.00	384.98	58,400
17.00	385.98	62,900
18.00	386.98	67,400
19.00	387.98	72,000
20.00	388.98	78,000
21.00	389.98	84,000
22.00	390.98	91,400
23.00	391.98	99,000
24.00	392.98	108,000
25.00	393.98	118,000
26.00	394.98	129,000
27.00	395.98	142,000
28.00	396.98	158,000
29.00	397.98	174,000
30.00	398.98	192,000
31.00	399.98	210,000
32.00	400.98	230,000
33.00	401.98	250,000
34.00	402.98	270,000
35.00	403.98	290,000

Topographic and Bathymetric Data

All topographic data used in this study are referenced vertically to NAVD 88 and horizontally to the North American Datum of 1983 (NAD 83). Elevation data were obtained from a digital elevation model (DEM) that was derived from light detection and ranging (lidar) data courtesy of FEMA. The DEM was obtained from the USGS National Elevation Dataset (USGS, 2016f). The original lidar data have a horizontal resolution of 1/9-arc-second (~10 ft) and a vertical accuracy of 0.69 ft at a 95-percent confidence level.

Because lidar data cannot provide ground elevations below a stream's water surface, channel cross sections were surveyed by a USGS field crew in January 2016. Cross-sectional depths were measured by using hydroacoustic instrumentation at 73 locations along the study reach, typically spaced every half mile. A differential global positioning system (GPS) with real-time kinematic (RTK) technology was used to derive horizontal locations and the elevation of the water surface at each surveyed cross section.

In the ArcMap (version 10.4.1) application of ArcGIS (Esri, 2016), these field data were used with a bathymetry mesh tool, created by Merwade and others (2008), to interpolate below-water ground elevations throughout the study reach. The density of ground elevations in the mesh was determined by two variables: (1) the number of parallel longitudinal profiles that were evenly spaced across the channel and ran the length of the study reach, and (2) the user-specified spacing between cross sections. Ground elevations were either extracted or interpolated from the field data at the intersections of the longitudinal profiles and cross sections that were spaced approximately 250 ft apart. Instructions for the bathymetry mesh tool are presented by Merwade (2011). The mesh elevations were then combined with the DEM data, resulting in a single, merged DEM (overbank and in-channel elevations), which was subsequently input into the SMS software for the SRH–2D model.

Hydraulic Structures

Various man-made structures (bridges, culverts, roadway embankments, and levees) in and along the Wabash River affect or have the potential to affect water-surface elevations during floods along the river. To properly account for these features in the model, structural dimensions for two bridges (I–64 and a railroad bridge) were obtained from field surveys and as-built plans. Bridge piers were modeled as flow obstructions in SRH–2D. Culvert locations in the Wabash River flood plain were confirmed in a field survey conducted in January 2016. This confirmation was needed to aid in determining whether disconnected flood-inundation areas were actually connected with the main river or just low areas in the topography. The DEM resolution was high enough to accurately capture the roadway embankment and levee elevations, and the computational mesh was created to align with the top of these features.

Energy-Loss Factors

Hydraulic analyses require the estimation of energy losses that result from frictional resistance exerted by a channel on the flow. These energy losses are quantified by the Manning's roughness coefficient (*n*-value) (Arcement and Schneider, 1989). Initial (precalibration) *n*-values were selected on the basis of field observations, high-resolution aerial photographs, and previous studies. An *n*-value of 0.03 was selected for the main channel because it has a low gradient, smooth bed, occasional variation in cross section, negligible in-channel obstructions, limited vegetation due to point bars and cut banks, and moderate meandering.

The overbank areas have mixed land uses but are dominated by agricultural fields and forests. An *n*-value of 0.08 was selected for the primarily agricultural overbank areas, and an *n*-value of 0.16 was selected for the primarily forested overbank areas.

The initial *n*-values were adjusted as part of the calibration process, which involved minimizing the differences between simulated and observed water-surface elevations at GPS points and the streamgage in the study reach. The calibration process was a two-step process. First, the in-channel portion of the model was calibrated based on 73 GPS measurements of water-surface elevation (fig. 2*A*) during a known flow condition (30,300 cubic feet per second). This iterative process involved running the model for the known discharge, comparing the model water-surface elevations with the GPS measurements of water-surface elevation, adjusting the *n*-values in different sections of the reach, and then rerunning the model. This process was repeated until a satisfactory result was obtained. The final calibration had *n*-values that ranged from 0.020 to 0.029 and had a mean difference between model and GPS water-surface elevations of 0.01 ft with 96 percent of the differences falling within ± 0.50 ft (fig. 2*B*).

