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Floods of September 2010 in Southern Minnesota

Scientific Investigations Report 2011–5045

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

Cover. Left: Flood-inundation map prepared by Chris Sanocki, U.S. Geological Survey, January 2011. Map base from 2009 National Agricultural Imagery program (U.S. Department of Agriculture, 2009).
Right: View of the Zumbro River near the intersection of State Route 60 and U.S. Route 63 at Zumbro Falls, Minn., September 25, 2010. (Photograph by Bill Holmes, resident of the community of Zumbro Falls).

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KEN SALAZAR, Secretary

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Contents

Figures

Appendix 2

Appendix 3

Tables

Appendix 1

Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per hour (in/h)	0 .0254	meter per hour (m/h)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88) or the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Water year is the 12-month period of October 1 through September 30 designated by the calendar year in which it ends.

Abbreviations and Acronyms

DEM	digital elevation model
FEMA	Federal Emergency Management Agency
GIS	geographic information system
HAZUS–MH	Hazards U.S. Multi-Hazards
HEC–RAS	Hydrologic Engineering Center River Analysis System
LiDAR	Light detection and ranging
MDNR	Minnesota Department of Natural Resources
MDPS	Minnesota Department of Public Safety
MHSEM	Minnesota Homeland Security and Emergency Management
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
RTK–GPS	Real-Time Kinematic Global Positioning System
TIN	triangular irregular network
USGS	U.S. Geological Survey

Floods of September 2010 in Southern Minnesota

By Christopher A. Ellison[1], Chris A. Sanocki[1], David L. Lorenz[1], Gregory B. Mitton[1], and Gregory A. Kruse[2]

Abstract

During September 22–24, 2010, heavy rainfall ranging from 3 inches to more than 10 inches caused severe flooding across southern Minnesota. The floods were exacerbated by wet antecedent conditions, where summer rainfall totals were as high as 20 inches, exceeding the historical average by more than 4 inches. Widespread flooding that occurred as a result of the heavy rainfall caused evacuations of hundreds of residents, and damages in excess of 64 million dollars to residences, businesses, and infrastructure. In all, 21 counties in southern Minnesota were declared Federal disaster areas.

Peak-of-record streamflows were recorded at nine U.S. Geological Survey and three Minnesota Department of Natural Resources streamgages as a result of the heavy rainfall. Flood-peak gage heights, peak streamflows, and annual exceedance probabilities were tabulated for 27 U.S. Geological Survey and 5 Minnesota Department of Natural Resources streamgages and 5 ungaged sites. Flood-peak streamflows in 2010 had annual exceedance probabilities estimated to be less than 0.2 percent (recurrence interval greater than 500 years) at 7 streamgages and less than 1 percent (recurrence interval greater than 100 years) at 5 streamgages and 4 ungaged sites. High-water marks were identified and tabulated for the most severely affected communities of Faribault along the Cannon and Straight Rivers, Owatonna along the Straight River and Maple Creek, Pine Island along the North Branch and Middle Fork Zumbro River, and Zumbro Falls along the Zumbro River. The nearby communities of Hammond, Henderson, Millville, Oronoco, Pipestone, and Rapidan also received extensive flooding and damage but were not surveyed for high-water marks. Flood-peak inundation maps and water-surface profiles for the four most severely affected communities were constructed in a geographic information system by combining high-water-mark data with the highest resolution digital elevation model data available. The flood maps and profiles show the extent and height of flooding through the communities and can be used for flood response and recovery efforts by local, county, State, and Federal agencies.

Introduction

Flood data are needed by Federal, State, and local agencies to make informed decisions in meeting mission requirements related to flood hazard mitigation, planning, and response. For example, the Federal Emergency Management Agency (FEMA), Minnesota Department of Natural Resources (MDNR), Minnesota Department of Public Safety (MDPS), and Minnesota Homeland Security and Emergency Management (MHSEM) need timely information on the magnitudes and frequency of floods to help respond to flood damage, enhance emergency response management, protect infrastructure, provide recovery guidance from the National Flood Insurance Program and State regulatory programs, and plan for future flood events.

