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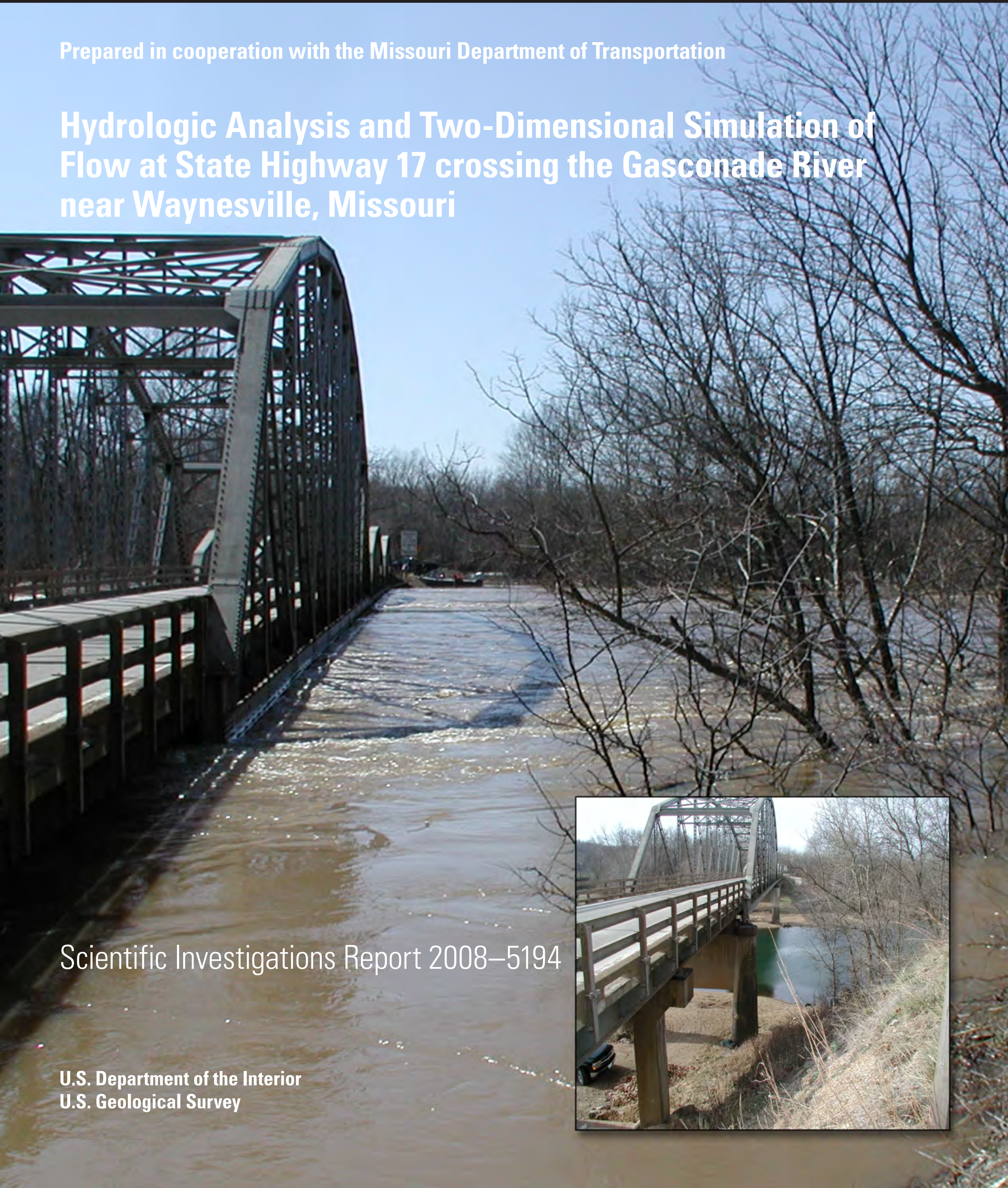
# Hydrologic Analysis and Two-Dimensional Simulation of Flow at State Highway 17 crossing the Gasconade River near Waynesville, Missouri



Scientific Investigations Report 2008–5194

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

**Cover photographs.** Bridge over the Gasconade River (structure J-802) on Missouri State Highway 17, facing west, March 20, 2008, and January 4, 2008 (inset).

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**U.S. Department of the Interior**
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# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 25.4 | millimeter (mm) |
| inch (in.) | 2.54 | centimeter (cm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 4,047 | square meter ($m^2$) |
| acre | 0.4047 | hectare (ha) |
| acre | 0.004047 | square kilometer ($km^2$) |
| square foot ($ft^2$) | 0.09290 | square meter ($m^2$) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |
| | Flow rate | |
| foot per second (ft/s) | 0.3048 | meter per second (m/s) |
| 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) |
| | Kinematic viscosity | |
| square foot per second ($ft^2/s$) | 0.09290 | square meter per second ($m^2/s$) |
| | Unit discharge* | |
| cubic foot per second per foot [($ft^3/s$)/ft] | 0.09290 | cubic meter per second per meter [($m^3/s$)/m] |

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).

*Unit discharge: The standard unit for unit discharge is cubic foot per second per foot [($ft^3/s$)/ft]. In this report, the mathematically reduced form, square foot per second ($ft^2/s$), is used for convenience.

In this report, the words “left” and “right” generally refer to directions that would be reported by an observer facing downstream.

# Hydrologic Analysis and Two-Dimensional Simulation of Flow at State Highway 17 crossing the Gasconade River near Waynesville, Missouri

By Richard J. Huizinga


## Abstract

In cooperation with the Missouri Department of Transportation, the U.S. Geological Survey determined hydrologic and hydraulic parameters for the Gasconade River at the site of a proposed bridge replacement and highway realignment of State Highway 17 near Waynesville, Missouri. Information from a discontinued streamflow-gaging station on the Gasconade River near Waynesville was used to determine streamflow statistics for analysis of the 25-, 50-, 100-, and 500-year floods at the site. Analysis of the streamflow-gaging stations on the Gasconade River upstream and downstream from Waynesville indicate that flood peaks attenuate between the upstream gaging station near Hazelgreen and the Waynesville gaging station, such that the peak discharge observed on the Gasconade River near Waynesville will be equal to or only slightly greater (7 percent or less) than that observed near Hazelgreen.

A flood event occurred on the Gasconade River in March 2008, and a flood measurement was obtained near the peak at State Highway 17. The elevation of high-water marks from that event indicated it was the highest measured flood on record with a measured discharge of 95,400 cubic feet per second, and a water-surface elevation of 766.18 feet near the location of the Waynesville gaging station. The measurements obtained for the March flood resulted in a shift of the original stage-discharge relation for the Waynesville gaging station, and the streamflow statistics were modified based on the new data.

A two-dimensional hydrodynamic flow model was used to simulate flow conditions on the Gasconade River in the vicinity of State Highway 17. A model was developed that represents existing (2008) conditions on State Highway 17 (the “model of existing conditions”), and was calibrated to the floods of March 20, 2008, December 4, 1982, and April 14, 1945. Modifications were made to the model of existing conditions to create a model that represents conditions along the same reach of the Gasconade River with preliminary proposed replacement bridges and realignment of State Highway 17 (the “model of proposed conditions”). The models of existing and proposed conditions were used to simulate the 25-, 50-, 100-, and 500-year recurrence floods, as well as the March 20, 2008 flood.

Results from the model of proposed conditions show that the proposed replacement structures and realignment of State Highway 17 will result in additional backwater upstream from State Highway 17 ranging from approximately 0.18 foot for the 25-year flood to 0.32 foot for the 500-year flood. Velocity magnitudes in the proposed overflow structures were greater than in the existing structures [by as much as 4.9 feet per second in the left (west) overflow structure for the 500-year flood], and shallow, high-velocity flow occurs at the upstream edges of the abutments of the proposed overflow structures in the 100- and 500-year floods where flow overtops parts of the existing road embankment that will be left in place in the proposed scenario. Velocity magnitude in the main channel of the model of proposed conditions increased by a maximum of 1.2 feet per second over the model of existing conditions, with the maximum occurring approximately 1,500 feet downstream from existing main channel structure J-802.


## Introduction

Locating and designing bridges and culverts on roadways that cross streams and rivers needs to take into consideration the hydrology of the basin upstream from the road crossing and the hydraulics of the channel that is being crossed. The hydrology of a basin can be used to estimate the volume of water that a basin will experience during floods, and the hydraulics of the channel can be used to estimate how the channel will convey the flood discharge. Under-design of bridges and culverts could result in the disruption of traffic flow, costly maintenance to bridges and culverts, and possible loss of life; conversely, overdesign could result in excessive costs (Alexander and Wilson, 1995). In 2007, the U.S. Geological Survey (USGS), in cooperation with the Missouri Department of Transportation (MoDOT), began a study to determine hydrologic and hydraulic parameters for existing and proposed grade crossings of streams and rivers throughout Missouri.

One-dimensional computer models often are used to establish the hydraulic characteristics necessary for the design of a stream crossing (Missouri Department of Transportation, 2004), and have been used in the hydraulic assessments performed to date (2008) in the study by the USGS and MoDOT. Occasionally, however, the simplifying assumptions that must be made to apply a one-dimensional hydraulic analysis to a two-dimensional flow scenario are deemed inadequate. This is the case at State Highway 17 over the Gasconade River near Waynesville, Missouri (hereinafter referred to as “the State Highway 17 crossing”; fig. 1). The Gasconade River meanders substantially in the immediate vicinity of the State Highway 17 crossing, and Roubidoux Creek flows into the Gasconade River immediately upstream from State Highway 17 (fig. 2). This unique configuration is beyond the reasonable bounds for a one-dimensional hydraulic analysis, indicating the need for a two-dimensional hydraulic analysis of the site.

## Purpose and Scope

This report describes and presents the results of a hydrologic analysis and two-dimensional simulation of flow at the State Highway 17 crossing. The report describes the development of and results from two-dimensional hydrodynamic flow models that represent part of the Gasconade River at State Highway 17 near Waynesville, Missouri, using the depth-averaged flow model Flo2DH [part of the Federal Highway Administration’s Finite Element Surface-Water Modeling System (FESWMS) designed for hydraulic structures and flood plains (Froehlich, 2002)]. A two-dimensional hydrodynamic flow model was developed for the Gasconade River that represents conditions as they exist (as of 2008) (hereinafter referred to as the “model of existing conditions”). The model of existing conditions was calibrated to the floods of March 20, 2008, December 4, 1982, and April 14, 1945, and used to simulate the 25-, 50-, 100-, and 500-year recurrence floods. Based on information provided by MoDOT (David Stevenson, Missouri Department of Transportation, written commun,. 2008; Keith Ferrell, Missouri Department of Transportation, written commun,. 2008), the model of existing conditions was modified to create another model that represents conditions along the same reach of the Gasconade River with preliminary proposed replacement structures in place (hereinafter referred to as the “model of proposed conditions”). The model of proposed conditions was used to simulate the flood of March 20,

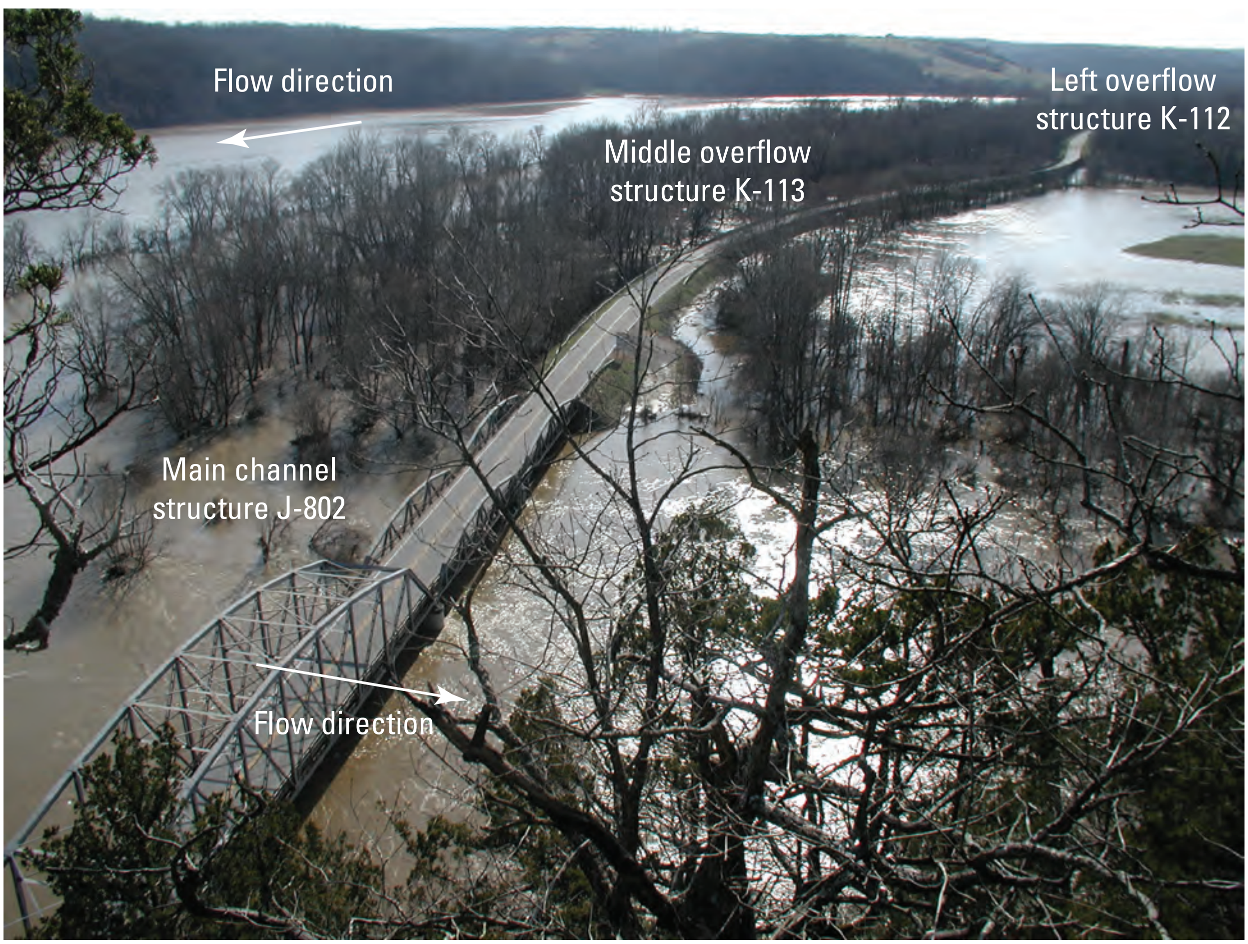



**Figure 1.** State Highway 17 crossing the Gasconade River near Waynesville, Missouri, as viewed from a bluff on the downstream right bank facing west-south-west on March 21, 2008, one day after the peak for a flood on March 20, 2008.

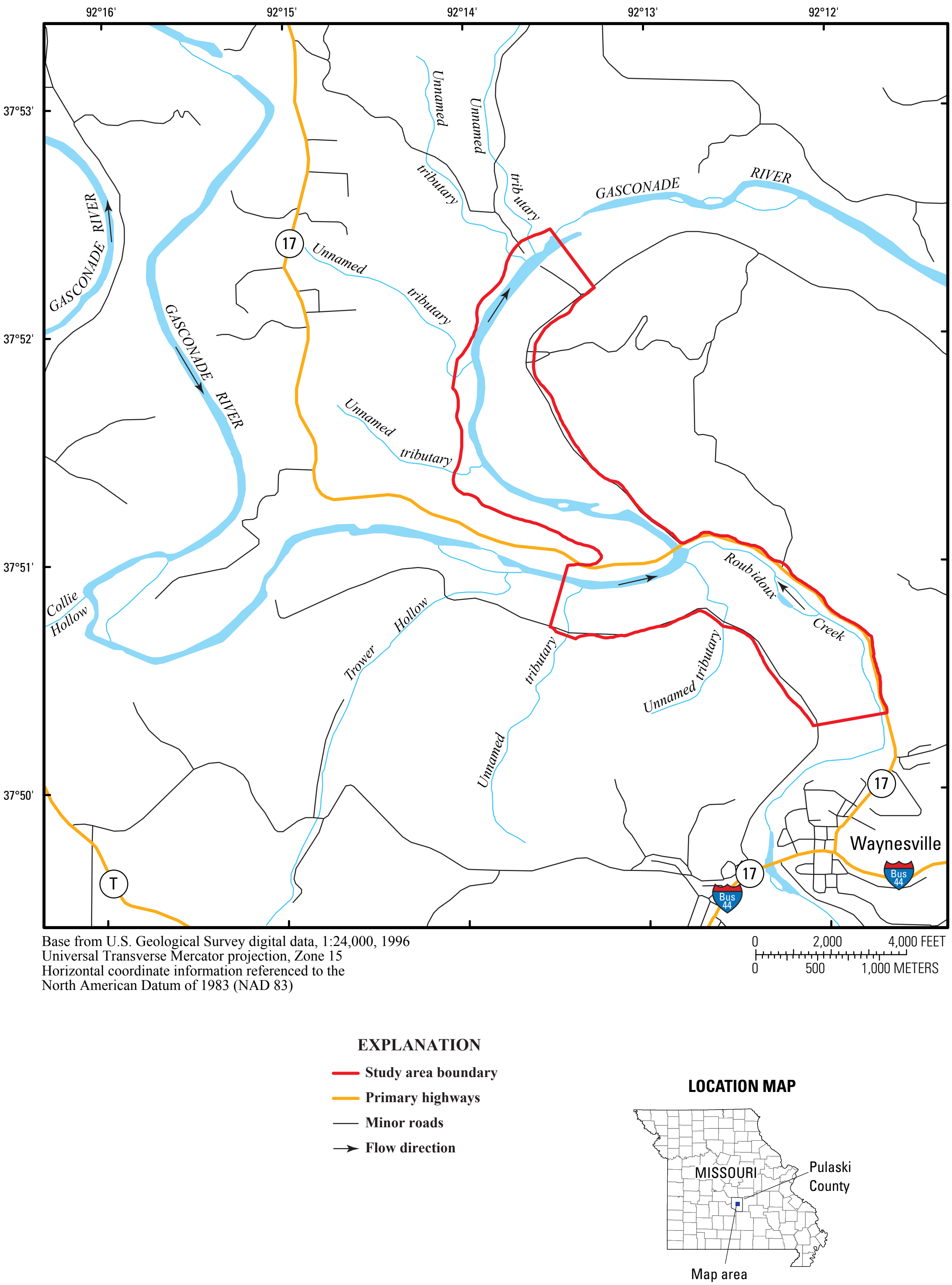



**Figure 2.** Location of the study area on the Gasconade River near Waynesville, Missouri.

2008, and the 25-, 50-, 100-, and 500-year recurrence floods under the proposed conditions. The difference between the hydraulic parameters (particularly water-surface elevation and velocity magnitude) determined for the existing conditions and the proposed conditions are shown.

## Description of Study Area

The study area is located on the Gasconade River in the central part of Pulaski County, Missouri, north of Waynesville, where Roubidoux Creek flows into the Gasconade River (figs. 2 and 3). The study area begins approximately 2.4 miles (mi) downstream from the State Highway 17 crossing, near the location of a discontinued gage on the Gasconade River (06928500, Gasconade River near Waynesville), and extends approximately 3,600 feet (ft) upstream from State Highway 17 on the Gasconade River. The study area also extends approximately 1.5 mi along Roubidoux Creek upstream from its confluence with the Gasconade River (figs. 2 and 3).

State Highway 17 is the primary highway across the Gasconade River between Crocker and Waynesville, which has access to Interstate 44 (fig. 4). The nearest alternate bridge is approximately 12.4 river miles away, and the shortest detour resulting from the closure of this road is approximately 23 mi (David Stevenson, written commun., 2008); therefore, MoDOT wanted to minimize disruption to traffic and minimize road closure times during the replacement of the structures on State Highway 17. Results described in this report are needed by MoDOT to develop design and replacement plans at the State Highway 17 crossing.

In the vicinity of the study area, the dominant physiographic feature is the Ozarks Plateaus, characterized by gravel-bed streams with flood plains bordered with limestone and dolomite bluffs (figs. 3 and 5). State Highway 17 crosses the Gasconade River from east to west at a point where the Gasconade River makes an approximately 170 degree bend, just downstream from the confluence with Roubidoux Creek (figs. 2 and 3). The main bridge over the Gasconade River is structure J-802, a 482-ft long bridge, consisting of a 200-ft through-truss main span, two 100-ft pony truss approach spans, and two 35-ft steel I-beam approach spans with concrete piers founded on rock (figs. 1, 3, and 5A). Two overflow bridges exist on the left (west) flood plain: structure K-112 is furthest to the left (west), and consists of nine 40-ft long steel I-beam spans with concrete bents founded on rock (figs. 1, 3, and 5B); structure K-113 is between K-112 and main bridge J-802, and also consists of nine 40-ft long steel I-beam spans with concrete bents founded on rock (figs. 1, 3, and 5C). An elevated, level road embankment exists between structures J-802 and K-113, and between K-113 and K-112. A series of horizontal curves cause the road to weave north and south as State Highway 17 crosses the flood plain from east to west (figs. 1 through 3).

In the study area, the flood plain predominantly consists of agricultural land used for growing corn, soybeans, and pasture, with areas of timber and brush (fig. 3). A riparian corridor of variable thickness is present along the Gasconade River and Roubidoux Creek (fig. 3). The bluffs on either side of the flood plain are covered with thick timber and brush (figs. 1 and 3).

In this report, all vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). In the study area, the difference between the NAVD 88 and the National Geodetic Vertical Datum of 1929 (NGVD 29) is approximately 0.10 meters (m) or 0.33 ft.

# Hydrologic Analysis

Hydrologic analysis of the State Highway 17 crossing of the Gasconade River near Waynesville involved an analysis of the Gasconade River Basin upstream from the State Highway 17 crossing as well as of the various streamflow-gaging stations (hereinafter referred to as “gages”) on the Gasconade River near Waynesville. These analyses were updated after a record flood event occurred in March 2008.

## Basin and Gage Analysis

A gage was operated by the USGS on the Gasconade River near Waynesville from 1915 to 1975 (station number 06928500, hereinafter referred to as “the Waynesville gage”). Information from this gage was used to determine peak discharges for calibrating the two-dimensional hydraulic models of the State Highway 17 crossing, and to determine the streamflow statistics for analysis of the 25-, 50-, 100-, and 500-year floods at the site. The 25-year flood is the discharge that has a 1 in 25 chance of occurring in any given year [0.04 (4 percent) probability]; similarly, the 50-year flood is the discharge that has a 1 in 50 chance [0.02 (2 percent) probability], the 100-year flood is the discharge that has a 1 in 100 chance [0.01 (1 percent) probability], and the 500-year flood is the discharge that has a 1 in 500 chance of occurring in any given year [0.002 (0.2 percent) probability].