The second step in the calibration process used roughness-coefficient adjustment factors (flow roughness factors), which are a method that allows the specified *n*-values to adjust with changes in flow, to minimize the differences between simulated and observed water-surface elevations at the two streamgages. The water-surface elevation at the upstream end of the model was extrapolated to the Mount Carmel streamgage to calculate a difference in water-surface elevations. Flow roughness factors ranged from 1.00 at the 9-ft stage and increased to 1.43 at the 35-ft stage. The actual *n*-values were computed by multiplying the initial *n*-value by each of the roughness-coefficient adjustment factors. Main channel *n*-values ranged from 0.020 to 0.041, and overbank *n*-values ranged from 0.08 to 0.11 for primarily agricultural areas and from 0.16 to 0.23 for primarily forested areas.

Hydraulic Model

The hydraulic analysis for this study was done using SRH–2D with a series of constant discharges (steady state). The computational mesh developed in the SMS software contained 110,225 nodes (points) that were connected to form 209,720 elements (cells). These elements were shaped as quadrilaterals for the in-channel areas and triangles for the overbank areas. Normal depth, based on an exit water surface elevation, was used as the reach's downstream boundary condition. Steady flow was the upstream boundary condition, and the flows that were used in the model were discussed in the "Hydrologic Data" section. These flows coincided with even 1-ft increments of stage, referenced to the local gage datum at USGS streamgage 03377500 (table 3).

The SRH–2D model was calibrated to the current stage-discharge relations at USGS streamgage 03378500, Wabash River at New Harmony, Ind., and USGS streamgage 03377500, Wabash River at Mount Carmel, Ill. The model was calibrated by adjusting Manning's *n*-values until the results of the hydraulic computations closely agreed with the observed water-surface elevations for given flows. For the New Harmony streamgage (USGS 03378500), the mean difference between model and target water-surface elevations was 0.04 ft with a range from –0.09 ft to 0.28 ft (table 4). For the Mount Carmel streamgage (USGS 03377500), the mean difference between model and target water-surface elevations was –0.04 ft with a range from –0.52 ft to 0.09 ft (table 4). The results demonstrate that the model is capable of simulating reasonable water levels over a wide range of flows at the streamgages.

Development of Water-Surface Elevations

The calibrated hydraulic model was used to generate water-surface elevations corresponding to flows for a total of 27 stages at 1-ft intervals ranging from 9 ft to 35 ft as referenced to USGS streamgage 03377500. These stages correspond to elevations between 377.98 ft and 403.98 ft, NAVD 88, respectively. Discharges corresponding to the various stages were obtained from the current stage-discharge relation (USGS rating no. 18.0) at the Mount Carmel streamgage. Discharges for all profiles (table 3) were selected with the assumption that there are no significant tributary inflows within the 30-mi modeled reach. The discharges were estimated to be uniform and steady throughout the modeled reach.

Development of Flood-Inundation Maps

Flood-inundation maps were created for a reach of the Wabash River upstream and downstream of the I–64 Bridge near Grayville, Ill. The maps were created in a GIS by combining the 27 water-surface elevations and DEM data. The DEM data were derived from the same lidar data described previously in the "Topographic and Bathymetric Data" section and therefore have an estimated vertical accuracy of 1 ft. Estimated flood-inundation boundaries for each simulated flow were developed with geoprocessing tools in ArcMap. Shapefile polygons and depth grids of the inundated areas for each flow were modified, as required, in the ArcMap application of ArcGIS to ensure a hydraulically reasonable transition of the flood boundaries (Whitehead and Ostheimer, 2009). The resulting inundation maps have a vertical accuracy of about plus or minus 1.0 ft. The datasets used in this study are available through a data release (Boldt, 2018).

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.