Heavy rains caused severe flooding during September 2010 in parts of southern Minnesota (National Oceanic and Atmospheric Administration, 2010a), and prompted the National Weather Service (NWS) to issue flash-flood warnings, areal flood warnings, and river flood warnings. The flood peaks were exacerbated by an exceptionally wet summer as a result of a wet June and heavy downpours in August. Summer rainfall totals as high as 20 inches (in.) were reported in southern Minnesota, exceeding the historical average by more than 4 in. (Minnesota Department of Natural Resources State Climatology Office, 2010a). During September 22 through 25, evacuations, water rescues, and road closures were common in communities affected by the flooding. In Goodhue, Rice, Steele, and Wabasha Counties, damages from flooding were extensive and included major transportation disruptions and damage to hundreds of homes and businesses, dams and flood-control structures, agricultural crops, and critical facilities including utilities (Minnesota State Emergency Operations Center, 2010). On October 1, 2010, Minnesota Governor Tim Pawlenty requested a major disaster declaration because of the severe storms and flooding. Damage caused by the flooding resulted in a Presidential Disaster Declaration on October 13, 2010, for 21 southern Minnesota counties (Federal Emergency Management Agency, 2010a; fig. 1).

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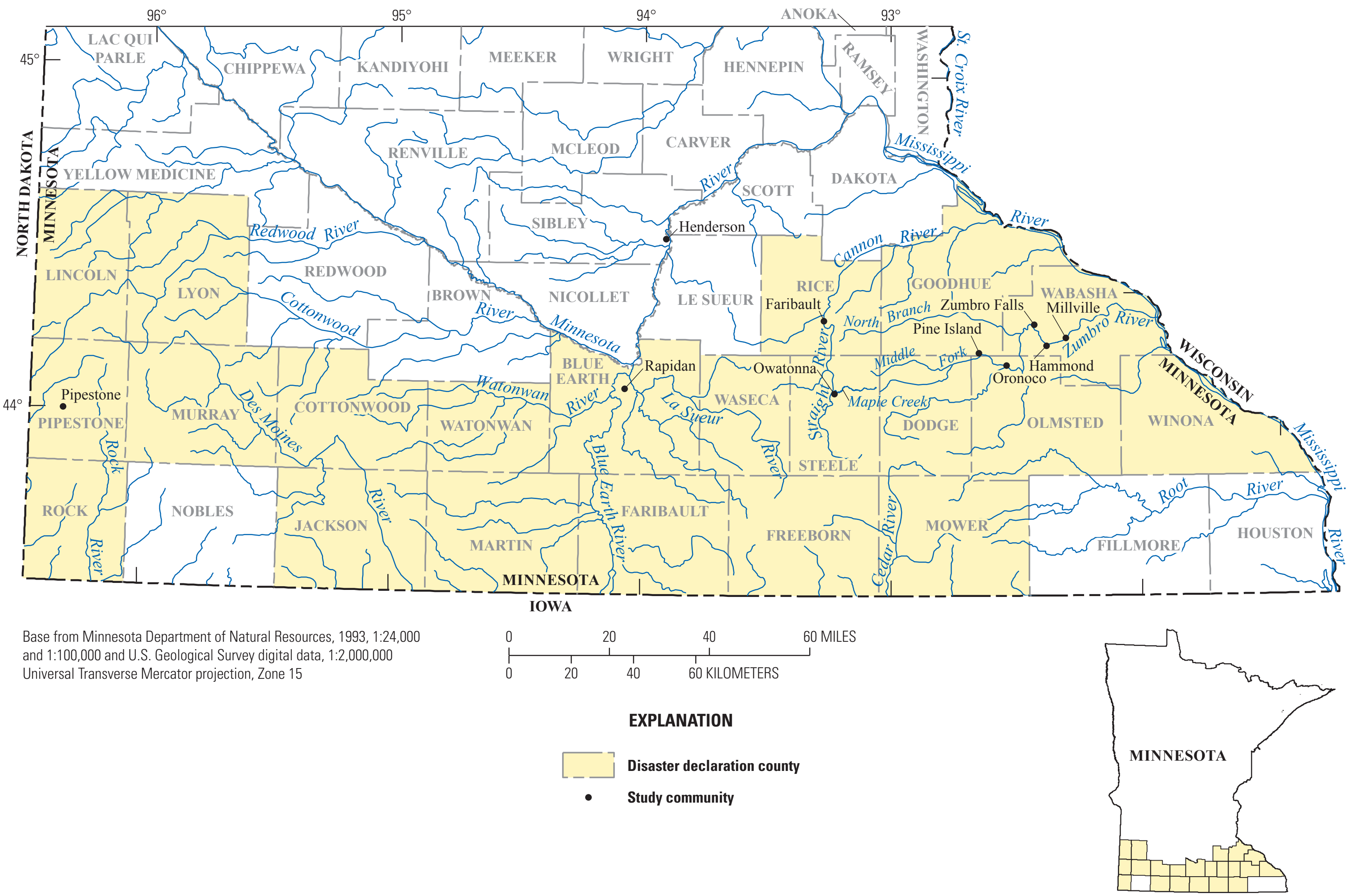
[1] U.S. Geological Survey.