Basin characteristics derived from 30-m digital elevation model (DEM) data (Missouri Spatial Data Information Service, 2008) were determined for the Waynesville gage, as well as the gages on the Gasconade River near Hazelgreen (station number 06928000, hereinafter referred to as “the Hazelgreen gage”) and at Jerome (station number 06933500, hereinafter referred to as “the Jerome gage”) (fig. 4), and are compared to values reported in Alexander and Wilson (1995; table 1). Streamflow statistics for these three gages as determined by Alexander and Wilson (1995) using log-Pearson Type III distribution analyses (Hydrologic Subcommittee of Interagency Advisory Committee on Water Data, 1982) are shown in table 2. As would be expected, the drainage area increases and the channel slope decreases in a downstream direction (table 1); however, the streamflow statistics for the three gages do not follow a particular trend (table 2). The 2- and 5-year

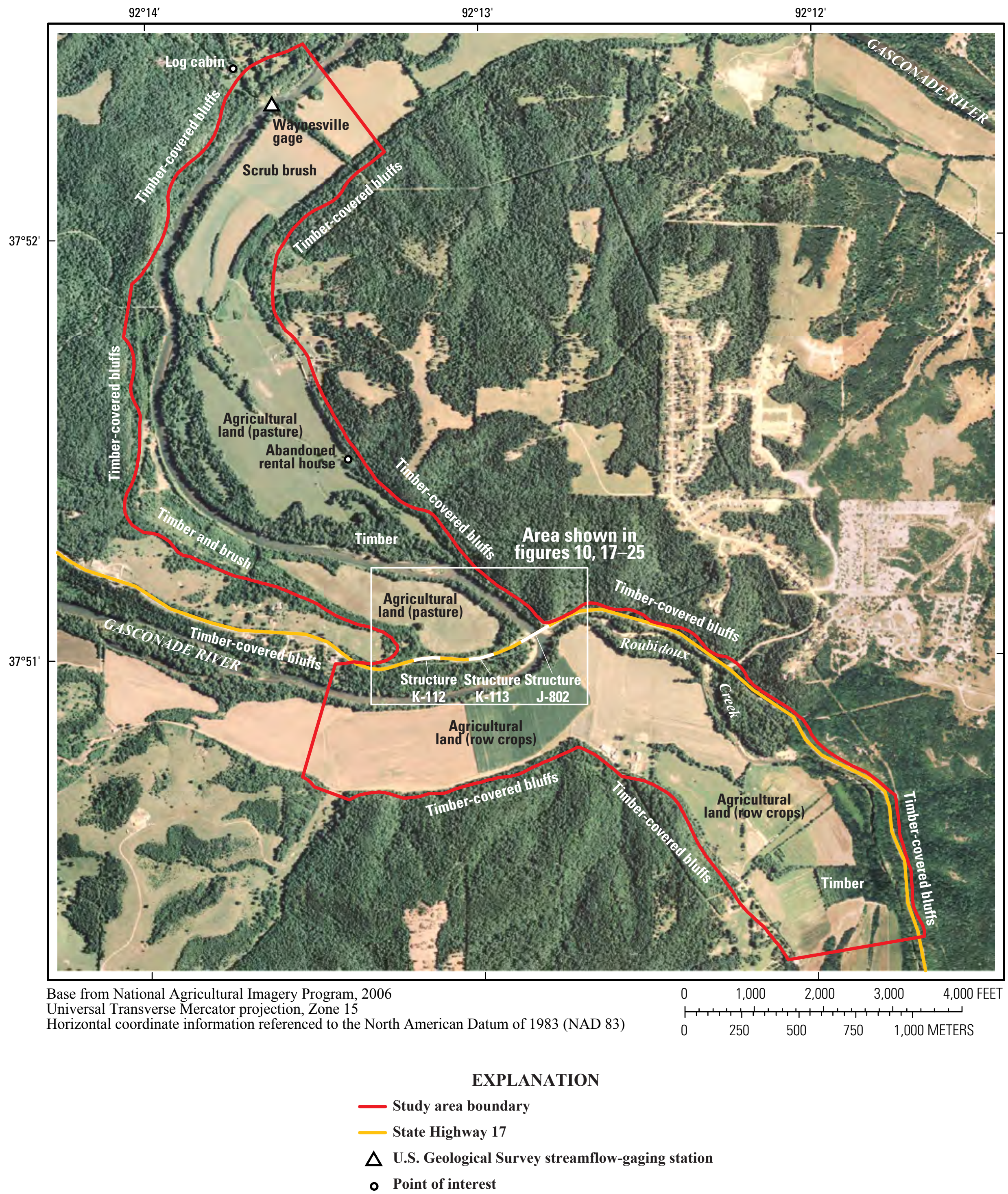



**Figure 3.** Study area on the Gasconade River near Waynesville, Missouri.

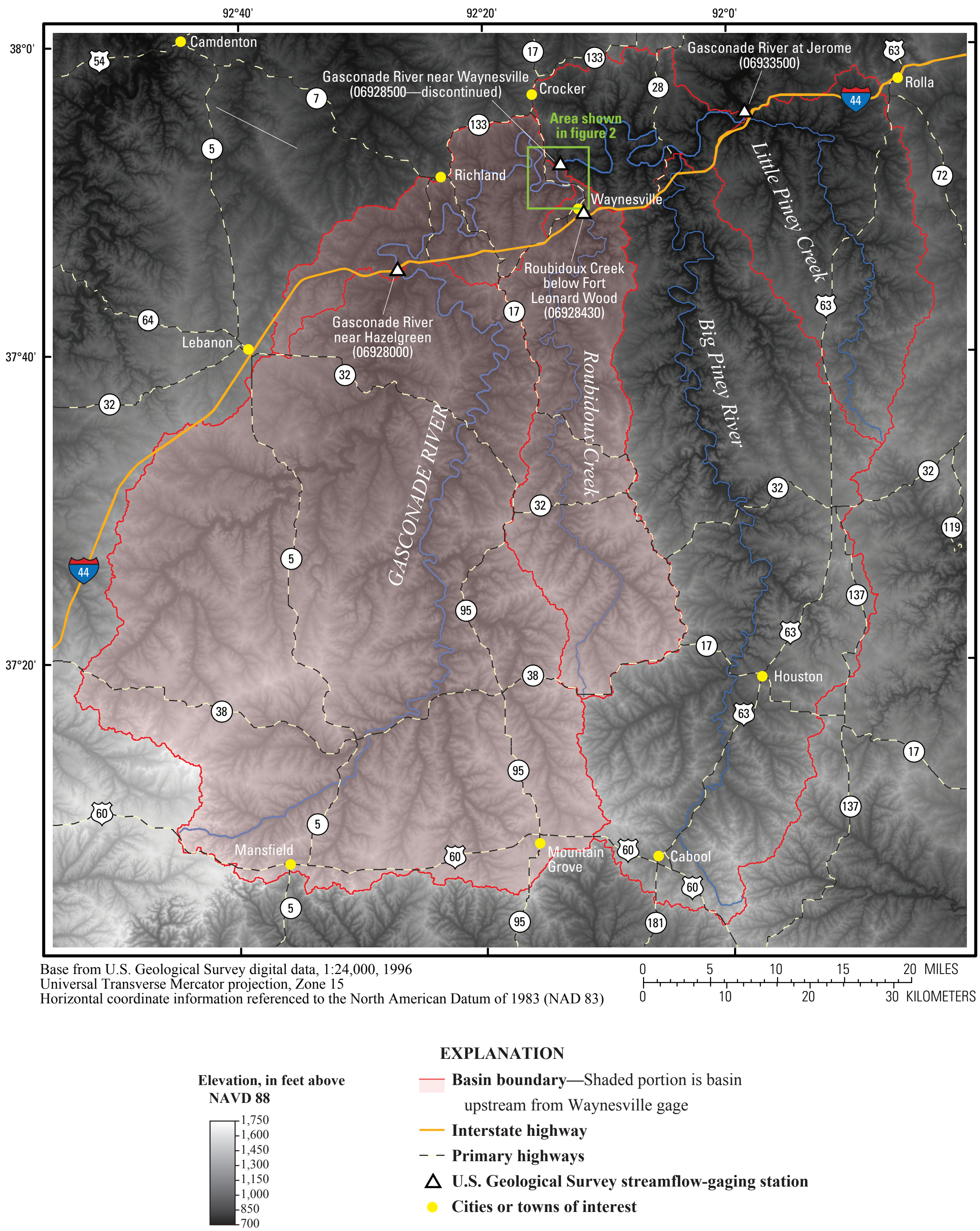



**Figure 4.** Digital elevation model (DEM) data depiction of the basins comprising the Gasconade River Basin and streamflow-gaging stations near Waynesville, Missouri.


**Figure 5.** State Highway 17 crossing of the Gasconade River near Waynesville, Missouri, on January 4, 2008; *A*, Upstream face of main channel structure J-802, spanning the gravel bed of the river, as viewed from the right bank immediately upstream from the right (east) abutment at the base of a limestone and dolomite bluff, *B*, upstream face of left (west) overflow structure K-112, as viewed from the upstream top of the right (east) abutment; and *C*, downstream face of middle overflow structure K-113, as viewed from the downstream top of the right (east) abutment.

discharges increase in a downstream direction, but for the 10- to 500-year recurrence intervals, the discharge values at the Waynesville gage are less than those at the Hazelgreen gage.

The attenuation of flow that is evident in the streamflow statistics between the Hazelgreen and Waynesville gages likely is a function of the drainage area and channel length; whereas the area increases by 35 percent between the Hazelgreen and Waynesville gages [from 1,250 to 1,680 square miles ($mi^2$)], the channel length increases by 47 percent (from 92.8 to 136 mi). By comparison, between the Waynesville and Jerome gages, the area increases by 69 percent (from 1,680 to 2,840 $mi^2$), and the channel length increases by only 24 percent (from 136 to 169 mi). Most of the difference in area between the Hazelgreen and Waynesville gages is from Roubidoux Creek (290 $mi^2$), which joins the Gasconade River at State Highway 17, just upstream from the Waynesville gage. The flow length of the Gasconade between the Hazelgreen and Waynesville gages generally allows peak flows on Roubidoux Creek to dissipate well before the arrival of a flood peak from Hazelgreen, resulting in attenuation of the flood peak at the

**Table 1.** Basin characteristics for three streamflow-gaging stations on the Gasconade River near Waynesville, Missouri.

[DEM, digital elevation model; $mi^2$, square miles, ft/mi, feet per mile; mi, mile]

| Basin characteristic | Gasconade River near Hazelgreen (06928000) | | Gasconade River near Waynesville (06928500) | | Gasconade River at Jerome (06933500) | |
|---|---|---|---|---|---|---|
| | Alexander and Wilson (1995) | 30-meter DEM data | Alexander and Wilson (1995) | 30-meter DEM data | Alexander and Wilson (1995) | 30-meter DEM data |
| Drainage area ($mi^2$) | 1,250 | 1,250 | 1,680 | 1,700 | 2,840 | 2,830 |
| Main channel slope (ft/mi) | 3.97 | 4.23 | 3.18 | 3.47 | 3.01 | 3.17 |
| Main channel length (mi) | 92.8 | 92.8 | 136 | 136 | 169 | 169 |

**Table 2.** The 2- to 500-year flood discharges for three streamflow-gaging stations on the Gasconade River near Waynesville, Missouri (from Alexander and Wilson, 1995).

[USGS, U.S. Geological Survey; WY, water years; $ft^3/s$, cubic feet per second]

| USGS station name | USGS station number | Period of record used (WY) | Flood discharge ($ft^3/s$) for indicated recurrence interval (years) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 2 | 5 | 10 | 25 | 50 | 100 | 500 |
| Gasconade River near Hazelgreen | 06928000 | 1929–1983 | 21,600 | 40,100 | 53,700 | 72,000 | 85,900 | 100,000 | 133,000 |
| Gasconade River near Waynesville | 06928500 | 1915–1975 | 23,300 | 40,800 | 53,400 | 69,800 | 82,300 | 94,700 | 124,000 |
| Gasconade River at Jerome | 06933500 | 1923–1993 | 31,200 | 53,000 | 68,900 | 90,500 | 107,000 | 125,000 | 168,000 |

Waynesville gage. Discussions with long-term local residents confirm this observation (Richard and Jim Hamilton, oral commun., 2008).

Attenuation is not a constant, and the peak discharge measured at the Hazelgreen gage is not always equal to or greater than that at the Waynesville gage, as implied by the streamflow statistics. Examining the common period of record between the gages (1929–1975) shows that the highest peak event occurred on the Gasconade River in mid-April 1945, and was recorded at all three gages (table 3). The peak at the Hazelgreen gage occurred April 14, with a stage of 29.6 ft, and a discharge of 76,400 cubic feet per second ($ft^3/s$). The peak at the Waynesville gage also occurred April 14, with a stage of 23.5 ft and a discharge of 81,600 $ft^3/s$, which is 6.8 percent larger than the Hazelgreen gage. The peak at the Jerome gage occurred April 15, with a stage of 27.7 ft and a discharge of 101,000 $ft^3/s$ (23.8 percent larger than the Waynesville gage).

The next highest peak event on the Gasconade River that was common to and recorded at all three stations occurred in mid-March 1935 (table 3). The peak at the Hazelgreen gage occurred March 12, with a stage of 27.5 ft and a discharge of 68,700 $ft^3/s$. The peak at the Waynesville gage occurred March 13, with a stage of 21.62 ft and a discharge of 69,000 $ft^3/s$ (0.4 percent larger than the Hazelgreen gage). The peak at the Jerome gage also occurred March 13, with a stage of 25.8 ft and a discharge of 76,800 $ft^3/s$ (11.3 percent larger than the Waynesville gage).

The Jerome gage had another peak discharge in August 1946 (stage 26.55 ft, discharge 87,500 $ft^3/s$) for which the discharge ranges between the 1945 and 1935 discharges at that gage, but this flood did not register in the top 10 floods at either the Hazelgreen or Waynesville gages (table 3). The top four floods for the Waynesville gage (highlighted in table 3) in the common period of record for the three gages (1929–1975) are not necessarily the top four floods for the Hazelgreen or Jerome gages. These differences are caused by variable rainfall over the substantial area covered by the Gasconade River Basin (fig. 5), resulting in localized flooding of tributaries.

A particularly large flood occurred on the Gasconade River in early December 1982, which up until 2008 had been viewed as the flood of record on the Gasconade. The entire December 1982 event was recorded at the Jerome gage, and a peak stage was recorded at the Hazelgreen gage; however, the Waynesville gage had not been operational for several years, and no peak stage or discharge was recorded there. The peak stage recorded at the Jerome gage was 31.34 ft, which corresponds to a discharge of 136,000 $ft^3/s$ (U.S. Geological Survey, 2008b). The peak stage recorded at the Hazelgreen gage was 34.46 ft, which corresponds to a discharge of approximately 87,000 $ft^3/s$, based on an extension of the stage-discharge relation at that gage (U.S. Geological Survey, 2008a). During a field visit in January 2008, approximate high-water elevations were recovered for the December 1982 flood at a log cabin near the location of the Waynesville gage and at an aban-

**Table 3.** Ten highest annual floods for the common period of record (1929–1975) for three streamflow-gaging stations on the Gasconade River near Waynesville, Missouri.

[ft$^3$/s, cubic feet per second; shaded areas highlight four annual floods common to all three stations]

| Flood event rank | Gasconade River near Hazelgreen (06928000) | | Gasconade River near Waynesville (06928500) | | Gasconade River at Jerome (06933500) | |
|---|---|---|---|---|---|---|
| | Water year | Peak discharge (ft$^3$/s) | Water year | Peak discharge (ft$^3$/s) | Water year | Peak discharge (ft$^3$/s) |
| 1 | 1945 | 76,400 | 1945 | 81,600 | 1945 | 101,000 |
| 2 | 1935 | 68,700 | 1935 | 69,000 | 1946 | 87,500 |
| 3 | 1947 | 58,000 | 1943 | 64,700 | 1935 | 76,800 |
| 4 | 1941 | 54,500 | 1941 | 57,700 | 1943 | 74,000 |
| 5 | 1933 | 53,800 | 1947 | 55,700 | 1961 | 62,800 |
| 6 | 1943 | 51,000 | 1933 | 52,200 | 1933 | 62,600 |
| 7 | 1958 | 49,000 | 1958 | 45,100 | 1947 | 60,000 |
| 8 | 1969 | 46,200 | 1957 | 44,500 | 1957 | 57,400 |
| 9 | 1950 | 44,600 | 1961 | 43,300 | 1941 | 54,600 |
| 10 | 1961 | 39,400 | 1969 | 41,700 | 1950 | 48,700 |

doned rental house approximately midway between the State Highway 17 crossing and the Waynesville gage (fig. 3). The unusual trend in the streamflow statistics and the measured peak discharges for the Waynesville gage with respect to the Hazelgreen and Jerome gages results in a lack of confidence in any estimate of the discharge at the Waynesville gage for the 1982 flood; therefore, for this report the peak from April 14, 1945, initially was considered the peak of record at the Waynesville gage.

## Recent Flood Events and Resultant Modifications to Gage Analysis

A major rainfall event occurred March 18–19, 2008, with recorded amounts of up to 12 inches (in.) of rain falling over most of southern Missouri (National Weather Service, 2008). This rainfall event caused extreme flooding for many of the streams in southern Missouri, including the Gasconade River. On March 19, the Hazelgreen gage crested at a stage of 34.92 ft, approximately 0.46 ft higher than the previous flood of record on December 3, 1982. The discharge measured at Hazelgreen near the peak was 89,500 ft$^3$/s. On March 20, a discharge measurement was made on the Gasconade River just downstream from the State Highway 17 crossing, approximately 1 hour after the Gasconade River peaked at this location. High-water marks indicating the peak flood elevation were recovered along the upstream and downstream sides of the Highway 17 road embankment on March 21, 2008. On April 9, 2008, additional high-water marks were recovered at the log cabin near the location of the Waynesville gage, at the abandoned rental house approximately midway between the Waynesville gage and the State Highway 17 crossing, and near the upstream end of the study area on Roubidoux Creek. A comparison of the 2008 high-water marks to the approximate high-water marks recovered for the 1982 flood indicated that the 2008 flood also exceeded the 1982 flood near Waynesville by approximately 0.5 ft. The measurement made on March 20, 2008, was sufficiently near the peak to match the high-water marks recovered for the peak.

The discharge measured near the peak flow conditions downstream from the State Highway 17 crossing was 95,400 ft$^3$/s (approximately 6.5 percent larger than at the Hazelgreen gage), and the corresponding peak stage near the Waynesville gage was 27.25 ft. The peak at the Jerome gage also occurred March 20, with a stage of 30.43 ft and a discharge of 118,000 ft$^3$/s (approximately 23.7 percent larger than the Waynesville gage). Based on the latest stage-discharge relation for the Waynesville gage, the measured peak stage should have resulted in a discharge of approximately 121,000 ft$^3$/s, which is substantially greater than the 95,400 ft$^3$/s measured at State Highway 17, as well as the 118,000 ft$^3$/s measured at the Jerome gage; therefore, it was assumed that the Gasconade River had undergone a change in flow control since the time the Waynesville gage was discontinued in 1975, and a modified stage-discharge relation was developed that incorporated the leftward shift seen in the 2008 flood (table 4 and fig. 6). The leftward shift caused by the 2008 flood partially may be the result of the discharge measurement being made after the peak occurred at the State Highway 17 crossing, which can result in a lower discharge being measured at a given stage than would be observed before the peak occurs (backwater effect). Using the modified relation resulted in a discharge of 92,300 ft$^3$/s for the December 1982 flood at the Waynesville gage, which is more in line with the discharge of 87,000 ft$^3$/s measured at the Hazelgreen gage for that flood (approximately 6.1 percent greater). These two similar floods in recent history seem to confirm the change in flow control.

**Table 4.** Original and modified stage-discharge relation for the streamflow-gaging station on the Gasconade River near Waynesville, Missouri (06928500).

[ft, feet; ft$^3$/s, cubic feet per second; --, not determined]

| Gage height (ft) | Original discharge (ft$^3$/s) | Modified discharge (ft$^3$/s) |
|---|---|---|
| 2.0 | 140 | 140 |
| 5.0 | 1,930 | 1,930 |
| 7.5 | 4,850 | 4,850 |
| 10.0 | 8,350 | 8,350 |
| 13.0 | 13,500 | 13,500 |
| 15.0 | 18,500 | 18,500 |
| 16.0 | 23,000 | 22,100 |
| 20.0 | 47,900 | 40,800 |
| 22.5 | 70,400 | 56,400 |
| 25.0 | 99,000 | 75,300 |
| [a]27.25 | -- | [a]95,400 |
| 27.5 | -- | 97,800 |
| 30.0 | -- | 124,000 |
| 30.5 | -- | 130,000 |

[a] This point on the modified stage-discharge relation is from the discharge measurement made on March 20, 2008.

Additionally, the streamflow statistics for the Waynesville gage were recomputed, incorporating the 2008 flood peak. The updated 25- to 500-year flood recurrence intervals are shown in table 5, with the corresponding water-surface elevations at the location of the Waynesville gage resulting from the modified stage-discharge relation. These values were used in the two-dimensional flow model analysis of existing and proposed conditions.

# Two-Dimensional Simulation of Flow

The FESWMS Flo2DH model simulates flow in two dimensions in the horizontal plane, using a finite-element mesh and the Galerkin finite-element method of solving three partial-differential equations representing conservation of mass and momentum (Froehlich, 2002). This two-dimensional flow model can simulate longitudinal and lateral variations in water-surface elevations and velocities, and can accommodate geometric features such as highway embankments, bridge structures, channel bends, berms, buildings, and other flow obstructions. A graphic user interface called the Surface-Water Modeling System (SMS; Environmental Modeling Research Laboratory, 1999) was used to construct the two-dimensional finite-element mesh, facilitate assignment of roughness coefficients and other hydraulic and material parameters to the mesh elements, execute the model, and evaluate the model output numerically and graphically.

## Model of Existing Conditions

The model of existing conditions was used to provide results for the study area with channel conditions and bridge structures as they currently (2008) exist. Results from the model of existing conditions were used with information provided by MoDOT to assess the need for replacement overflow structures at the State Highway 17 crossing. The model of existing conditions in turn was used as the base model to develop the model of proposed conditions.