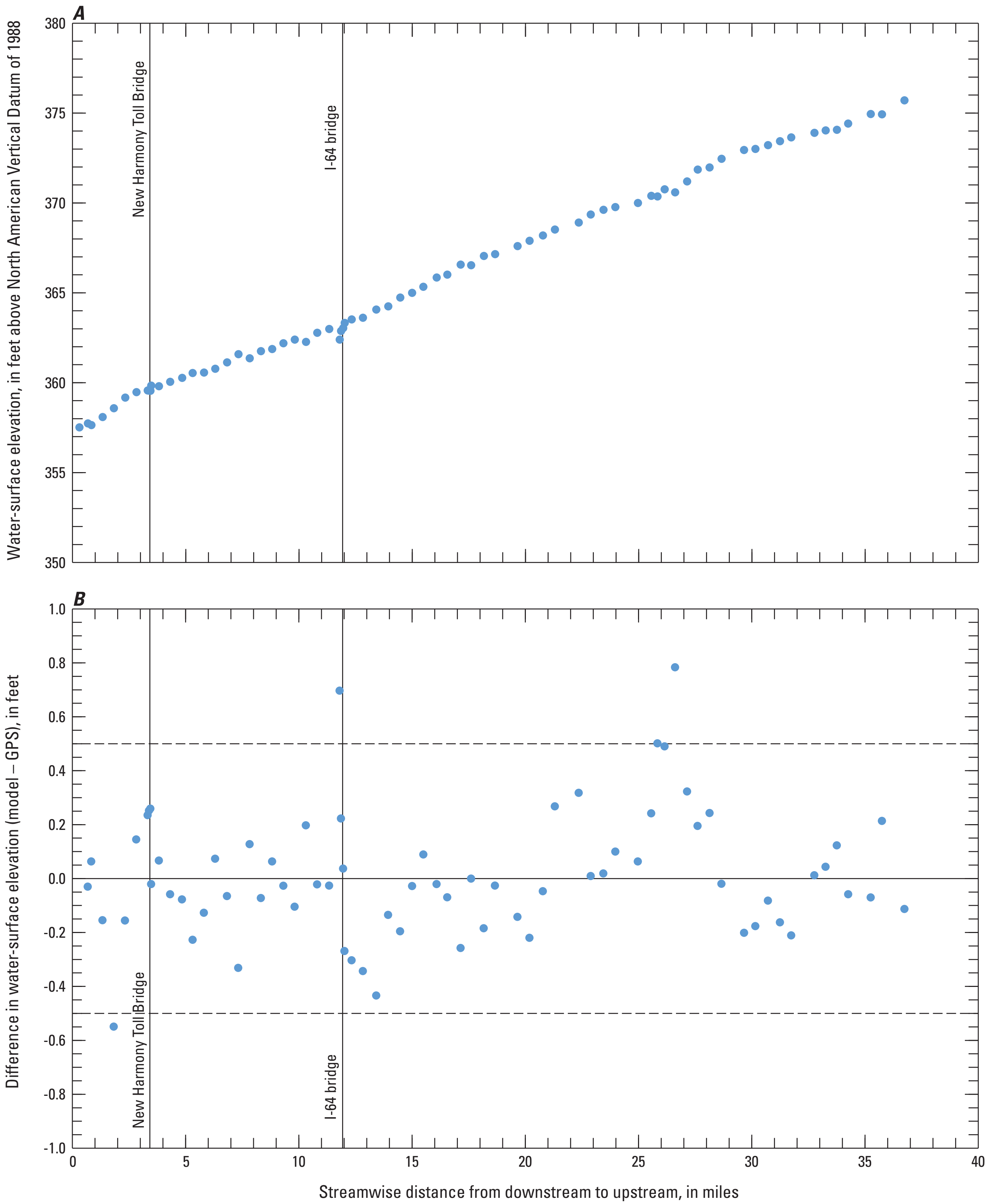


Figure 2. *A*, Water-surface elevations determined with GPS measurements along the study reach of the Wabash River on January 27–28, 2016, and *B*, a residual plot of differences in water-surface elevations determined with the hydraulic model and GPS measurements for a calibration flow event on January 27–28, 2016.