Primary reconnaissance of the study area in the vicinity of the State Highway 17 crossing was conducted by MoDOT, but additional field reconnaissance and surveying of the study area was done by the USGS on January 3–4, 2008. During the USGS field visit, the channel bathymetry was defined, and information and photographs were gathered for the bridges, road embankment, channel, and flood plain in the vicinity of the State Highway 17 crossing.

### Development of the Model of Existing Conditions

The extent of the mesh for the model of existing conditions was from bluff to bluff, starting from a point just downstream from the Waynesville gage to a point approximately 3,600 ft upstream from State Highway 17 on the Gasconade River, and extended approximately 1.5 mi up Roubidoux Creek (figs. 2 and 3). Ground-elevation information for the study area was obtained from 10-m DEM data (Missouri Spatial Data Information Service, 2008) of the area supplemented with surveyed information on and adjacent to State Highway 17 obtained during the field visit in January 2008. Bathymetry data of the channel bed also were collected during the January 2008 field visit. These data formed the base topographic dataset for the model of existing conditions.

Mesh elements were designed with consideration to the level of detail of the hydraulic information required from the simulation results (fig. 7). The area around State Highway 17 was of critical interest, so smaller elements were used in this part of the study area, whereas larger elements were used to represent the channel and flood plains away from State Highway 17 (fig. 7).

The piers and bents for the main channel structure J-802 were hard-coded as elements directly into the model mesh. Position, orientation, and dimensions of each pier and bent were obtained from bridge plans (Missouri Department of Transportation, 1932a) to accurately position and size the piers and bents. The circular columns of the main piers of structure

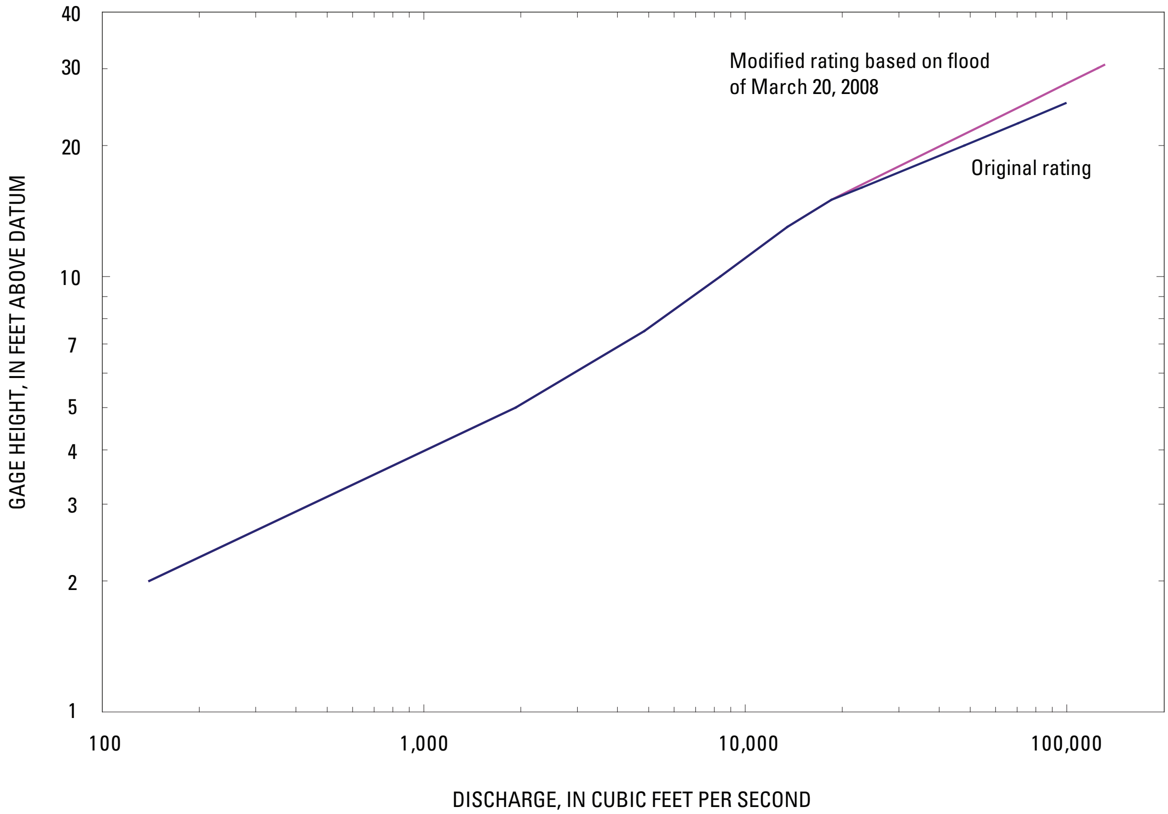
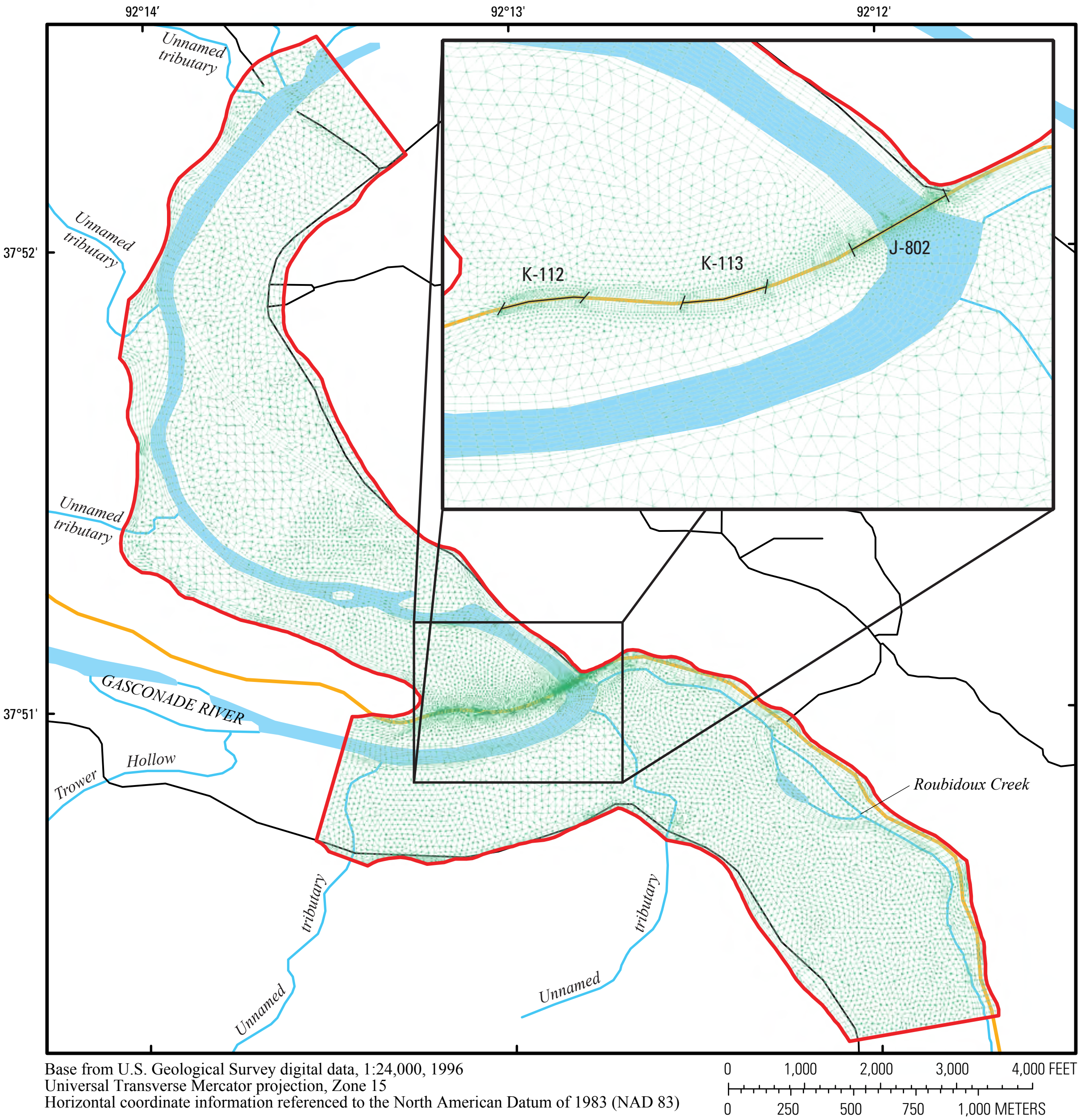



**Figure 6.** Original and modified stage-discharge relation for the streamflow-gaging station on the Gasconade River near Waynesville, Missouri.

**Table 5.** Original and updated flood discharges, gage heights, and water-surface elevations for the 25- to 500-year floods for the streamflow-gaging station on the Gasconade River near Waynesville, Missouri (06928500), and corresponding boundary conditions used in the models of existing and proposed conditions. Elevation referenced to North American Vertical Datum of 1988 (NAVD 88).

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

| Recurrence interval (years) | Original flood discharge value at gaging station (from Alexander and Wilson, 1995) ($ft^3/s$) | Updated values at gaging station | | | Upstream boundary—discharge | | Downstream boundary—water-surface elevation (ft) |
|---|---|---|---|---|---|---|---|
| | | Flood discharge ($ft^3/s$) | Gage height (ft) | Water-surface elevation (ft) | Gasconade River ($ft^3/s$) | Roubidoux Creek ($ft^3/s$) | |
| 25 | 69,800 | 72,100 | 24.61 | 763.54 | 68,630 | 3,470 | 763.1 |
| 50 | 82,300 | 85,300 | 26.16 | 765.09 | 81,190 | 4,110 | 764.6 |
| 100 | 94,700 | 98,700 | 27.59 | 766.52 | 93,950 | 4,750 | 766.0 |
| 500 | 124,000 | 130,000 | 30.50 | 769.43 | 123,740 | 6,260 | 768.9 |




Base from U.S. Geological Survey digital data, 1:24,000, 1996
Universal Transverse Mercator projection, Zone 15
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)

**EXPLANATION**

- **Study area boundary**
- **State Highway 17**
- **Minor roads**
- **Bridge structures**
- **Mesh elements and nodes**—Elements have nodes at each corner and at the midpoint of each side

**Figure 7.** Finite-element mesh used in the model of existing conditions on the Gasconade River near Waynesville, Missouri.

J-802 were approximated as octagons, whereas the square columns of the left and right overbank bents were coded as squares; the elements within each of these piers and bents were disabled to force flow around them.

The bents for overflow structures K-112 and K-113 were incorporated into the model mesh using the pier module in Flo2DH. These overflow structure bents would affect flow in the model, but would have resulted in inordinate mesh refinement to incorporate directly into the model mesh as disabled elements, as had been done for the main channel structure piers and bents. Once again, position, orientation, and dimensions of each bent were obtained from bridge plans (Missouri Department of Transportation, 1932b, 1932c) to accurately position and size the bents. Each column of the bents of structures K-112 and K-113 were coded as square-nosed columns 2.5 ft wide and 2.5 ft long in the pier module, as noted from the bridge plans.

The finite-element mesh for the model of existing conditions consisted of 23,755 elements that ranged in size from 2.96 to 10,295 square feet (ft$^2$). Each element had a node at each corner and at the midpoint of each side, which created a total of 53,814 nodes.

## Calibration of the Model of Existing Conditions to Known Floods

The simulation of a particular flow scenario with Flo2DH requires an iterative process called spindown (Huizinga, 2007a, 2007b; Huizinga and Rydlund, 2001). In a subcritical flow regime (deep, slow flow typical of non-alpine streams and rivers), spindown involves initializing the model with the desired discharge as the upstream boundary condition and a downstream water-surface elevation that is higher than the highest land-surface elevation in the mesh. This ensures that all nodes in the model are "wet" (having a positive depth of flow) and produces a flat water-surface elevation across the model grid, which promotes numerical stability for the initial model computations. The model is run with these conditions for a sufficient number of iterations to cause the water-surface elevation changes between iterations to be minimized within a preset limit. Once the limit is reached, the model is said to have "converged." The downstream water-surface elevation is then decreased by some finite amount, the model is restarted using the results of the previous run—called a hotstart—as the starting point for the new run, and the model is run until convergence occurs. This process is repeated until the desired downstream water-surface elevation is reached, as dictated by high-water marks, flood profiles, or other known site parameters. During the spindown process, if the simulated water-surface elevation at a particular node is less than the land-surface elevation assigned to the node, then the node is said to "go dry." If one or more of the nodes for a particular element go dry, the entire element is assumed to go dry, and it is not included in the computations during that iteration. As the simulation proceeds through iterations, an element can oscillate between wet and dry, which can lead to solution instability and a loss of convergence. To limit this instability, the user sets a tolerance on the depth of flow over a node (the storativity depth, table 6); however, if an element goes dry and stays dry for several iterations, it is manually disabled to prevent model instability. Once the spindown process is complete, the model calibration can be refined by adjusting other model parameters such as Manning's roughness coefficient and kinematic eddy viscosity.

Material and hydraulic properties were assigned to the model based on land use from aerial photography (fig. 8), and initial Manning's roughness coefficients were assigned based on published guidance (Chow, 1959; Barnes, 1967; Arcement and Schneider, 1989) and previously calibrated models of similar river reaches (Huizinga, 2007a, 2007b, Huizinga and Rydlund, 2001). A depth-dependent Manning's roughness coefficient (*n*-value) method was used, wherein the "lower depth" *n*-value is applied when the water depth over the nodes around an element is less than the lower depth, and the "upper depth" *n*-value is applied when the water depth is greater than the upper depth; when the water depth is between the lower and upper depths, the *n*-value is interpolated linearly from the upper and lower *n*-values (Froehlich, 2002). Depth-dependent *n*-values were used to account for changes in the roughness with increased depth of flow; generally, the roughness decreases with increased depth because the effect of the physical features causing the roughness decreases as the depth of flow increases (for example, grass and crops that lie over in high flows). In addition, each coverage initially was assigned a large value of kinematic eddy viscosity that would promote model stability [150 square feet per second (ft$^2$/s)] during the spindown process. After spinning the model down to the desired boundary conditions, the eddy viscosity was adjusted to more appropriate values (table 6) consistent with guidelines in Froehlich (2002).

Initially, the model of existing conditions was calibrated to a flood that occurred on the Gasconade River on April 14, 1945; however, on March 20, 2008, the Gasconade River experienced an extreme flood before completion of the model of proposed conditions. The model of existing conditions was recalibrated using the flood that occurred on the Gasconade River on March 20, 2008, as well as the floods of December 4, 1982, and April 14, 1945.

### Flood of March 20, 2008

A discharge measurement was made approximately 1,500 ft downstream from State Highway 17 on March 20, 2008, near the time that the peak occurred at that location. The measured discharge was 95,400 ft$^3$/s, and is the average of four individual measurement sections or "passes" across the flood plain downstream from State Highway 17. The discharge from Roubidoux Creek was estimated at 4,600 ft$^3$/s (4.8 percent of the total flow) at the time of the Gasconade River measurement, based on the stage and stage-discharge relation of the gage near Waynesville (Roubidoux Creek below Fort

**Table 6.** Material and hydraulic properties of various land-use coverages in the model of the Gasconade River near Waynesville, Missouri, resulting from calibration to the floods of March 20, 2008, December 4, 1982, and April 14, 1945.

[ft, feet; ft$^2$/s, square foot per second]

| Land-use coverage | Lower depth Manning's *n* | Lower depth Depth (ft) | Upper depth Manning's *n* | Upper depth Depth (ft) | Kinematic eddy viscosity (ft$^2$/s) | Storativity depth (ft) |
|---|---|---|---|---|---|---|
| Channel and bank | | | | | | |
| Main channel | 0.045 | 3 | 0.035 | 6 | 10 | 1.0 |
| Open timber and brush | .100 | 4 | .075 | 8 | 30 | 1.0 |
| Thick timber and thick brush | .180 | 6 | .150 | 12 | 50 | 1.0 |
| Flood plain | | | | | | |
| Pasture | 0.045 | 1 | 0.040 | 4 | 10 | 1.0 |
| Row crops (corn) | .060 | 2 | .040 | 8 | 10 | 2.0 |
| Thick grasses with sprouts | .080 | 3 | .065 | 6 | 10 | 1.0 |
| Highway embankment | .050 | 1 | .045 | 4 | 10 | 1.0 |
| Bridge deck area | .045 | 1 | .040 | 4 | 10 | .5 |
| Pavement and gravel | .025 | 1 | .020 | 2 | 10 | .5 |
| Grassy area with interspersed trees | .055 | 3 | .040 | 6 | 10 | 1.0 |
| Scrub brush | .100 | 2 | .075 | 8 | 10 | 2.0 |

Leonard Wood, 06928430, fig. 4); the balance of 90,800 ft$^3$/s was assumed to be flowing in the Gasconade River channel upstream from the confluence. High-water marks were recovered after the flood recession along the upstream and downstream faces of the State Highway 17 road embankments, at the log cabin near the Waynesville gage, at the abandoned rental house midway between the Waynesville gage and the State Highway 17 crossing, and near the upstream end of the study area on Roubidoux Creek. The water-surface elevation at structure J-802 was measured just after the peak on the receding limb of the flood from a surveyed reference point on the bridge.

For the model of existing conditions, the upstream boundary on the Gasconade River was set to the estimated discharge of 90,800 ft$^3$/s, the upstream boundary on Roubidoux Creek was set to 4,600 ft$^3$/s, and the downstream boundary initially was set to 820.0 ft. The model of existing conditions then was spun down to a downstream boundary condition of 765.6 ft to obtain a match with the surveyed high-water marks at the log cabin near the Waynesville gage.

To refine the model calibration, the material properties were adjusted to the values in table 6 to cause the water-surface elevations in the model to match the measured water-surface elevations based on the surveyed high-water marks. Measured and simulated water-surface elevations for the entire study area for the 2008 flood are shown in figure 9 and table 7. Measured and simulated water-surface elevations in the vicinity of the State Highway 17 crossing are shown in figure 10. The high-water mark recovered at the upstream end of the study area on Roubidoux Creek was not used as a calibration point, because it appeared to reflect the peak of the flood on Roubidoux Creek and was not indicative of the flooding on the Gasconade River.

Velocity magnitude and direction from one of the four measurement sections from the discharge measurement obtained downstream from State Highway 17 on March 20, 2008, are shown with simulated results in figure 11. The average measured discharge is shown in table 8 with the simulated discharge determined at a flux line created near the four measurement sections in the model of existing conditions. The magnitude and direction of the simulated velocities are similar to velocities along the representative measurement section shown in figure 11, and the average measured and simulated discharges are similar (table 8).

Velocity magnitude and direction from partial discharge measurements obtained near each existing bridge are shown with simulated results in figures 12 through 14. The discharge for the partial measurement at each existing bridge is shown in table 8 with the simulated discharge determined at a flux line created near each partial measurement section in the model of existing conditions. Generally, the magnitude and direction of the simulated velocities are similar to velocities along the measurement sections, except near the bents of the existing overflow structures; the measured flow magnitude is lower than simulated on the parts of the partial measurement sections immediately downstream from the bents, particularly for the existing overflow structures (figs. 13 and 14) and the left overbank bent of the existing main channel structure (fig. 12). Simulated results for the full bridge opening for each of the three existing bridges are shown in table 9.

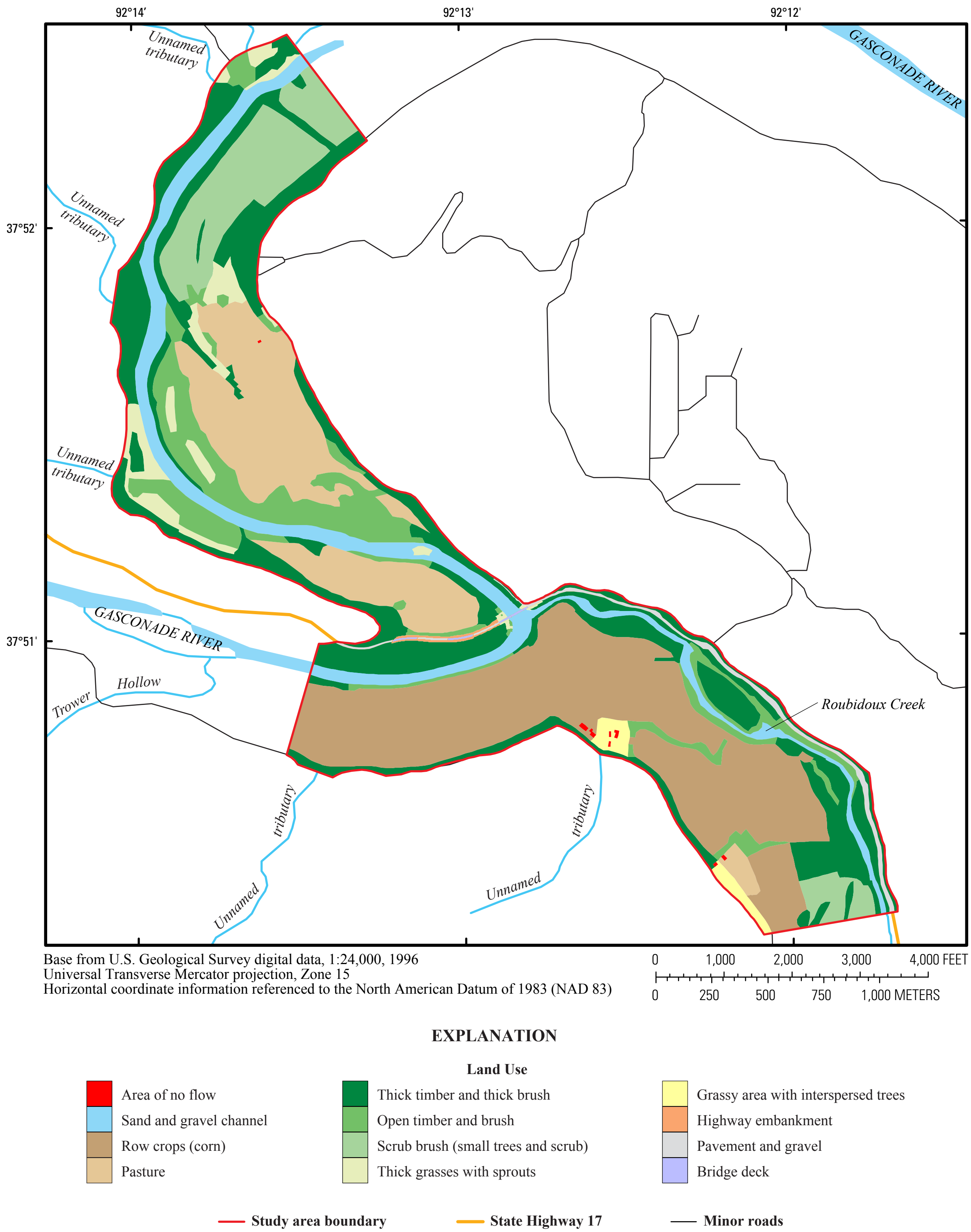



**Figure 8.** Land-use coverages used in the model of existing conditions on the Gasconade River near Waynesville, Missouri.

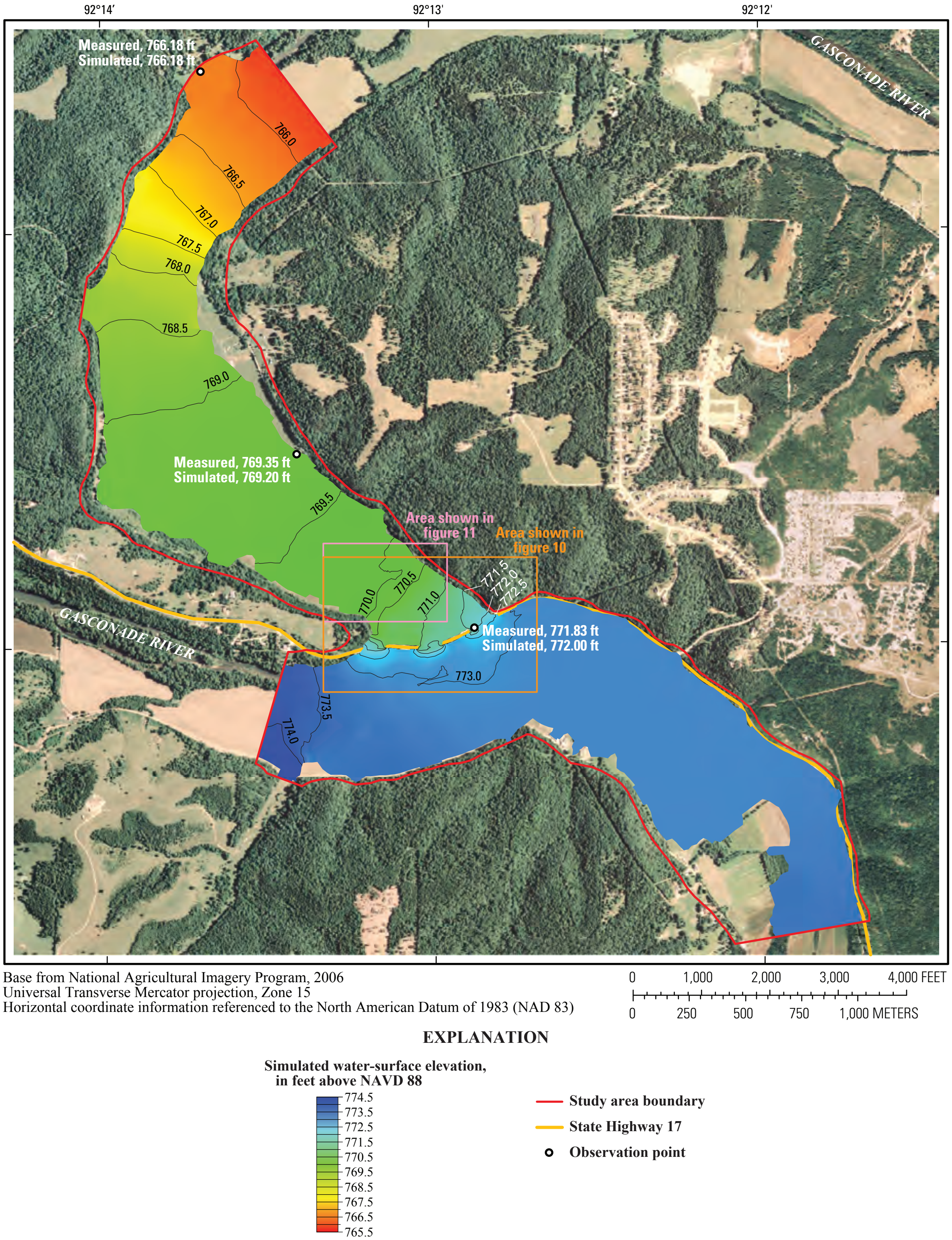



**Figure 9.** Measured and simulated water-surface elevations for the flood of March 20, 2008, on the Gasconade River near Waynesville, Missouri.

**Table 7.** Measured and simulated water-surface elevations for the calibration floods of March 20, 2008, December 4, 1982, and April 14, 1945, on the Gasconade River near Waynesville, Missouri. Elevation referenced to North American Vertical Datum of 1988 (NAVD 88).

[$ft^3/s$, cubic feet per second; ft, feet; --, not measured or computed]

| Location | Coordinates | March 20, 2008, flood ($95,400\ ft^3/s$) | | | December 4, 1982, flood ($92,300\ ft^3/s$) | | | April 14, 1945, flood ($81,600\ ft^3/s$) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Measured water-surface elevation (ft) | Simulated water-surface elevation (ft) | Simulated minus measured (ft) | Measured water-surface elevation (ft) | Simulated water-surface elevation (ft) | Simulated minus measured (ft) | Measured water-surface elevation (ft) | Simulated water-surface elevation (ft) | Simulated minus measured (ft) |
| Downstream handrail of State Highway 17 bridge | 37°51'03" N 92°12'52" W | [a]771.83 | 772.00 | 0.17 | -- | 771.55 | -- | [b]769.15 | 769.09 | -0.06 |
| Near abandoned rental house | 37°51'29" N 92°13'24" W | [c]769.35 | 769.20 | -.15 | [d]768.84 | 768.84 | 0 | -- | 765.41 | -- |
| Near log cabin (near location of Waynesville streamflow gaging station | 37°52'24" N 92°13'43" W | [c]766.18 | 766.18 | 0 | [d]765.85 | 765.80 | -0.05 | [e]762.43 | 762.43 | 0 |

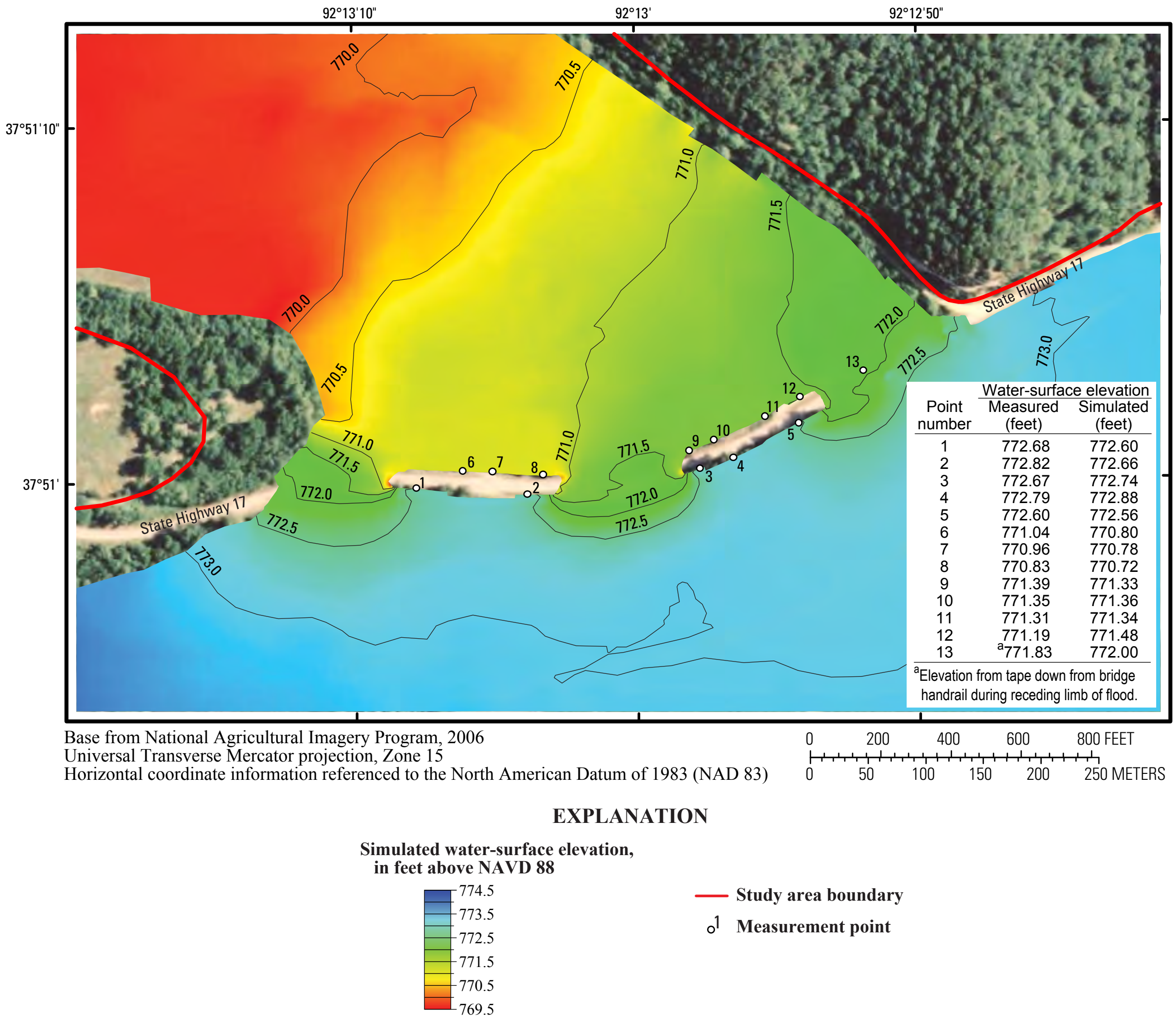
[a] Elevation from tape downs from reference point on downstream bridge handrail on the receding limb of the flood near the peak on March 20, 2008.

[b] Elevation from tape downs from reference point on downstream bridge handrail on the ascending limb of the flood near the peak on April 14, 1945.

[c] Elevation from surveyed high-water marks recovered after the flood.

[d] Elevation from surveyed points indicated by local residents to be the approximate level of high water for the 1982 flood.

[e] Elevation recorded at the gage for the peak on April 14, 1945, based on average elevation of high-water marks recovered after the flood.




| Point number | Water-surface elevation: Measured (feet) | Water-surface elevation: Simulated (feet) |
|---|---|---|
| 1 | 772.68 | 772.60 |
| 2 | 772.82 | 772.66 |
| 3 | 772.67 | 772.74 |
| 4 | 772.79 | 772.88 |
| 5 | 772.60 | 772.56 |
| 6 | 771.04 | 770.80 |
| 7 | 770.96 | 770.78 |
| 8 | 770.83 | 770.72 |
| 9 | 771.39 | 771.33 |
| 10 | 771.35 | 771.36 |
| 11 | 771.31 | 771.34 |
| 12 | 771.19 | 771.48 |
| 13 | [a]771.83 | 772.00 |

[a]Elevation from tape down from bridge handrail during receding limb of flood.

**Figure 10.** Measured and simulated water-surface elevations in the vicinity of State Highway 17 for the flood of March 20, 2008, on the Gasconade River near Waynesville, Missouri.

Approximately 1,350 ft downstream from State Highway 17 and approximately 150 ft upstream from where the total discharge measurement was obtained, high left flood plain ground elevations on the inside of a bend create a local valley constriction (fig. 11). Simulated results from a flux line created at this constriction (fig. 11) indicates the cross-sectional flow area at the constriction (16,030 $ft^2$) is less than the total flow area of the three bridges (20,281 $ft^2$, table 9), and the average velocity in this section [5.49 feet per second (ft/s)] is higher than any of the three existing bridges (table 9). This local constriction likely is a feature that controls flow characteristics upstream, and may affect flow velocities and water-surface elevations upstream through the bridge openings during major floods.

## Flood of December 4, 1982

The flood of December 1982 was considered the flood of record for the Gasconade River Basin up until the flood of March 2008. Although the Waynesville gage was not in operation during the 1982 flood, a discharge for that event was estimated from surveyed high-water marks in the vicinity of State Highway 17 and the Waynesville gage.

For the 1982 flood, the total estimated discharge at the Waynesville gage was 92,300 $ft^3/s$. The discharge at the upstream boundary on the Gasconade River in the model of existing conditions was set to 87,850 $ft^3/s$, and the upstream boundary on Roubidoux Creek was set to 4,450 $ft^3/s$, based on the ratio of flow observed in the flood of March 2008 (approximately 4.8 percent of the flow was on Roubidoux Creek). The downstream boundary was set to 765.2 ft to obtain a match with the surveyed high-water marks at the log cabin near the Waynesville gage.

Using the material properties shown in table 6, the water-surface elevations in the model matched the observed water-surface elevations based on the surveyed high-water marks. Measured and simulated water-surface elevations for the 1982 flood are shown in figure 15 and table 7. Other simulated results for the three bridges are shown in table 9.

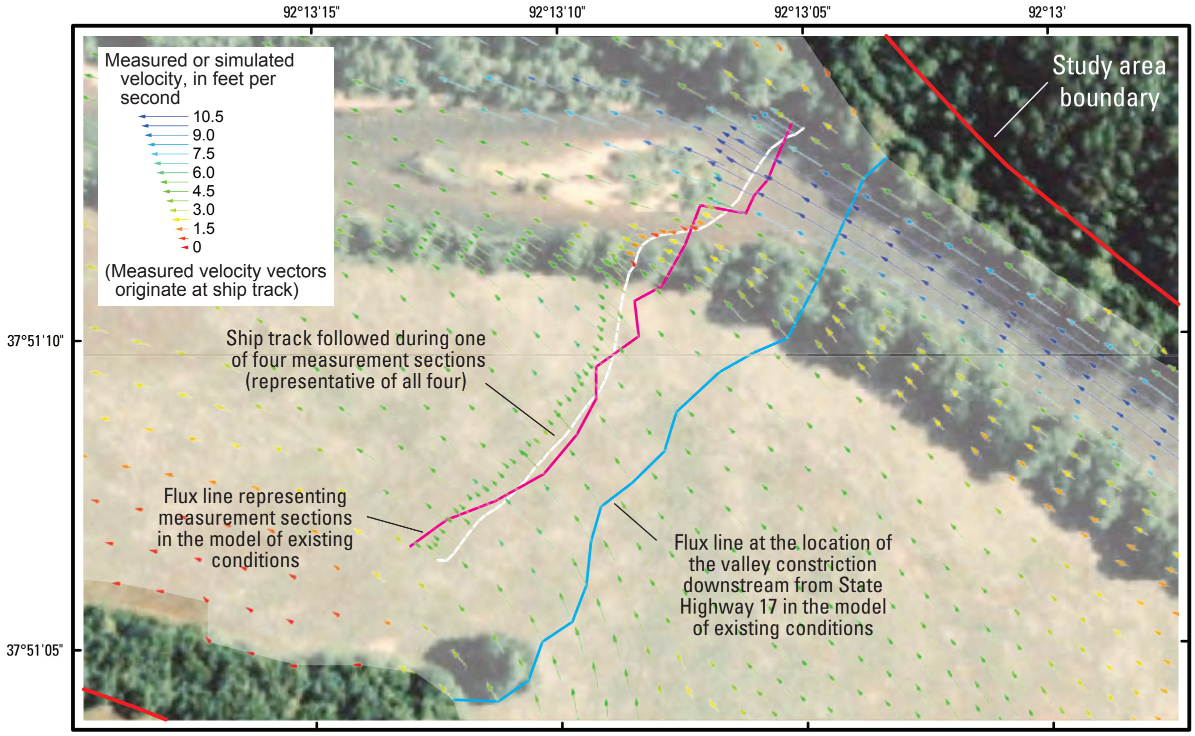



**Figure 11.** Measured and simulated velocity vectors in the vicinity of the measurement section downstream from State Highway 17 for the flood of March 20, 2008, on the Gasconade River near Waynesville, Missouri.

**Table 8.** Measured and simulated discharge at the main measurement section and locations downstream from structures J-802, K-112, and K-113 for the calibration flood of March 20, 2008, on the Gasconade River near Waynesville, Missouri.

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

| Location | Measured discharge (ft$^3$/s) | Simulated discharge (ft$^3$/s) | Percent difference from measured |
|---|---|---|---|
| Measurement section (ship track on fig. 11) | [a]95,359 | 93,650 | -1.8 |
| Structure J-802 (main channel bridge, ship track on fig. 12) | 49,677 | 50,067 | 0.8 |
| Structure K-112 (left overflow bridge, ship track on fig. 13) | 12,205 | 11,821 | -3.1 |
| Structure K-113 (middle overflow bridge, ship track on fig. 14) | 20,376 | 22,456 | 10.2 |

[a] Measured discharge is the average of four individual measurement sections or “passes” across the flood plain. The ship track shown in figure 11 is from one of the measurement sections that is representative of all four.

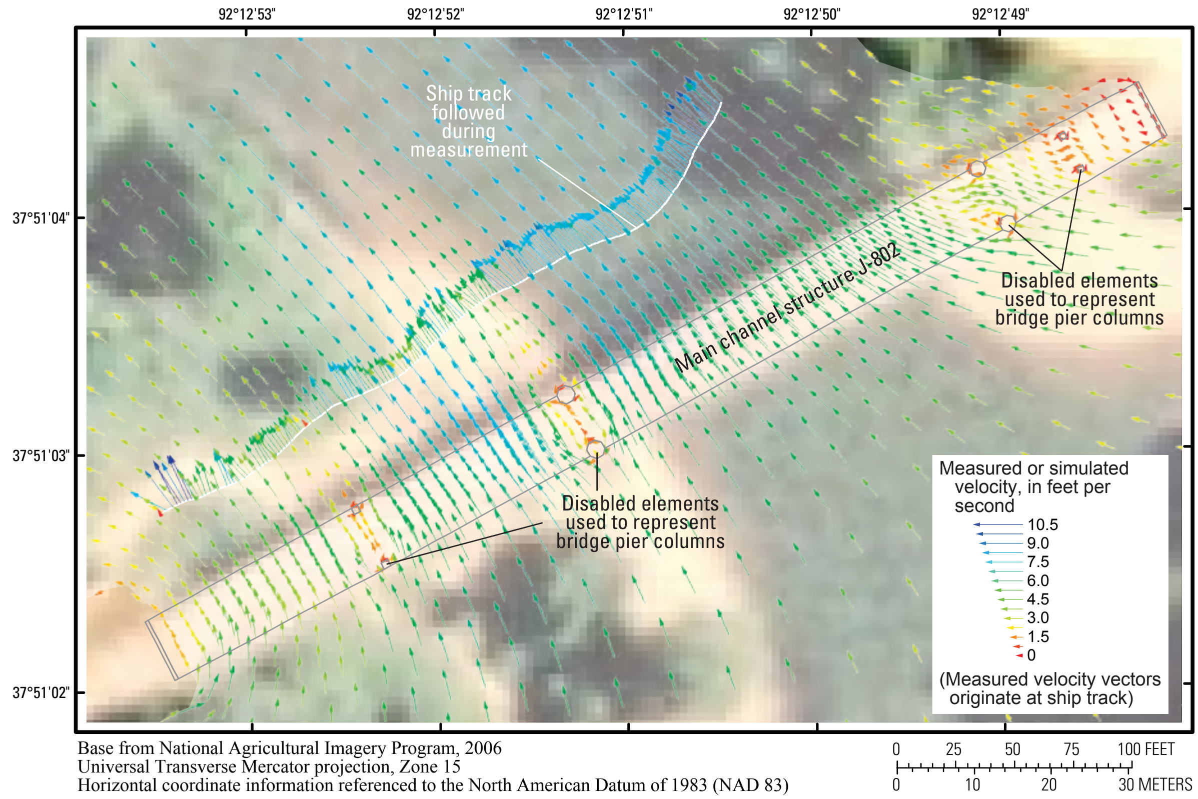



**Figure 12.** Measured and simulated velocity vectors in the vicinity of main channel structure J-802 on State Highway 17 for the flood of March 20, 2008, on the Gasconade River near Waynesville, Missouri.

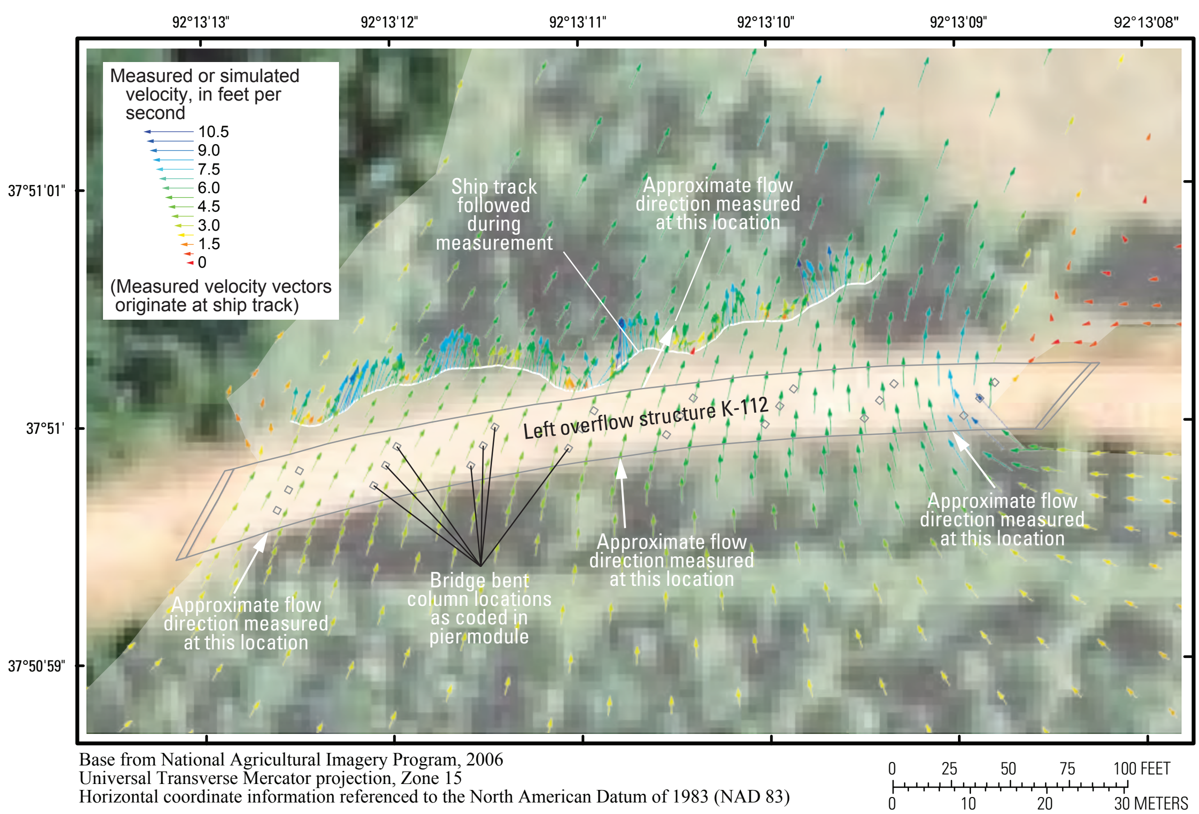



**Figure 13.** Measured and simulated velocity vectors in the vicinity of left overflow structure K-112 on State Highway 17 for the flood of March 20, 2008, on the Gasconade River near Waynesville, Missouri.