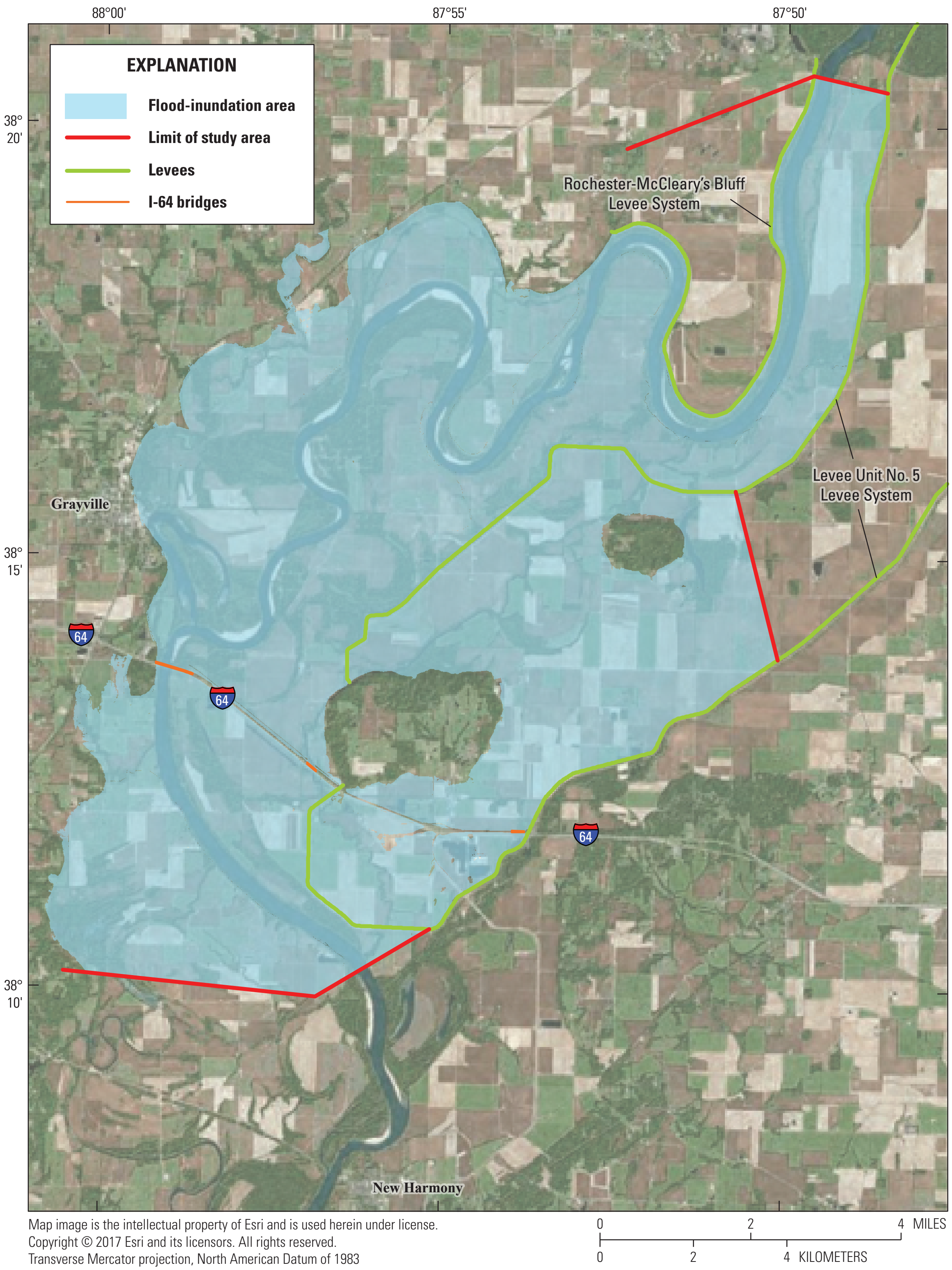
Table 4. Comparison of target water-surface elevations at U.S. Geological Survey streamgages 03378500 and 03377500 with water-surface elevations output from the hydraulic model of the study reach of the Wabash River.

[**Stage:** Above gage reference datum at USGS Streamgage 03377500. ft, feet; NAVD 88, North American Vertical Datum of 1988]