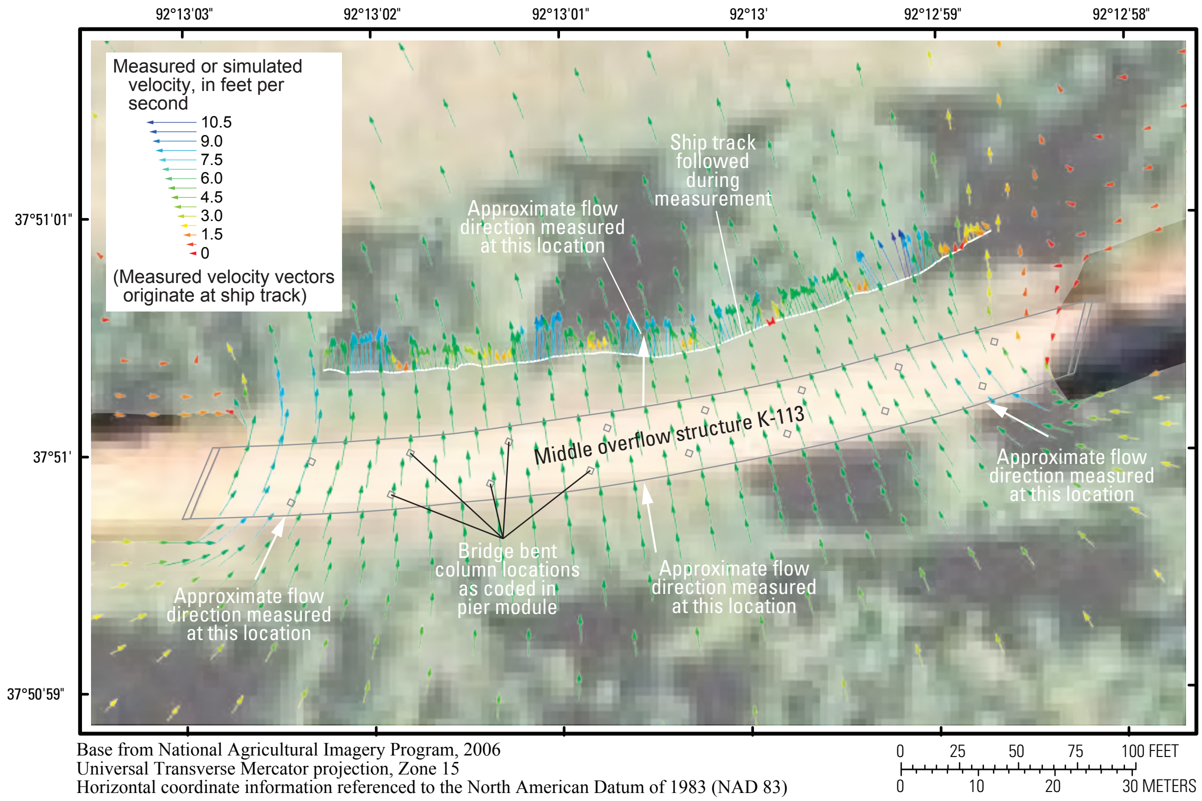



**Figure 14.** Measured and simulated velocity vectors in the vicinity of middle overflow structure K-113 on State Highway 17 for the flood of March 20, 2008, on the Gasconade River near Waynesville, Missouri.

### Flood of April 14, 1945

The flood of April 14, 1945 is the flood of record for the period of continuous streamflow record at the Waynesville gage. A discharge measurement was made at the State Highway 17 bridge just before the peak on April 14, and the peak discharge at the gage was determined based on that measurement adjusted for time of travel and an analysis of high-water marks at the gage. This flood was used as the primary calibration flood until the flood event of March 20, 2008. It became a secondary calibration flood after the model of existing conditions had been calibrated to the flood of March 20, 2008.

For the 1945 flood, the peak discharge at the Waynesville gage was 81,600 $ft^3/s$. The discharge at the upstream boundary on the Gasconade River was set to 77,670 $ft^3/s$, and the upstream boundary on Roubidoux Creek was set to 3,930 $ft^3/s$, based on the ratio of flow observed in the flood of March 2008 (approximately 4.8 percent of the flow was on Roubidoux Creek). The downstream boundary was set to 761.9 ft to obtain a match with the peak stage recorded at the Waynesville gage. The peak water-surface elevation at State Highway 17 was estimated from stage measurements made there during the discharge measurement, just before the peak at that location.

Using the material properties shown in table 6, the water-surface elevations in the model matched the observed water-surface elevations based on the gaging station record. Measured and simulated water-surface elevations for the 1945 flood are shown in figure 16 and table 7. Other simulated results for the three bridges are shown in table 9.

## Simulation of Design Floods

The MoDOT uses several flood recurrence intervals in the design of bridges over waterways (Missouri Department of Transportation, 2004). In consultation with MoDOT, the 25-year, 50-year, 100-year, and 500-year floods were simulated for the hydraulic analysis of the State Highway 17 crossing.

The discharges and corresponding water-surface elevations at the Waynesville gage for the desired recurrence-interval floods are shown in table 5. For each flood recurrence interval, the upstream boundary condition on Roubidoux Creek was set to 4.8 percent of the full discharge, based on the ratio of flow observed in the flood of March 2008, and the balance of the discharge was assigned to the upstream boundary on the Gasconade River, as shown in table 5. The downstream boundary condition was adjusted until the simulated water-surface elevation at the Waynesville gage matched the water-surface elevation from the stage-discharge relation; the final value for the downstream boundary condition is shown in table 5. Simulated results for the three bridges for the various design floods from the model of existing conditions are shown in table 9.

**Table 9.** Simulated discharge, cross-sectional area, and area-weighted average velocity through the main and two overflow structures of State Highway 17 for various design flows and the floods of March 20, 2008, December 4, 1982, and April 14, 1945, on the Gasconade River near Waynesville, Missouri.

[$ft^3/s$, cubic feet per second; $ft^2$, square feet; ft/s, feet per second; --, not determined]

| Flood event | Flood total ($ft^3/s$) | Model of existing conditions: Discharge: Through structure ($ft^3/s$) | Model of existing conditions: Discharge: Percent of total | Model of existing conditions: Cross-sectional area ($ft^2$) | Model of existing conditions: Area-weighted average velocity (ft/s) | Model of proposed conditions: Discharge: Through structure ($ft^3/s$) | Model of proposed conditions: Discharge: Percent of total | Model of proposed conditions: Cross-sectional area ($ft^2$) | Model of proposed conditions: Area-weighted average velocity (ft/s) |
|---|---|---|---|---|---|---|---|---|---|
| | | Left overflow structure (K-112) | | | | Left overflow structure | | | |
| 25-year flood | 72,100 | 9,705 | 13.5 | 3,005 | 3.23 | 7,020 | 9.7 | 1,466 | 4.79 |
| 50-year flood | 85,300 | 12,990 | 15.2 | 3,526 | 3.68 | 9,373 | 11.0 | 1,745 | 5.37 |
| 100-year flood | 98,700 | 16,141 | 16.4 | 4,181 | 3.86 | 11,764 | 11.9 | 2,004 | 5.87 |
| 500-year flood | 130,000 | [a]23,029 | 17.7 | 5,333 | 4.32 | [b]15,786 | 12.1 | 2,638 | 5.98 |
| March 20, 2008 flood | 95,400 | 15,477 | 16.2 | 3,894 | 3.97 | 11,188 | 11.7 | 1,944 | 5.76 |
| December 4, 1982 flood | 92,300 | 14,689 | 15.9 | 3,772 | 3.89 | -- | -- | -- | -- |
| April 14, 1945 flood | 81,600 | 11,086 | 13.6 | 2,999 | 3.70 | -- | -- | -- | -- |
| | | Middle overflow structure (K-113) | | | | Middle overflow structure | | | |
| 25-year flood | 72,100 | 16,315 | 22.6 | 4,009 | 4.07 | 14,967 | 20.8 | 2,416 | 6.19 |
| 50-year flood | 85,300 | 21,268 | 24.9 | 4,567 | 4.66 | 19,241 | 22.6 | 2,801 | 6.87 |
| 100-year flood | 98,700 | 25,860 | 26.2 | 5,086 | 5.08 | 23,436 | 23.7 | 3,152 | 7.44 |
| 500-year flood | 130,000 | [c]35,674 | 27.4 | 6,315 | 5.65 | 31,858 | 24.5 | 3,956 | 8.05 |
| March 20, 2008 flood | 95,400 | 24,745 | 25.9 | 4,962 | 4.99 | 22,381 | 23.5 | 3,061 | 7.31 |
| December 4, 1982 flood | 92,300 | 23,659 | 25.6 | 4,831 | 4.90 | -- | -- | -- | -- |
| April 14, 1945 flood | 81,600 | 19,088 | 23.4 | 3,890 | 4.91 | -- | -- | -- | -- |
| | | Main channel structure (J-802) | | | | Main channel structure | | | |
| 25-year flood | 72,100 | 46,026 | 63.8 | 10,126 | 4.55 | 50,148 | 69.6 | 9,523 | 5.27 |
| 50-year flood | 85,300 | 51,020 | 59.8 | 10,875 | 4.69 | 56,719 | 66.5 | 10,288 | 5.51 |
| 100-year flood | 98,700 | 56,663 | 57.4 | 11,594 | 4.89 | 63,500 | 64.3 | 10,969 | 5.79 |
| 500-year flood | 130,000 | [c]69,390 | 53.4 | 13,148 | 5.28 | 79,471 | 61.1 | 12,472 | 6.37 |
| March 20, 2008 flood | 95,400 | 55,130 | 57.8 | 11,425 | 4.83 | 61,832 | 64.8 | 10,795 | 5.73 |
| December 4, 1982 flood | 92,300 | 53,913 | 58.4 | 11,249 | 4.79 | -- | -- | -- | -- |
| April 14, 1945 flood | 81,600 | 51,468 | 63.1 | 10,092 | 5.10 | -- | -- | -- | -- |

[a] The 500-year flood resulted in 168 $ft^3/s$ of flow over the road embankments near structure K-112.

[b] The 500-year flood resulted in 2,802 $ft^3/s$ of flow over the road embankments near the left overflow structure.

[c] The 500-year flood resulted in 1,525 $ft^3/s$ of flow over the road embankment between structures J-802 and K-113.

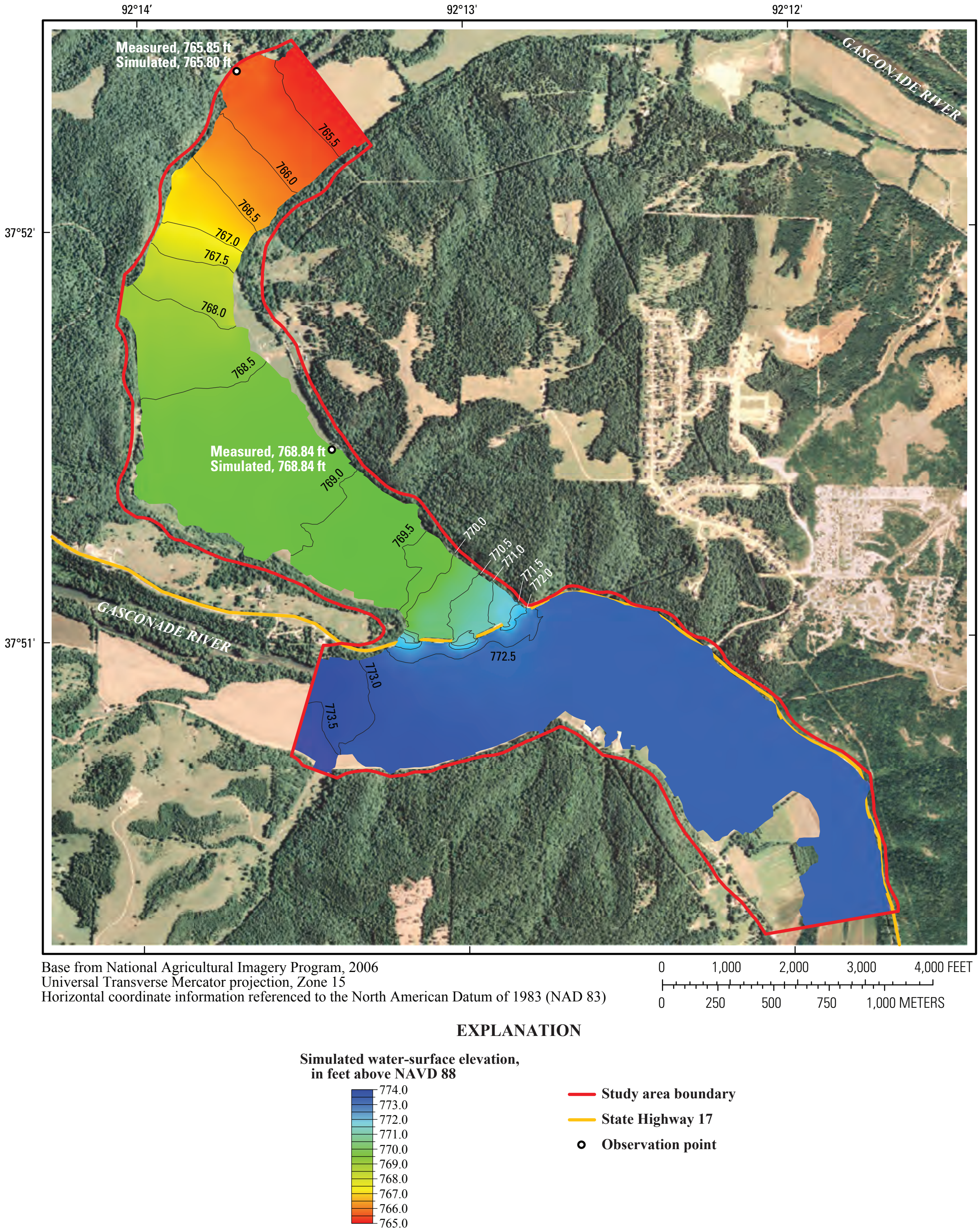



**Figure 15.** Measured and simulated water-surface elevations for the flood of December 4, 1982, on the Gasconade River near Waynesville, Missouri.

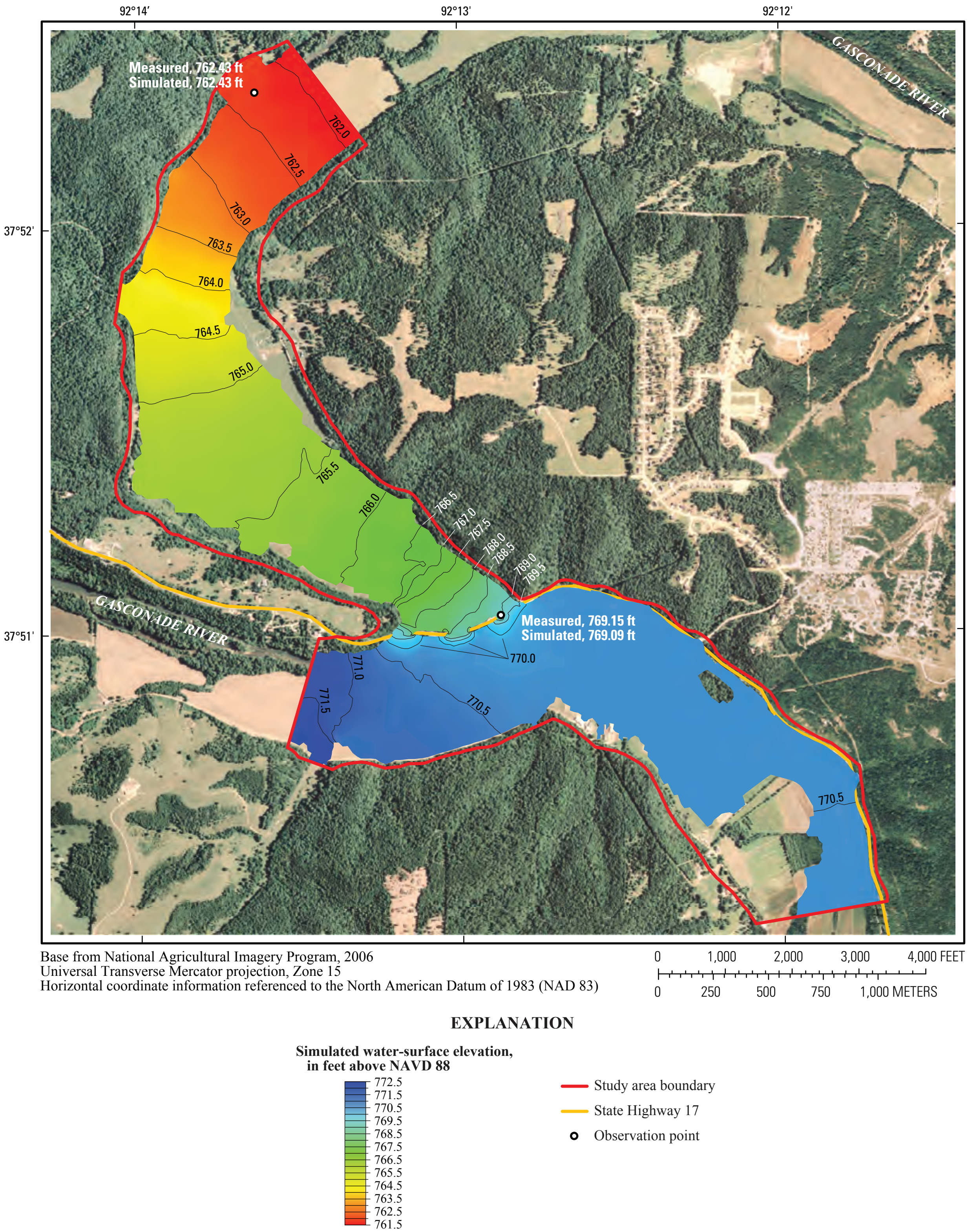



**Figure 16.** Measured and simulated water-surface elevations for the flood of April 14, 1945, on the Gasconade River near Waynesville, Missouri.

## Preliminary Evaluation of Proposed Modifications

After the initial calibration to the 1945 flood, simulations of two preliminary scenarios for the proposed modifications to the State Highway 17 crossing were done based on information provided by MoDOT using the boundary conditions from the initial calibration to the 1945 flood. This was a conceptual, qualitative analysis used by MoDOT to determine the effects of the overflow structures on velocities and water-surface elevations in the vicinity of State Highway 17 and water-surface elevations upstream. The discussion of the results from these preliminary evaluations is qualitative because the initial calibration to the April 1945 flood was superseded by the later calibration to the March 20, 2008, flood. Although the model of existing conditions was recalibrated to the April 1945 flood as part of the later calibration, there was enough change to the model to render the specific results of the initial calibration imprecise.

One preliminary scenario involved removing the overflow structures at the State Highway 17 crossing. Based on discussions with MoDOT (Keith Ferrell, oral commun., 2008), the elements representing the flow through the overflow structures were disabled in the model of existing conditions, effectively creating a solid road embankment without bridges. The model of existing conditions was run with the disabled elements, which resulted in increased velocity in the main channel through and downstream from the main bridge (up to 7 ft/s) and a substantial increase (about 2 ft) in the water level upstream from State Highway 17.

The other preliminary scenario involved using smaller overflow structures at the State Highway 17 crossing. Based on discussions with MoDOT (Keith Ferrell, oral commun., 2008), the elements representing the flow through the overflow structures were limited to a width of about 90 ft. The model of existing conditions was run with the narrower overflow structures, which resulted in velocities in the main channel through and downstream from the main bridge that were nearly equal to the existing conditions that were simulated in the initial calibration to the 1945 flood, and a smaller increase (approximately 0.75 ft) in the water level upstream from State Highway 17; however, the velocities through the narrower overflow structures were substantially greater than the existing conditions (more than 12 ft/s).

# Model of Proposed Conditions

While the design floods were being simulated in the model of existing conditions, MoDOT developed preliminary plans for the proposed replacement structures for J-802, K-112, and K-113. These preliminary plans were used to develop a model of proposed conditions to simulate the design floods for comparison to the existing conditions.

## Model Modifications

The preliminary proposed design of the State Highway 17 crossing is shown in figure 17A, and elevation data from the model of proposed conditions is shown in figure 17B. The proposed replacement structure over the main channel will be slightly downstream and angled to the existing structure J-802. State Highway 17 will be straightened from the existing roadway, which will permit construction of the replacement overflow structures upstream and downstream from the existing structures to occur with minimal disruption to traffic. The existing roadway is approximately level at an elevation of 772.00 ft, whereas the proposed roadway will be slightly elevated between the main channel bridge and the middle overflow bridge. The main channel structure will be 490 ft long, consisting of two 125-ft main spans and two 120-ft approach spans supported by concrete bents with dual 3.5-ft diameter circular columns. The left overflow structure will be 199 ft long, consisting of a 71-ft main span and two 64-ft approach spans supported by concrete bents with dual 3.5-ft diameter circular columns. The middle overflow structure will be 267 ft long, consisting of a 93-ft main span and two 87-ft approach spans supported by concrete bents with dual 3.5-ft diameter circular columns. The existing roadway upstream from the proposed realignment will be left in place and rounded to help guide flow into the middle overflow bridge and the main channel bridge (fig. 17B). A short guide bank is proposed upstream from the right end of the left overflow structure to guide flow into that structure as well (fig. 17B).

The bents for all of the proposed structures were incorporated into the model mesh using the pier module in Flo2DH. Because of their small size and circular cross section, these bents would not substantially affect flow in the model, and would have resulted in inordinate mesh refinement to incorporate directly into the model mesh as disabled elements, as had been done for the main channel structure piers and bents in the model of existing conditions. Position, orientation, and dimensions of each bent were obtained from preliminary bridge plans (David Stevenson, written comm., 2008) to accurately position and size the bents. Each column of the bents of the proposed replacement structures was coded as round 3.5-ft diameter columns in the pier module, as noted from the preliminary bridge plans.

Material and hydraulic properties developed in the model of existing conditions were used in the model of proposed conditions, and all new mesh elements were assigned values consistent with the model of existing conditions, based on the proposed land use in the model of proposed conditions (fig. 18; table 6). All the proposed modifications, such as clearing of trees, road realignment, and new structures, will occur in the vicinity of State Highway 17; therefore, most of the modified elements were assigned the “highway embankment” material properties.

The finite-element mesh for the model of proposed conditions consisted of 25,906 elements that ranged in size from 2.43 to 10,295 $ft^2$. Each element had a node at each corner and

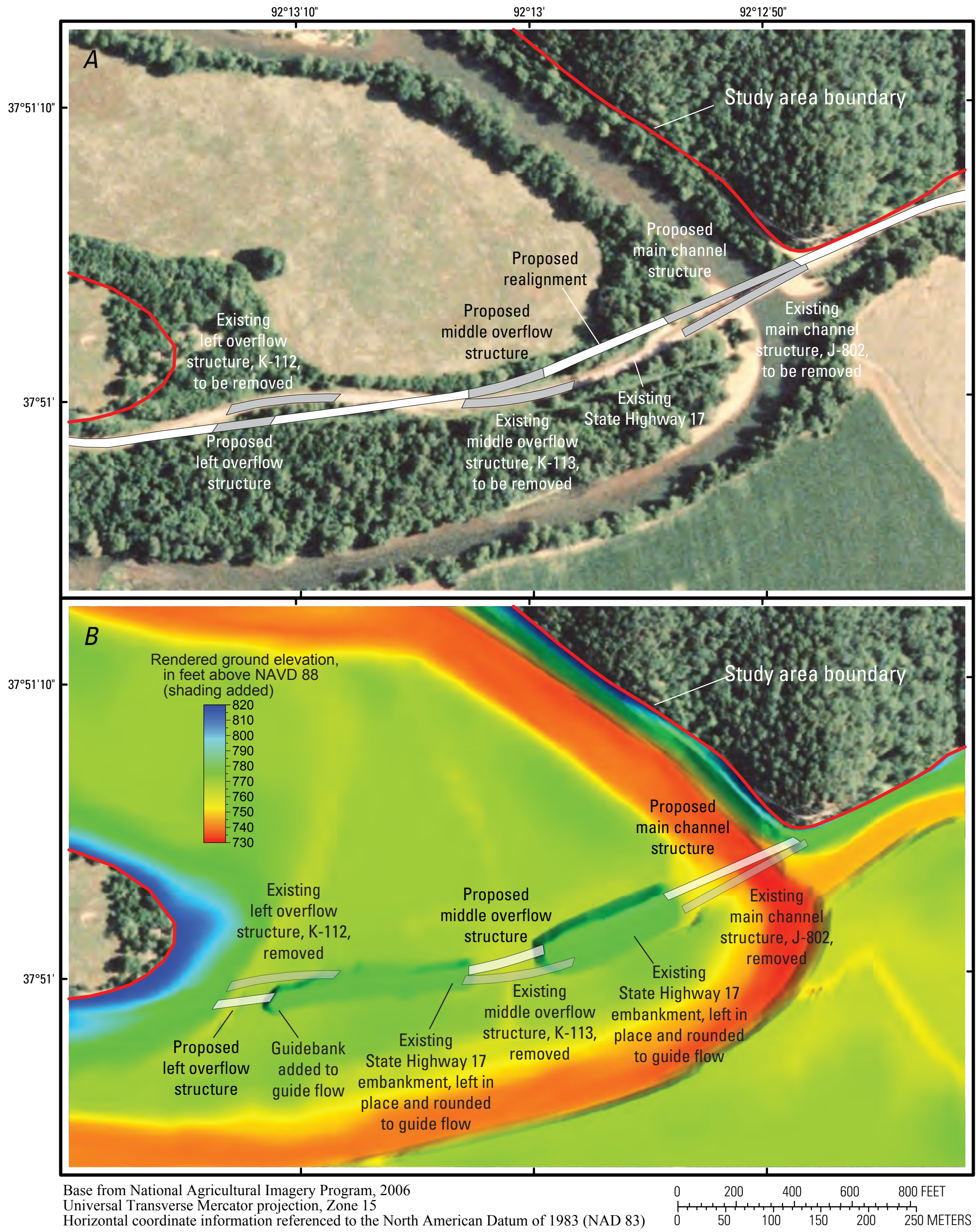
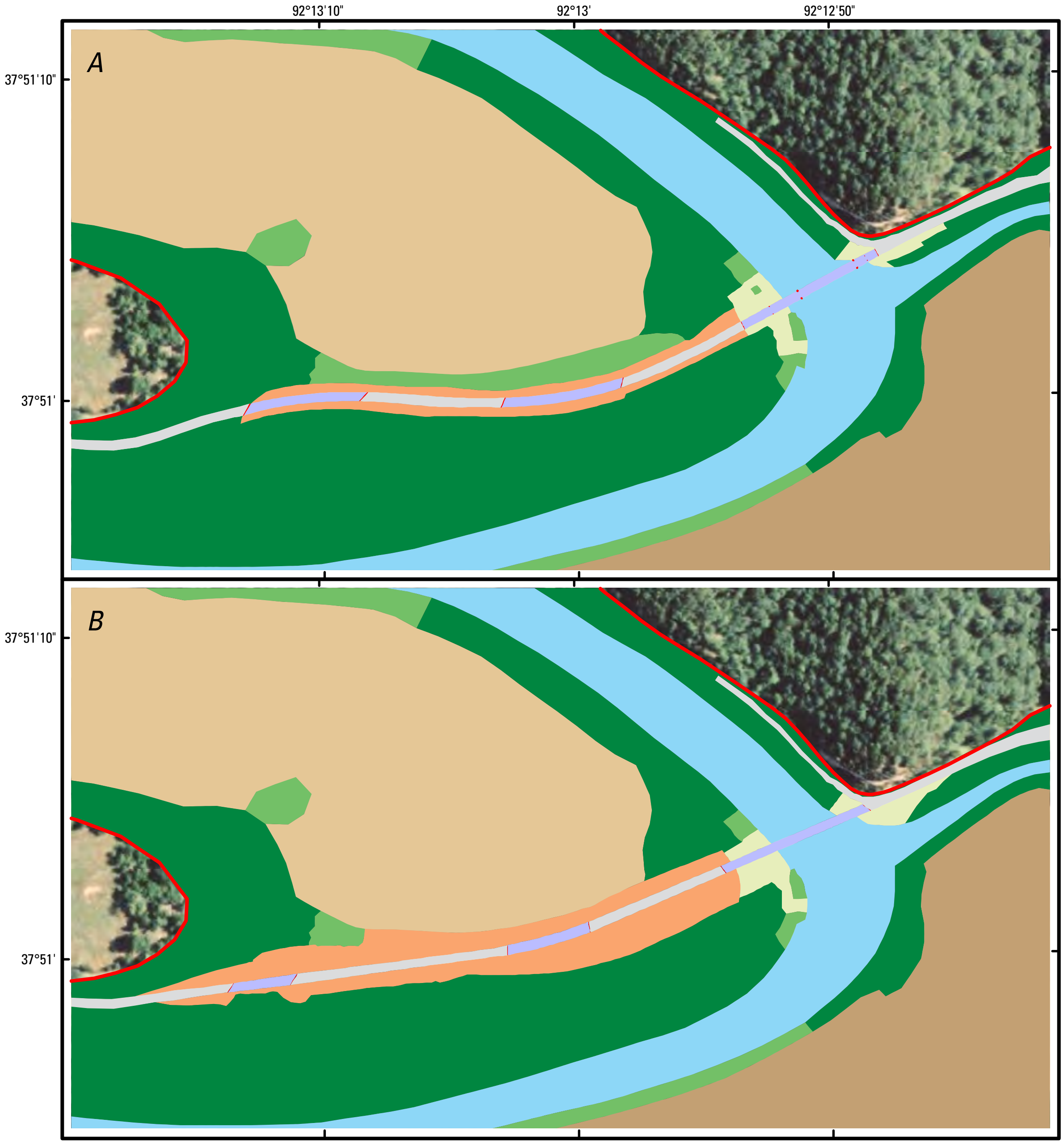



**Figure 17.** Preliminary proposed alignment of State Highway 17 over the Gasconade River near Waynesville, Missouri, *A,* in relation to the existing conditions and *B,* as rendered with shaded ground elevation data in the model of proposed conditions.




Base from National Agricultural Imagery Program, 2006
Universal Transverse Mercator projection, Zone 15
Horizontal coordinate information referenced to the North American Datum of 1983 (NAD 83)

0 200 400 600 800 FEET
0 50 100 150 200 250 METERS

**EXPLANATION**

**Land Use**

- Sand and gravel channel
- Row crops (corn)
- Pasture
- Thick timber and thick brush
- Open timber and brush
- Thick grasses with sprouts
- Highway embankment
- Pavement and gravel
- Bridge deck

**Figure 18.** Land-use coverages in the vicinity of State Highway 17 used in *A*, the model of existing conditions and *B*, the model of proposed conditions on the Gasconade River near Waynesville, Missouri.

at the midpoint of each side, which created a total of 58,291 nodes.

## Simulation of Design Floods

As with the model of existing conditions, simulations of the 25-, 50-, 100-, and 500-year recurrence-interval floods were conducted, as well as the flood of March 20, 2008. For each flood, the upstream boundary conditions on the Gasconade River and Roubidoux Creek were set to the discharge values from table 5, and the downstream boundary was set to the water-surface elevation determined from the model of existing conditions shown in table 5. Simulated results for the three bridges for the various design floods from the model of proposed conditions are shown in table 9.

Based on the simulated results for the flood of March 20, 2008, the proposed structures have a total cross-sectional flow area (15,800 $ft^2$) that is slightly smaller than the flow area of the downstream valley constriction (16,030 $ft^2$) as determined in the model of existing conditions. The downstream constriction may continue to act as a flow control feature to upstream flow velocities and water-surface elevations in major floods, but the smaller area of the proposed structures will cause them to act as flow control features to areas upstream from themselves.

## Effect of Proposed Changes

The effects of the proposed road alignment and bridge replacements are of critical interest to MoDOT (Missouri Department of Transportation, 2004). An increase in velocity in the main channel could result in damaging stream bed and bank erosion in the channel as well as scour near the bridge piers, and an increase in depth of flow upstream from State Highway 17 could result in more inundated area, which, in turn, creates more flooding for upstream property.

The existing roadway upstream from the proposed realignment will be left in place and rounded to help guide flow into the middle overflow bridge and the main channel bridge (fig. 17). A short guidebank is proposed upstream from the right end of the left overflow structure to guide flow into that structure as well (fig. 17). Model simulations indicate that the 100- and 500-year floods partially or completely inundate the existing road embankments in the model of proposed conditions, resulting in shallow, high-velocity flow at the upstream edges of the abutments of the overflow structures (fig. 19); however, model simulations indicate that the existing road embankments are not inundated by the 25- or the 50-year floods in the model of proposed conditions, and the embankments effectively guide flow through the bridges (fig. 20). A higher embankment at the bridge openings would guide flow through the bridges at higher flows.

The simulated water-surface elevations from the model of existing conditions and the model of proposed conditions in the vicinity of State Highway 17 for the flood of March 20, 2008, as well as the 25-, 50-, 100-, and 500-year floods are shown in figures 21 through 25. Generally, the simulated water-surface elevations from the model of proposed conditions are slightly greater upstream from the State Highway 17 crossing than from the model of existing conditions in all of the flow scenarios examined.

Because the model mesh was different between the model of existing conditions and the model of proposed conditions, a direct, node-by-node comparison of results from the two models was not possible; however, the SMS package allows the user to create observation profile lines in a model, from which model results can be extracted. Four observation profile lines were created (fig. 26) in the model of existing conditions and the model of proposed conditions. One line was drawn along the centerline of the Gasconade River main channel from the upstream boundary of the model to a point approximately 2,300 ft downstream from the existing main channel structure J-802. Another line was drawn parallel to flow on the right flood plain upstream from the State Highway 17 crossing. Two additional lines were drawn through the left and middle overflow structures from a point upstream from State Highway 17 on the main channel observation line to the downstream end of the main channel line downstream from State Highway 17 (fig. 26). Data from the observation lines could be extracted from the models for the various flow simulations and compared.

The water-surface elevation departure of the proposed conditions from the existing conditions along the main channel is shown in figure 27, and the velocity magnitude departure of the proposed conditions from the existing conditions is shown in figure 28. The maximum water-surface elevation departure ranges from approximately 0.18 ft for the 25-year flood (increase in depth from 27.58 ft to 27.76 ft) to 0.32 ft for the 500-year flood (increase in depth from 33.79 ft to 34.11 ft), and occurs approximately midway between the upstream boundary of the model and the main channel structure on State Highway 17. The smaller overflow structures in the model of proposed conditions cause this increase in water-surface elevation upstream from State Highway 17, with a commensurate decrease in velocity magnitude. There is a decrease in the water-surface elevations downstream from State Highway 17, with a commensurate increase in velocity in this reach (figs. 27 and 28). The maximum departure in velocity magnitude is approximately 1.2 ft/s, and occurs approximately 1,500 ft downstream from the main channel structure, near the location of the downstream valley constriction (fig. 28). Downstream from the main channel structure, the magnitude of the departure in water-surface elevation does not increase with increasing discharge, as it does upstream from the main channel structure (fig. 27); the flood of March 20, 2008, has the largest departure, whereas the departures of the 100- and 500-year floods are similar to the departure of the 50-year flood. It should be noted that the maximum departure downstream from the main channel structure is approximately -0.11 ft.

For the left (west) overflow structure, the water-surface elevation departure of the proposed conditions from the existing conditions is shown in figure 29, and the velocity magni-

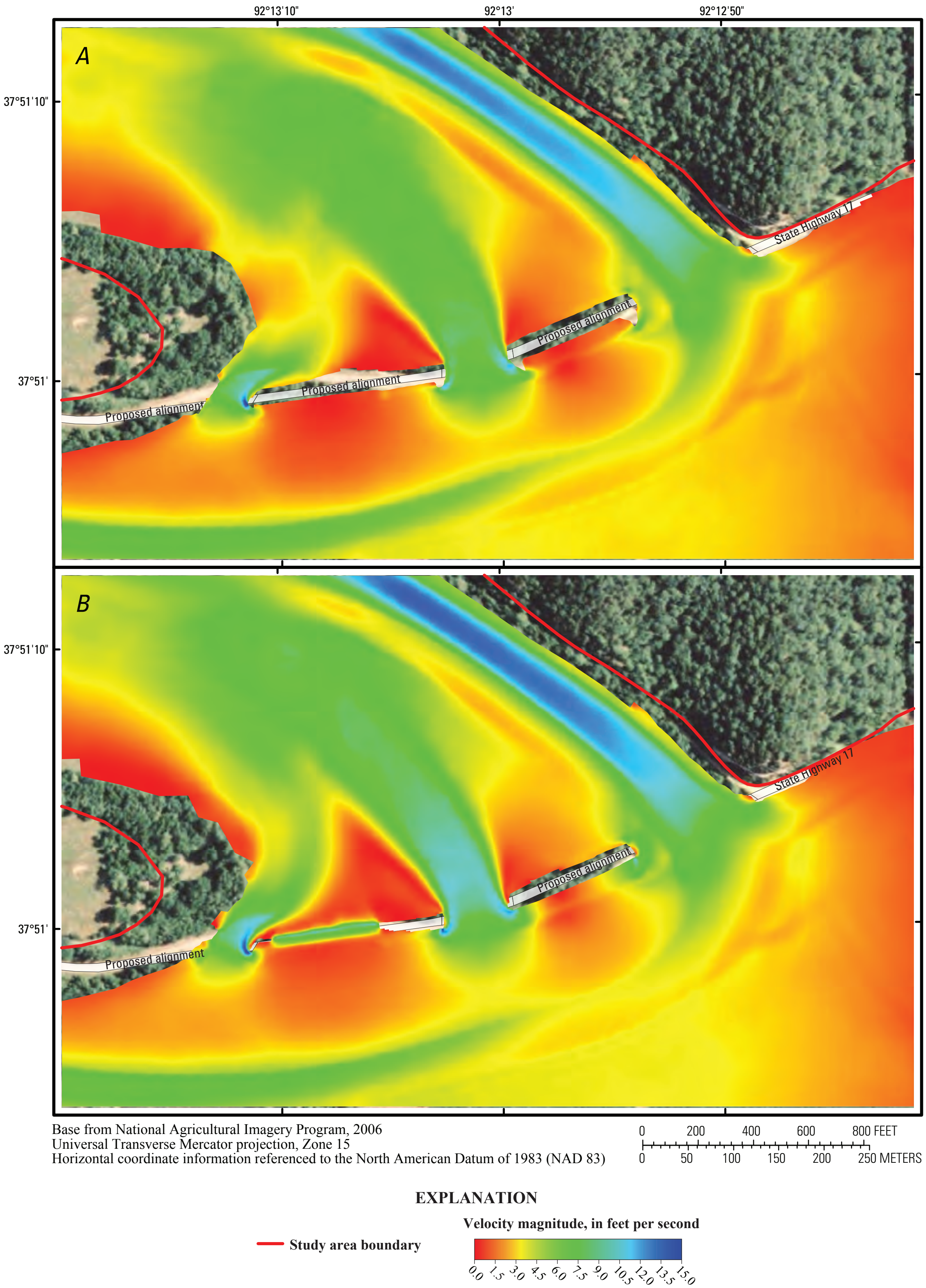



**Figure 19.** Simulated velocity magnitudes in the vicinity of State Highway 17 from the model of proposed conditions for the *A,* 100-year and *B,* 500-year floods on the Gasconade River near Waynesville, Missouri.

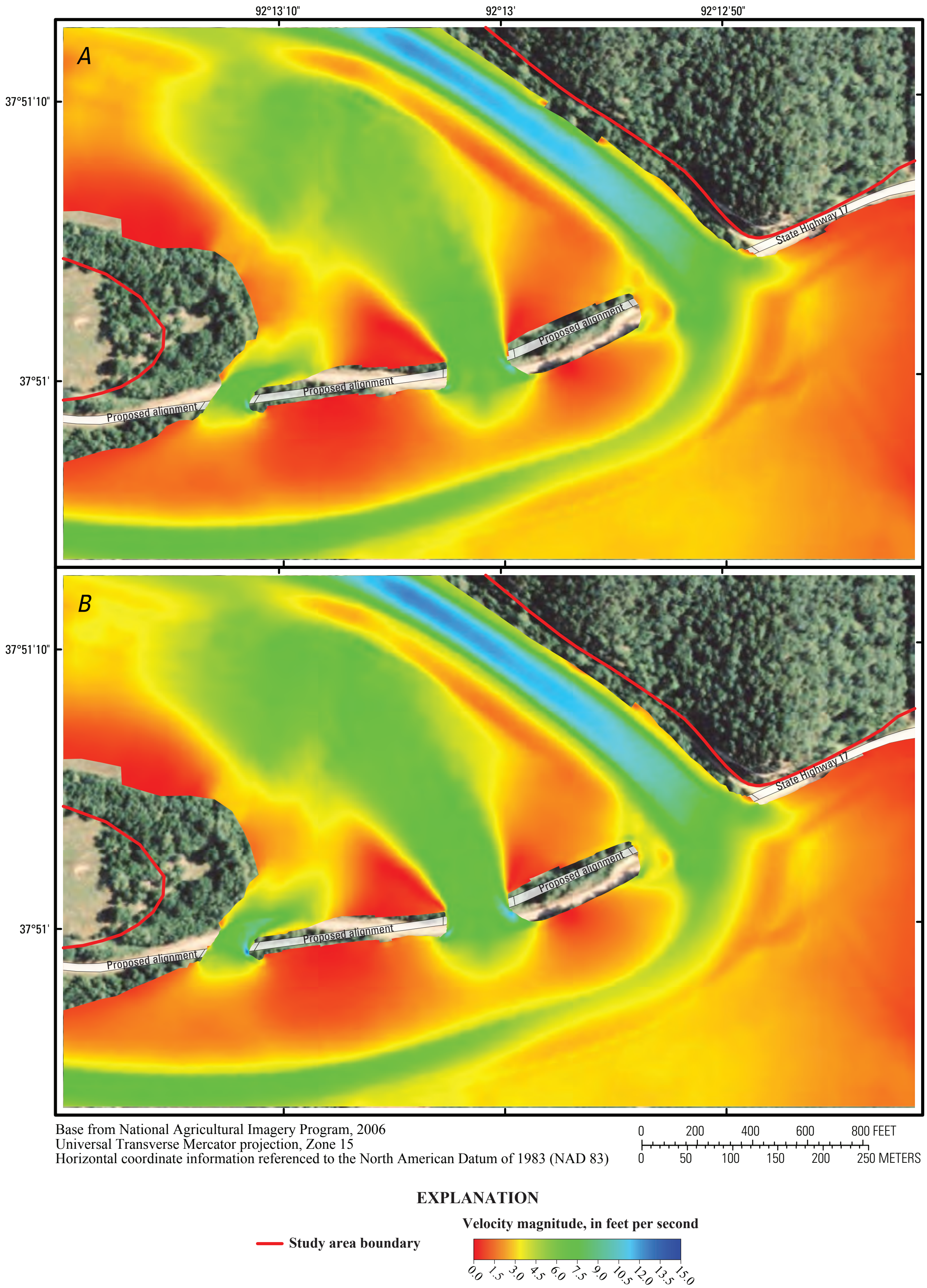



**Figure 20.** Simulated velocity magnitudes in the vicinity of State Highway 17 from the model of proposed conditions for the *A,* 25-year and *B,* 50-year floods on the Gasconade River near Waynesville, Missouri.