Stage (ft)	New Harmony streamgage (USGS 03378500)			Mount Carmel streamgage (USGS 03377500)		
	Target water-surface elevation (ft, NAVD 88)	Modeled water-surface elevation (ft, NAVD 88)	Elevation difference (ft)	Target water-surface elevation (ft, NAVD 88)	Modeled water-surface elevation (ft, NAVD 88)	Elevation difference (ft)
9.00	359.45	359.43	-0.02	377.98	377.73	-0.25
10.00	360.33	360.29	-0.04	378.98	378.89	-0.09
11.00	361.21	361.14	-0.07	379.98	380.01	0.03
12.00	362.05	361.97	-0.08	380.98	381.02	0.04
13.00	362.89	362.80	-0.09	381.98	382.05	0.07
14.00	363.69	363.60	-0.09	382.98	382.99	0.01
15.00	364.48	364.47	-0.01	383.98	384.00	0.02
16.00	365.26	365.29	0.03	384.98	385.01	0.03
17.00	366.05	366.08	0.03	385.98	386.00	0.02
18.00	366.83	366.85	0.02	386.98	386.98	0.00
19.00	367.52	367.54	0.02	387.98	387.98	0.00
20.00	368.35	368.32	-0.03	388.98	388.98	0.00
21.00	369.03	369.00	-0.03	389.98	390.03	0.05
22.00	369.78	369.77	-0.01	390.98	391.07	0.09
23.00	370.41	370.42	0.01	391.98	392.04	0.06
24.00	370.92	370.93	0.01	392.98	392.92	-0.06
25.00	371.46	371.51	0.05	393.98	393.95	-0.03
26.00	372.03	372.10	0.07	394.98	394.93	-0.05
27.00	372.62	372.71	0.09	395.98	395.87	-0.11
28.00	373.29	373.42	0.13	396.98	396.97	-0.01
29.00	373.93	374.00	0.07	397.98	398.04	0.06
30.00	374.60	374.63	0.03	398.98	399.05	0.07
31.00	375.05	375.21	0.16	399.98	400.07	0.09
32.00	375.31	375.44	0.13	400.98	401.00	0.02
33.00	375.56	375.74	0.18	401.98	401.76	-0.22
34.00	375.78	375.98	0.20	402.98	402.67	-0.31
35.00	376.00	376.28	0.28	403.98	403.46	-0.52

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 were overlaid on high-resolution, georeferenced aerial photographs of the study area. The I–64 Bridge road surface was clipped to be displayed as not inundated, because the highest modeled flow resulted in a water-surface elevation below the lowest structural chord of the bridge or the bridge deck. However, other bridge surfaces are displayed as inundated regardless of the actual water-surface elevation in relation to the lowest structural chord of the bridge or the bridge deck. Finally, the downstream portions of the flood-inundation maps were clipped so as to not overlap the existing flood-inundation maps for New Harmony (Fowler, 2016).

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 USGS mapping application described in the following section, “Flood-Inundation Map Delivery.” The flood-inundation map corresponding to the highest simulated water-surface profile, a stage of 35 ft, is presented in figure 3.



Transverse Mercator projection, North American Datum of 1983

Figure 3. Flood-inundation map for the Wabash River near the I–64 Bridge near Grayville, Illinois, corresponding to a stage of 35 feet at the U.S. Geological Survey streamgage (station number 03377500).

Inundation Verification

A set of high-water marks were collected during the receding limb of a flood event on January 7, 2016, to help verify the flood-inundation maps. The flood had a peak of 29.11 ft (176,000 cubic feet per second) on January 6, 2016 (USGS, 2016b). The gage height during the field survey ranged from 28.42 to 28.61 ft, and an additional model simulation was run to best match the flow during the field survey. To spot check the flooding extent, 14 GPS-referenced elevations were collected at various points along public roads around the inundated area. The modeled water-surface elevations were within ± 1.0 ft at 10 of the 14 high-water marks and ranged from 1.8 to 2.3 ft high at the other 4 high-water marks. Overall, there was good agreement between the model simulation and the flood extent on January 7, 2016.