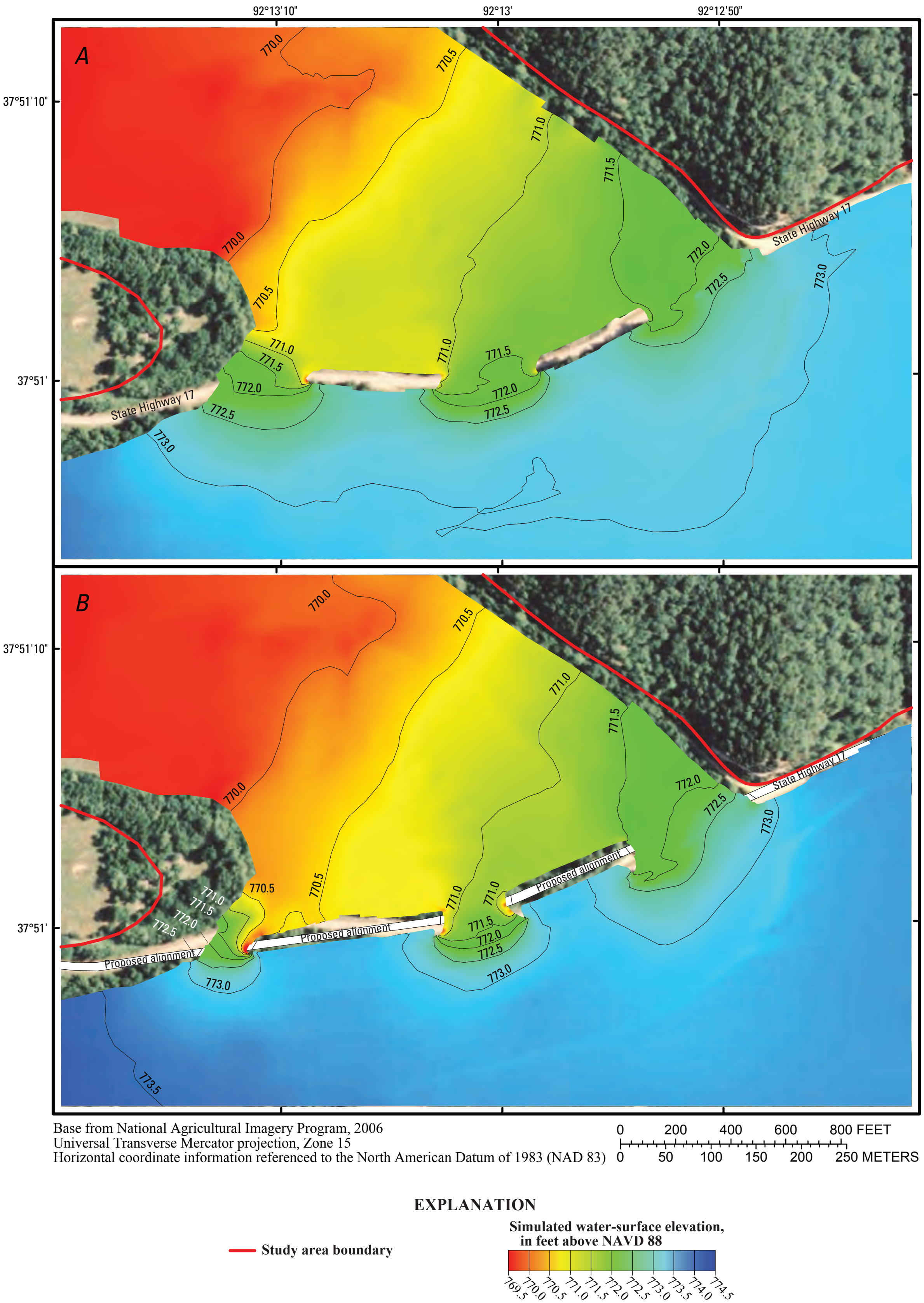



**Figure 21.** Simulated water-surface elevations in the vicinity of State Highway 17 for the flood of March 20, 2008 from *A,* the model of existing conditions and *B,* the model of proposed conditions on the Gasconade River near Waynesville, Missouri.

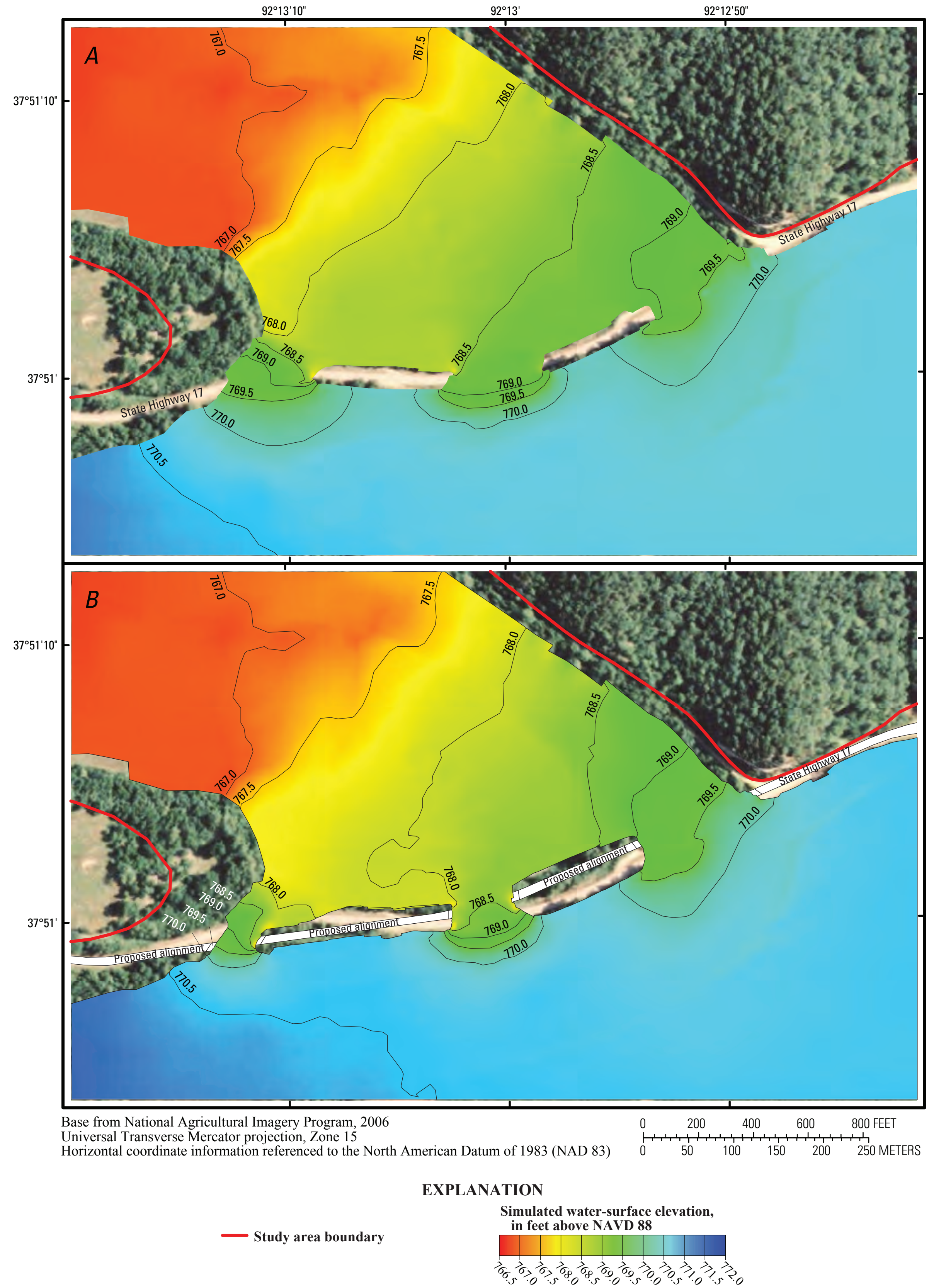



**Figure 22.** Simulated water-surface elevations in the vicinity of State Highway 17 for the 25-year flood from *A*, the model of existing conditions and *B*, the model of proposed conditions on the Gasconade River near Waynesville, Missouri.

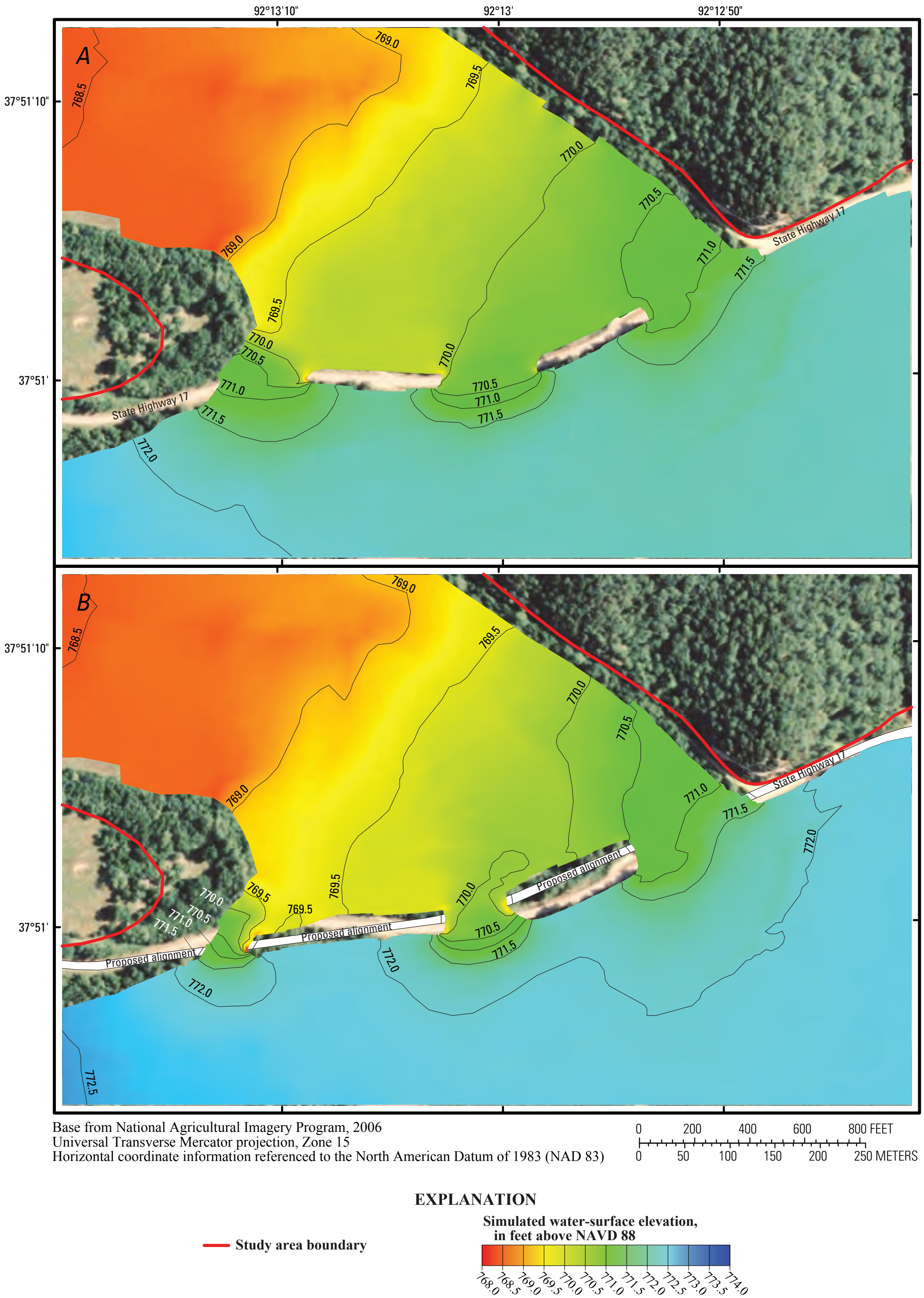



**Figure 23.** Simulated water-surface elevations in the vicinity of State Highway 17 for the 50-year flood from *A,* the model of existing conditions and *B,* the model of proposed conditions on the Gasconade River near Waynesville, Missouri.

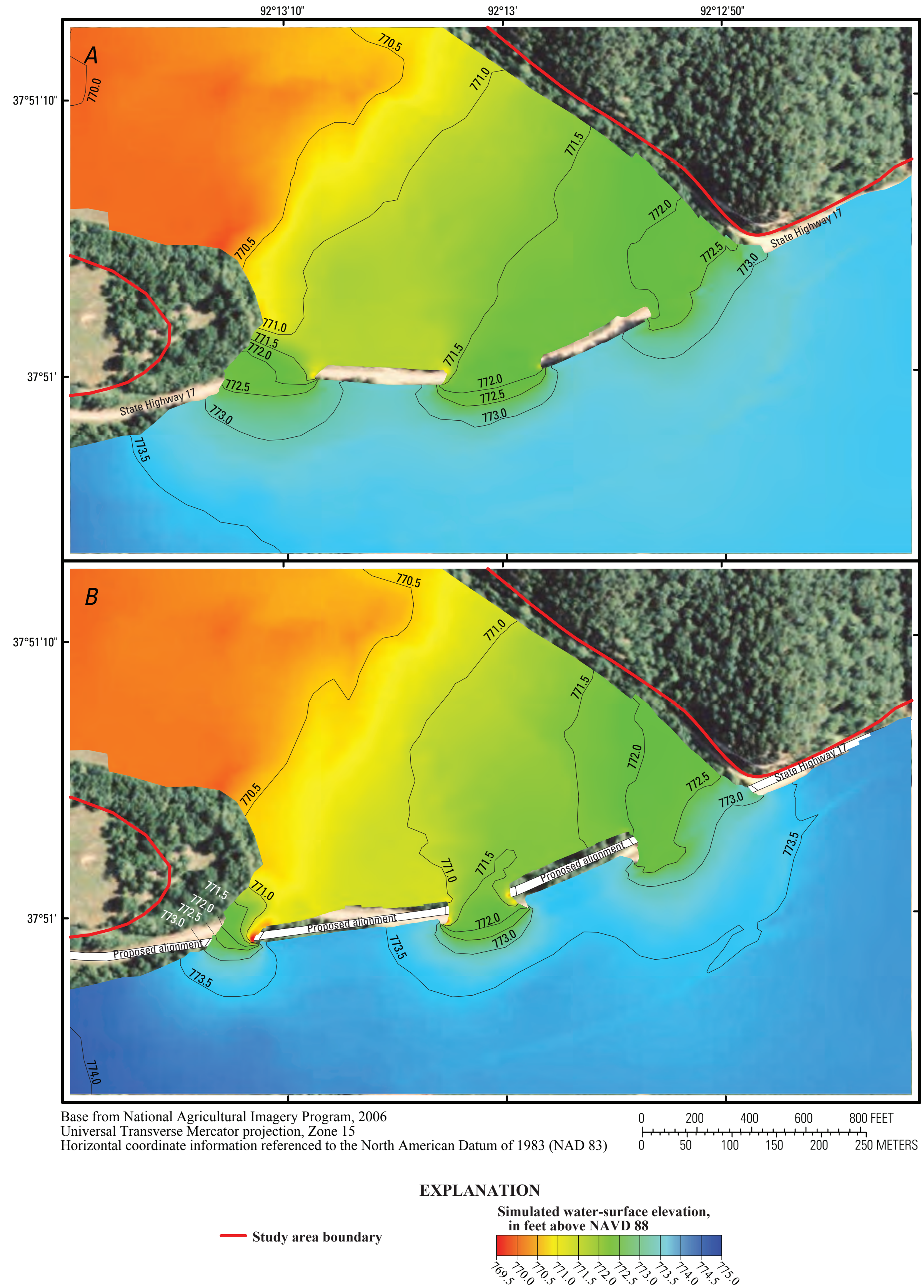



**Figure 24.** Simulated water-surface elevations in the vicinity of State Highway 17 for the 100-year flood from *A,* the model of existing conditions and *B,* the model of proposed conditions on the Gasconade River near Waynesville, Missouri.

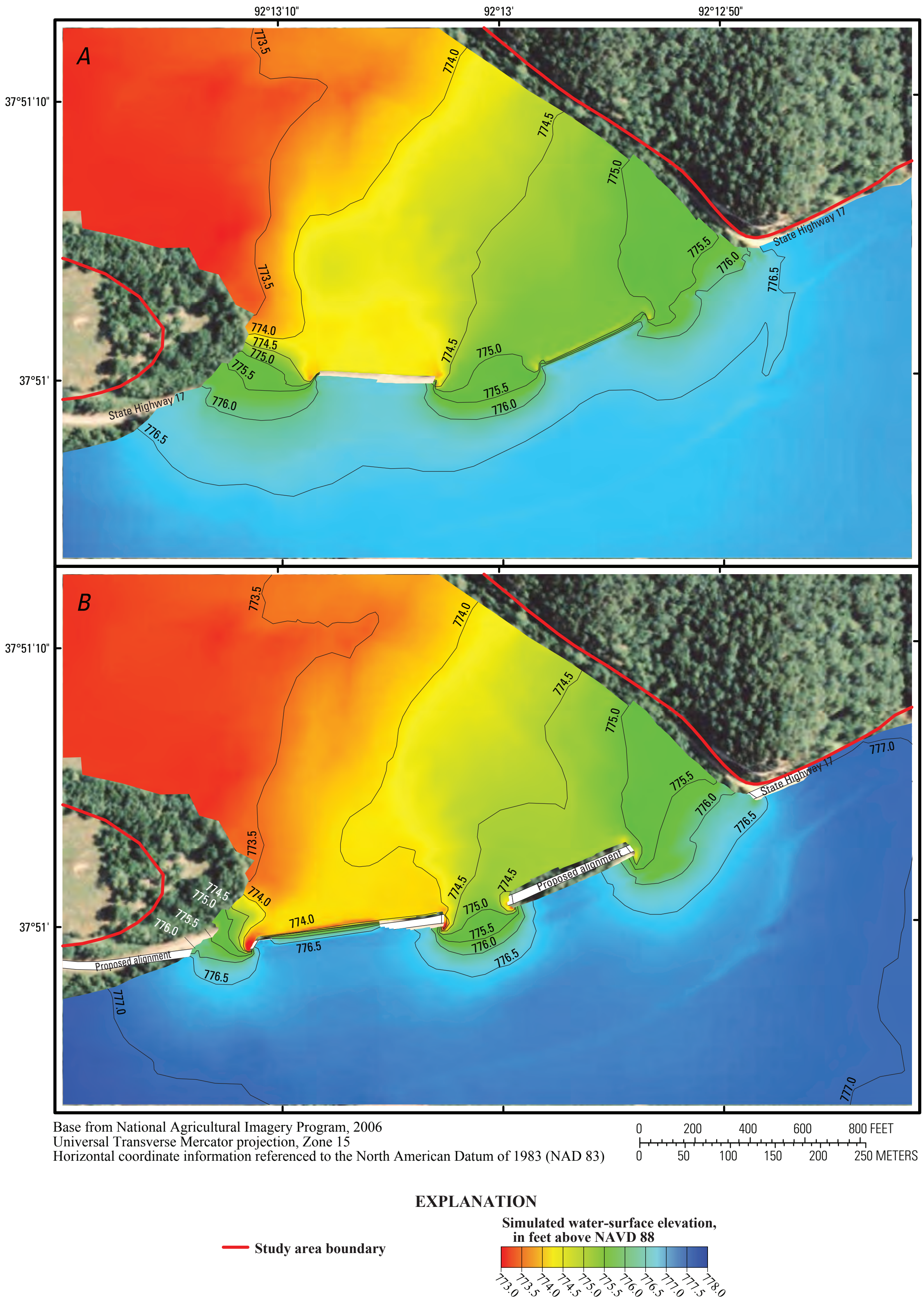



**Figure 25.** Simulated water-surface elevations in the vicinity of State Highway 17 for the 500-year flood from *A*, the model of existing conditions and *B*, the model of proposed conditions on the Gasconade River near Waynesville, Missouri.

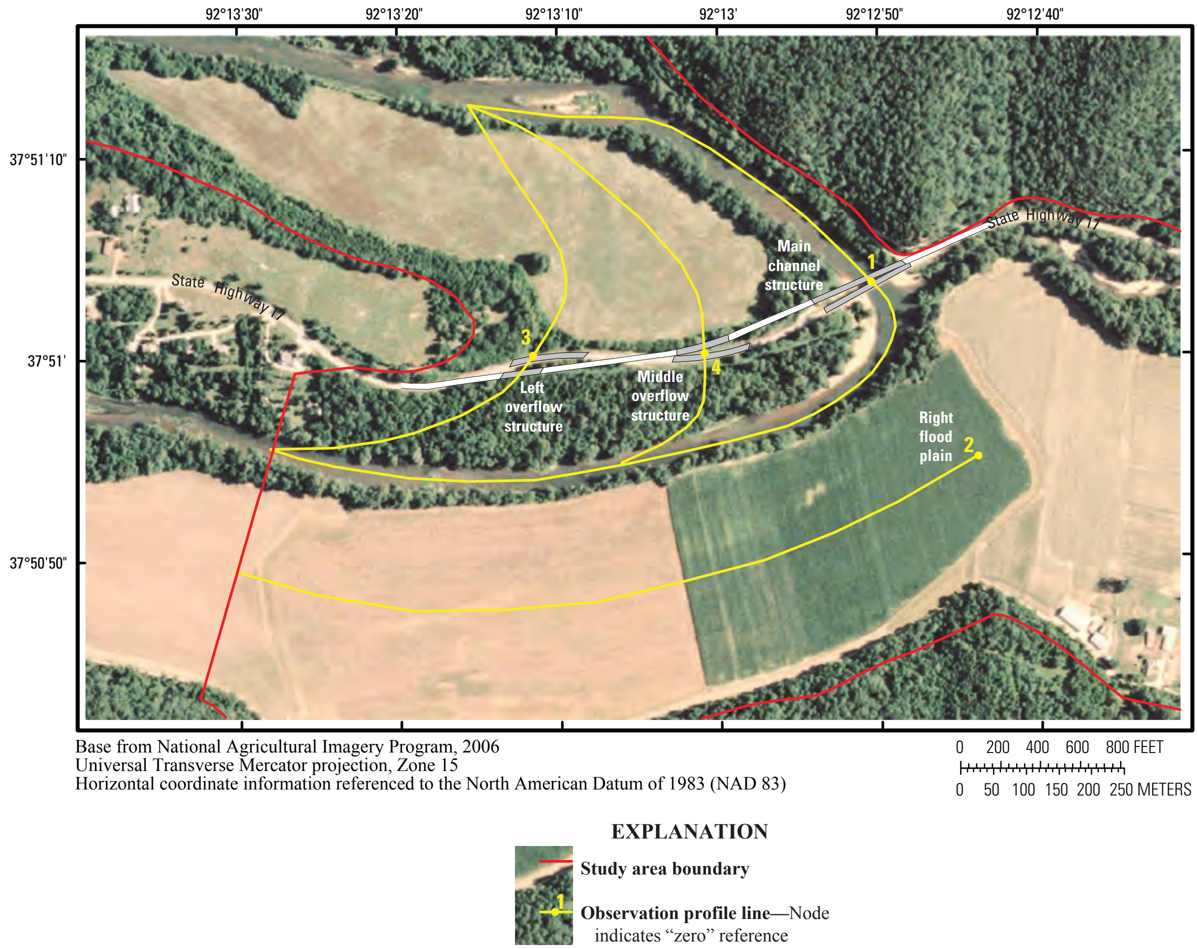



**Figure 26.** Arcs used as observation profile lines in the vicinity of State Highway 17 on the Gasconade River near Waynesville, Missouri.

tude departure of the proposed conditions from the existing conditions is shown in figure 30. The maximum water-surface elevation departure occurs downstream from the new overflow structure, at the location of the existing structure K-112 (fig. 29). The smaller overflow structure in the proposed conditions causes a substantial increase in the velocity (approximately 4.9 ft/s on the observation line for the 500-year flood) through the new bridge opening (fig. 30), which remains until the downstream face of the existing State Highway 17 embankment is reached. This increase in velocity magnitude results in a commensurate decrease in water-surface elevation (fig. 29). Downstream from State Highway 17, the velocity magnitudes from the model of proposed conditions are less than those from the model of existing conditions.

For the middle overflow structure, the water-surface elevation departure of the proposed conditions from the existing conditions is shown in figure 31, and the velocity magnitude departure of the proposed conditions from the existing conditions is shown in figure 32. The maximum water-surface elevation departure occurs approximately 130 ft upstream from the existing structure K-113 (increase in depth from 19.79 ft to 20.14 ft for the 500-year flood). The smaller overflow structure in the proposed conditions once again causes an increase in the velocity (approximately 2.15 ft/s on the observation line for the 500-year flood) through the new bridge opening (fig. 32), which continues into the flood plain downstream from State Highway 17. This increase in velocity magnitude results in a commensurate decrease in water-surface elevation (fig. 31). Downstream from State Highway 17, the velocity magnitudes from the model of proposed conditions are greater than those from the model of existing conditions; however, the departures are less than for the left overflow structure.

Whereas the flood of March 20, 2008, and the 25-, 50-, 100-year floods generally display similarly shaped curves in figures 27 through 32, the 500-year flood often has a more unique shape. The difference of the 500-year flood data is most obvious in the velocity magnitude departures (figs. 28, 30, and 32), but it also is apparent in the water-surface elevation departures for the overflow structures (figs. 29 and 31). The unique shape of the 500-year flood data likely is the result of the flow over State Highway 17 road embankment. In the 500-year flood scenario, the location of road overflow changes from the embankment between the main channel structure J-802 and the middle overflow structure K-113 in the model of

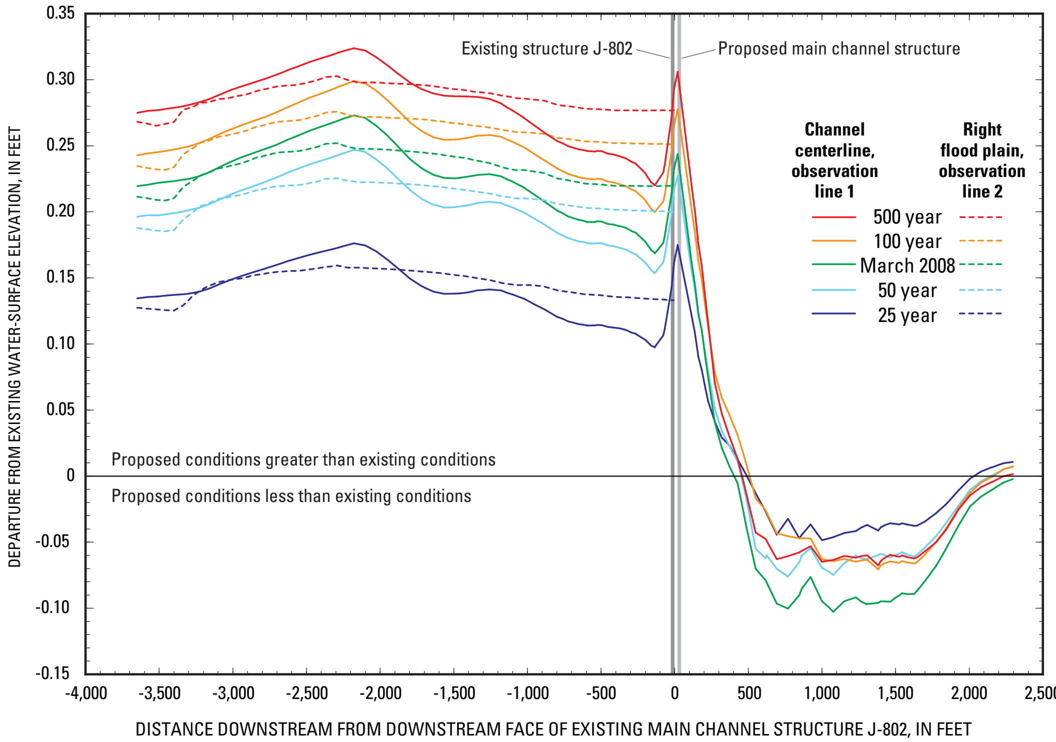



**Figure 27.** Departure of simulated water-surface elevation in the model of proposed conditions from the model of existing conditions along the channel centerline and on the right flood plain upstream from State Highway 17 on the Gasconade River near Waynesville, Missouri.

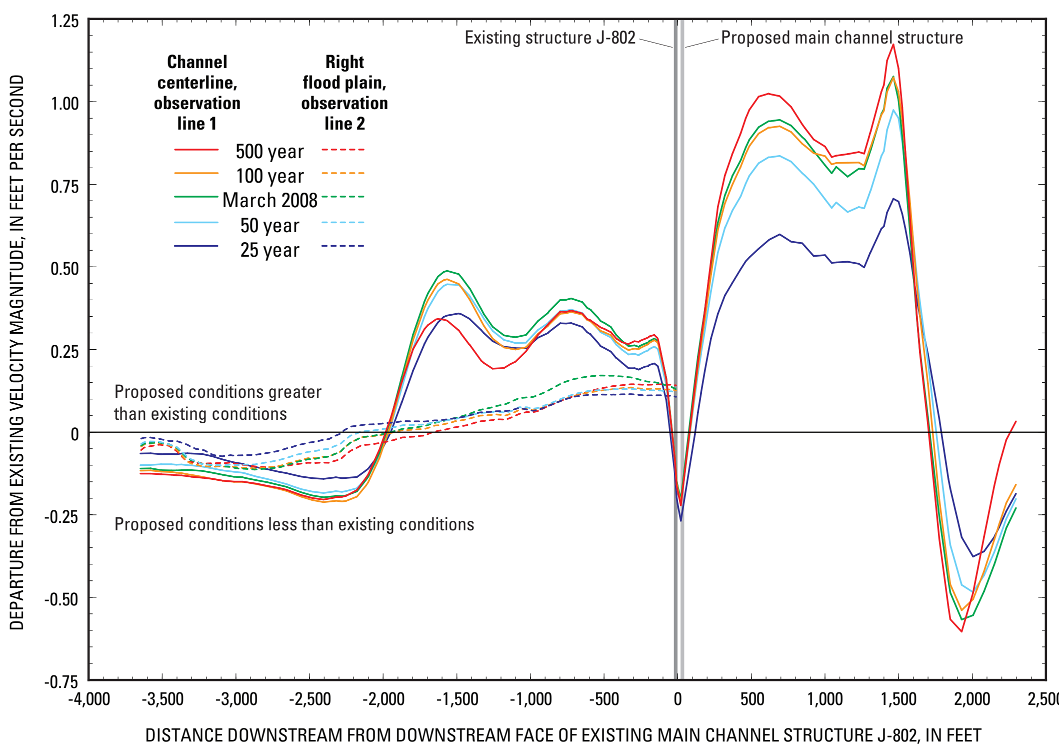



**Figure 28.** Departure of simulated velocity magnitude in the model of proposed conditions from the model of existing conditions along the channel centerline and on the right flood plain upstream from State Highway 17 on the Gasconade River near Waynesville, Missouri.

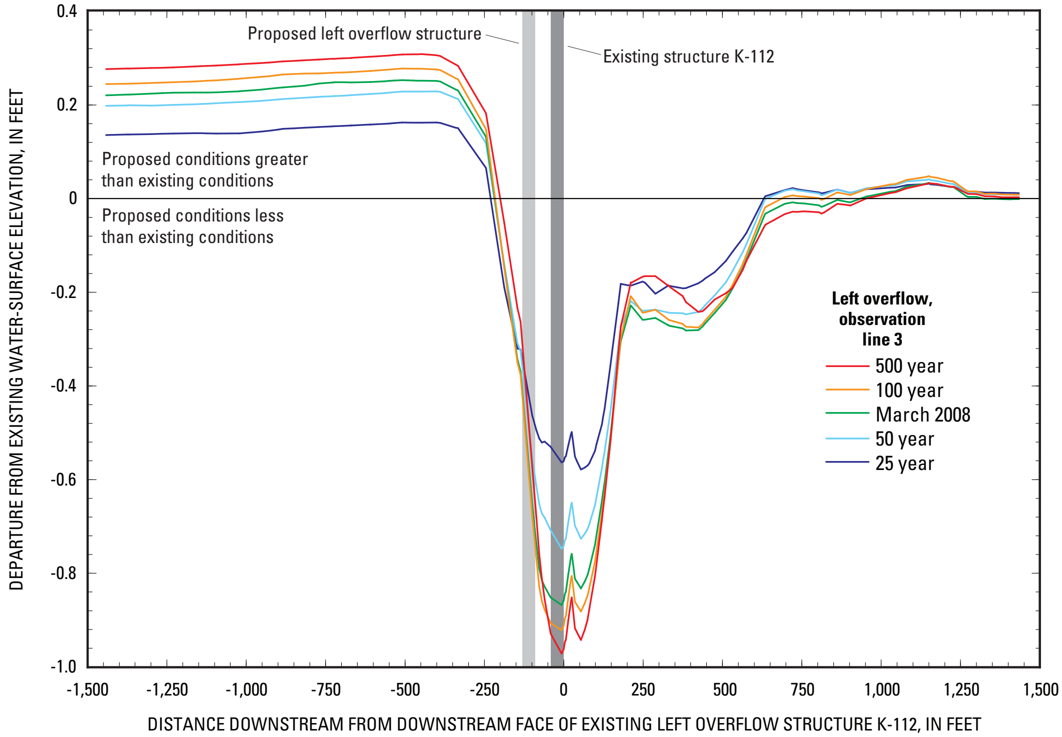



**Figure 29.** Departure of simulated water-surface elevation in the model of proposed conditions from the model of existing conditions along the observation profile line through the left overflow structure of State Highway 17 on the Gasconade River near Waynesville, Missouri.

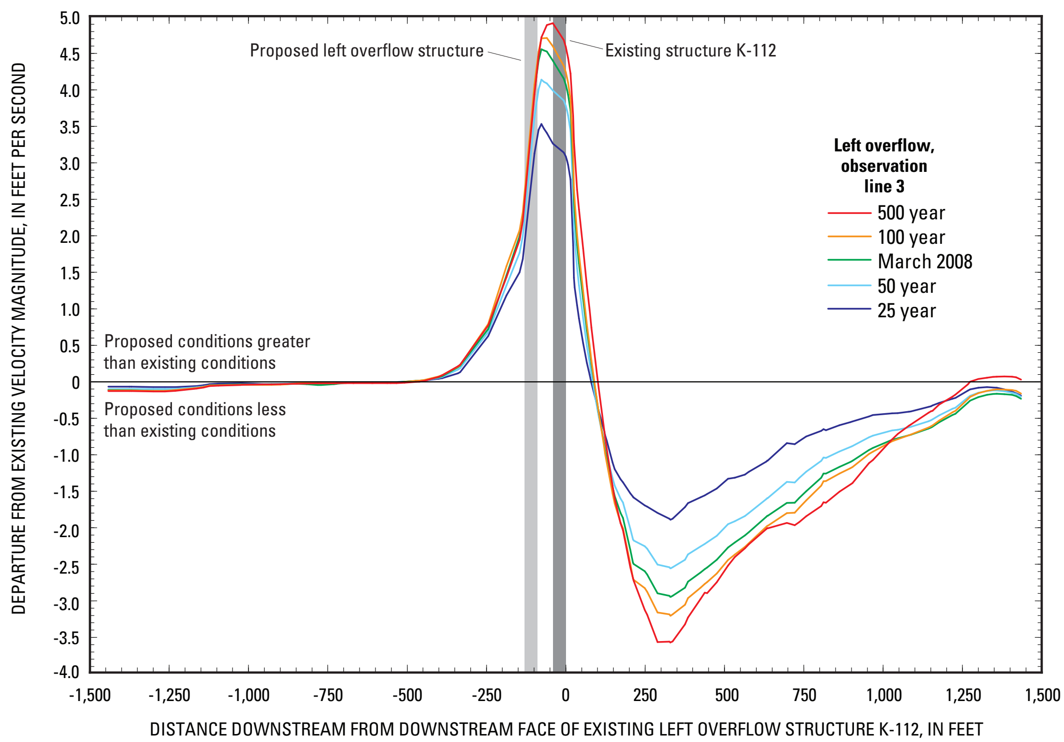



**Figure 30.** Departure of simulated velocity magnitude in the model of proposed conditions from the model of existing conditions along the observation profile line through the left overflow structure of State Highway 17 on the Gasconade River near Waynesville, Missouri.

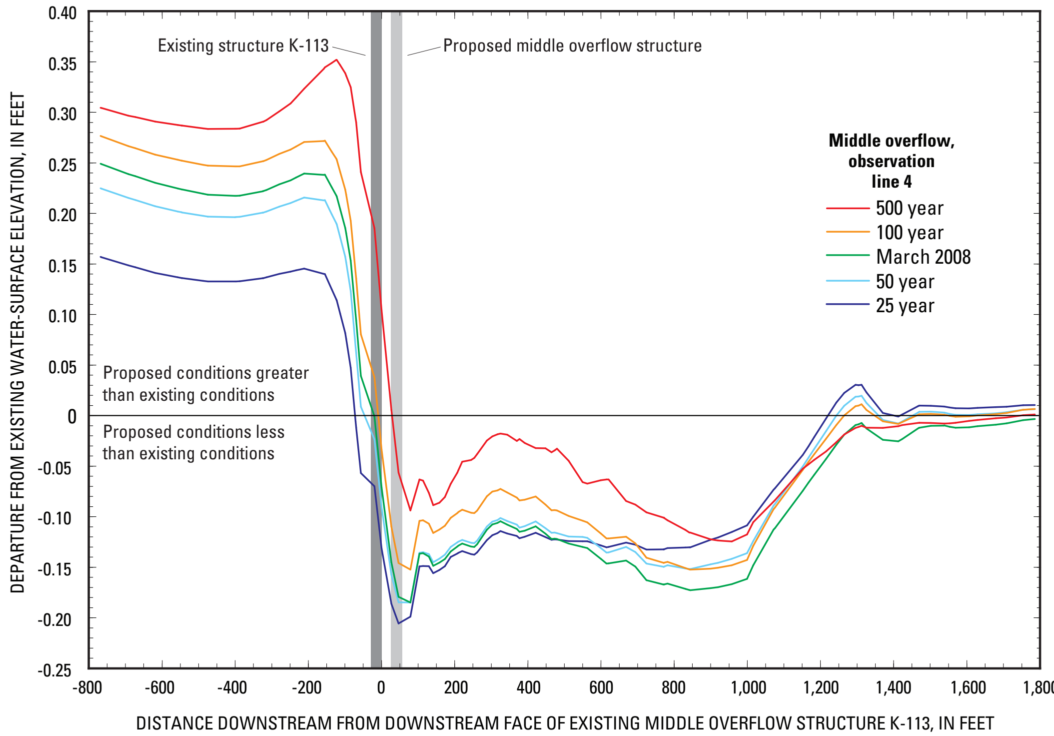



**Figure 31.** Departure of simulated water-surface elevation in the model of proposed conditions from the model of existing conditions along the observation profile line through the middle overflow structure of State Highway 17 on the Gasconade River near Waynesville, Missouri.

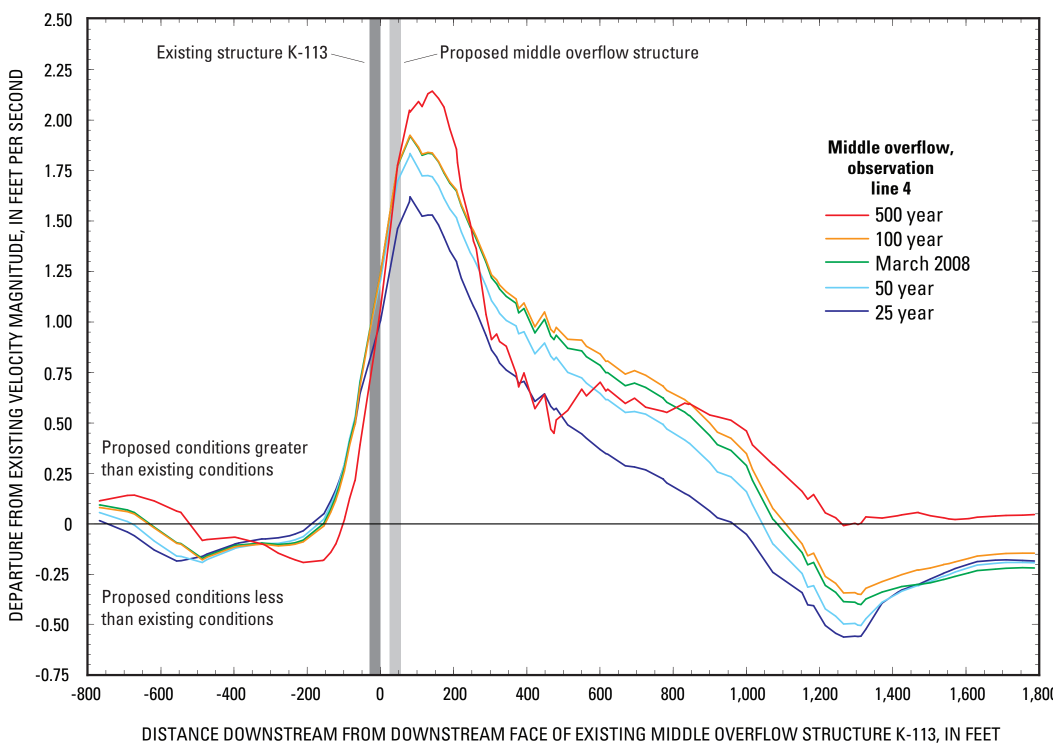



**Figure 32.** Departure of simulated velocity magnitude in the model of proposed conditions from the model of existing conditions along the observation profile line through the middle overflow structure of State Highway 17 on the Gasconade River near Waynesville, Missouri.

existing conditions to the embankment between the overflow structures in the model of proposed conditions (fig. 25). Road overflow does not occur in the other flood scenarios (figs. 21 through 24).

## Summary

Hydrologic and hydraulic parameters were determined for the Gasconade River at the site of a proposed bridge replacement and highway realignment of State Highway 17 near Waynesville, Missouri. Existing main channel structure, J-802, and two overflow structures, K-112 and K-113, are planned to be replaced and the highway realigned to permit staging of construction of the replacement structures.

Information from a discontinued streamflow-gaging station on the Gasconade River near Waynesville (station number 06928500, "the Waynesville gage") was used to determine streamflow statistics for analysis of the 25-, 50-, 100-, and 500-year floods at the site. Analysis of the streamflow-gaging stations on the Gasconade River upstream and downstream from Waynesville indicate that flood peaks are attenuated between the upstream gaging station near Hazelgreen and the Waynesville gage, so that the peak discharge observed on the Gasconade River near Waynesville will be equal to or only slightly greater (7 percent or less) than that observed near Hazelgreen.

A peak flood event occurred on the Gasconade River, and a flood measurement was obtained downstream from State Highway 17 on March 20, 2008, near the time of the peak at that location. The elevation of high-water marks from that event indicated it was the highest measured flood in the history of the Waynesville gage. The measured discharge was 95,400 cubic feet per second, with a corresponding water-surface elevation of 766.18 feet near the location of the Waynesville gage. The measurements obtained for the March flood resulted in a shift of the original stage-discharge relation for the Waynesville gage. Furthermore, the streamflow statistics were modified based on the new data. The shifted stage-discharge relation was used to estimate the peak discharges for calibrating the two-dimensional hydraulic models of the State Highway 17 crossing, and the modified streamflow statistics were used for the 25-, 50-, 100-, and 500-year floods at the site.

A two-dimensional hydrodynamic flow model was used to simulate flow conditions on the Gasconade River in the vicinity of State Highway 17, using the depth-averaged Finite Element Surface-Water Modeling System (FESWMS Flo2DH). A model was developed that represents conditions as they exist currently (2008) on State Highway 17 (the "model of existing conditions"). The model of existing conditions was calibrated to the floods of March 20, 2008, December 4, 1982, and April 14, 1945. Modifications were made to the model of existing conditions to create a model that represents conditions along the same reach of the Gasconade River with preliminary proposed replacement bridges and realignment of State Highway 17 (the "model of proposed conditions"). The models of existing and proposed conditions were used to simulate the 25-, 50-, 100-, and 500-year recurrence floods, as well as the March 20, 2008 flood.

Results from the model of proposed conditions indicate that the proposed replacement structures and realignment of State Highway 17 will result in additional backwater upstream from State Highway 17 ranging from approximately 0.18 foot for the 25-year flood (increase in depth from 27.58 feet to 27.76 feet) to 0.32 foot for the 500-year flood (increase in depth from 33.79 feet to 34.11 feet). Velocity magnitudes in the proposed overflow structures were higher than in the existing structures [by as much as 4.9 feet per second in the left (west) overflow structure for the 500-year flood], and shallow, high-velocity flow occurs at the upstream edges of the abutments of the proposed overflow structures in the 100- and 500-year floods where flow overtops parts of the existing road embankment that will be left in place in the proposed scenario. Velocity magnitude in the main channel of the model of proposed conditions increased by a maximum of 1.2 feet per second over the model of existing conditions, with the maximum occurring approximately 1,500 feet downstream from existing main channel structure J-802 near the location of a valley constriction.

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