Flood-Inundation Map Delivery

The flood-inundation maps from this study depict estimates of the areal extent and depth of flooding that correspond to selected water levels (stages) at USGS streamgage 03377500, Wabash River at Mount Carmel, Ill. The current study documentation is available online at the USGS Publications Warehouse (https://doi.org/10.3133/sir20175140). Also, a Flood Inundation Mapping Science web site (USGS, 2016e) has been established to make USGS flood-inundation study information available to the public. That site links to a mapping application (http://wim.usgs.gov/FIMI/FloodInundationMapper.html) that presents map libraries and provides detailed information on flood extent and depths for selected sites. The mapping application enables the production of customized flood-inundation maps from the map library for the Wabash River at Mount Carmel, Ill. A link on the map library web site connects to the USGS National Water Information System (USGS, 2016a), which presents the current stage and streamflow at USGS streamgage 03377500 to which the flood-inundation maps are referenced. A second link connects to the NWS AHPS site (NWS, 2016a) so that the user can obtain applicable information on forecasted peak stage. The estimated flood-inundation maps are displayed in sufficient detail so that preparations for flooding and decisions for emergency response can be performed efficiently. Depending on the flood magnitude, roadways are shown as shaded (inundated and likely impassable) or not shaded (dry and passable) to facilitate emergency planning and use. Bridges may be shaded—that is, shown as inundated—regardless of the flood magnitude. A shaded building should not be interpreted to mean that the structure is completely submerged, but rather that 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 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 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 (Bales and Wagner, 2009). The flood boundaries shown were estimated on the basis of water stages and streamflows at two USGS streamgages. Water-surface elevations along the stream reach were estimated by steady-state hydraulic modeling, assuming unobstructed flow, and using streamflows and hydrologic conditions anticipated at the USGS streamgages. The hydraulic model reflects the land-cover characteristics and any bridge, embankment, levee, or other hydraulic structures existing as of January 2016. Unique meteorological factors (timing and distribution of precipitation) may cause actual streamflows along the modeled reach to vary from those assumed during a flood, which may lead to deviations 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 main-stem river, or backwater from localized debris or ice jams. The accuracy of the floodwater extent portrayed on these maps will vary with the accuracy of the DEM used to simulate the land surface.

If this series of flood-inundation maps will be used in conjunction with NWS river forecasts, the user should be aware of additional uncertainties that may be inherent or factored into NWS forecast procedures. The NWS uses forecast models to estimate the quantity and timing of water flowing through selected stream reaches in the United States. These forecast models

1. Estimate the amount of runoff generated by precipitation and snowmelt,
2. Simulate the movement of floodwater as it proceeds downstream, and
3. Predict the flow and stage (and water-surface elevation) for the stream at a given location (AHPS forecast point) throughout the forecast period (every 6 hours and 3 to 5 days out in many locations).

For more information on AHPS forecasts, please see: http://water.weather.gov/ahps/forecasts.php. Additional uncertainties and limitations pertinent to this study may be described elsewhere in this report.

Summary

A series of 27 digital flood-inundation maps were developed in cooperation with the Indiana Department of Transportation for the Wabash River near the I–64 Bridge near Grayville, Illinois, extending 24.8 miles upstream and 5.2 miles downstream from the I–64 Bridge. The flood-inundation maps were developed by using the U.S. Bureau of Reclamation's SRH–2D model and Aquaveo's Surface-water Modeling System software to compute water surface elevations and to delineate estimated flood-inundation areas and depths of flooding for selected river stages. The SRH–2D hydraulic model was calibrated by using global positioning system measurements of water-surface elevation and the current stage-discharge relation at both U.S. Geological Survey (USGS) streamgage 03377500, Wabash River at Mount Carmel, Ill., and USGS streamgage 03378500, Wabash River at New Harmony, Indiana. The model was used to compute 27 water-surface elevations for flood stages at 1-foot (ft) intervals referenced to the Mount Carmel streamgage datum and ranging from less than the action stage (9 ft) to the highest stage (35 ft) of the current stage-discharge rating curve. The simulated water-surface elevations were then combined with a geographic information system digital elevation model derived from light detecting and ranging data to delineate estimated flood-inundation areas as shapefile polygons and depth grids for each flow. These flood-inundation polygons were overlaid on high-resolution, georeferenced aerial photographs of the study area. The flood maps show estimated (shaded) flood-inundation areas of the study area for river stages from 9 ft to 35 ft at the Wabash River at Mount Carmel, Ill. streamgage. The flood maps are available through a mapping application that can be accessed on the USGS Flood Inundation Mapping Science web site (http://water.usgs.gov/osw/flood_inundation).

Interactive use of the maps on the USGS mapping application can give users a general indication of depth of water at any point by using the mouse cursor to click within the shaded areas. The mapping application enables the production of customized flood-inundation maps from the map library for the Wabash River near the I–64 Bridge near Grayville, Ill. These maps, in conjunction with the near-real-time stage data from the USGS streamgage 03377500 and National Weather Service Advanced Hydrologic Prediction Service flood-stage forecasts, will help to guide the general public in taking individual safety precautions and will provide emergency management personnel with a tool to efficiently manage emergency flood operations and postflood recovery efforts.

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