[2] Minnesota Department of Natural Resources.



Base from Minnesota Department of Natural Resources, 1993, 1:24,000
and 1:100,000 and U.S. Geological Survey digital data, 1:2,000,000
Universal Transverse Mercator projection, Zone 15

Figure 1. Twenty-one counties were declared disaster areas because of severe storms and flooding during the period of September 22 through September 25, 2010 (Federal Emergency Management Agency, 2010a).

Given the severity of the September 2010 flooding in Minnesota, the U.S. Geological Survey (USGS), in cooperation with FEMA and MDNR, Division of Ecological and Water Resources, conducted a study to:

- Document the meteorological and hydrological conditions leading to the flood;
- Compile flood-peak **gage heights,**[3] **streamflows**, and **annual exceedance probabilities** at USGS and MDNR **streamgages**; and
- Compute streamflows and annual exceedance probabilities at selected ungaged locations.

The study also provided data to construct **flood profiles** and **flood-peak** inundation maps. Flood profiles and flood-peak inundation maps were constructed for four communities along six **streams** in southern Minnesota: Faribault along the Cannon and Straight Rivers; Owatonna along the Straight River and Maple Creek; Pine Island along the North Branch and Middle Fork Zumbro River; and Zumbro Falls along the Zumbro River.

Purpose and Scope

The purpose of this report is to provide meteorological and hydrologic information pertaining to the floods of September 2010 in southern Minnesota. The report summarizes meteorological and hydrologic conditions leading up to the flood. The report contains computed flood-peak magnitudes and annual exceedance probabilities for 27 USGS and 5 MDNR streamgages and 5 ungaged sites, except where otherwise noted. Data for **high-water marks** and flood-peak inundation maps and profiles are presented and described for four communities along six streams. Peak streamflows were calculated using a stage-to-discharge rating curve at most streamgages. At selected sites, peak streamflows were computed by using indirect methods. Flood damages and effects are summarized on the basis of information obtained from FEMA, NWS, MDPS, MHSEM, MDNR, local agencies, news accounts, photographs, and corroborated testimony from individuals in affected communities.

Conditions Leading to the 2010 Floods

The September 2010 flooding in southern Minnesota was caused by heavy rainfall on areas that had already received above-normal precipitation. An exceptionally wet summer preceded the September flooding. Large seasonal rainfall totals were primarily the result of a wet June and heavy downpours in August. Summer rainfall totals as high as 20 in. were reported in southern Minnesota, exceeding the historical average by more than 4 in. (Minnesota Department of Natural Resources State Climatology Office, 2010a). Preliminary analysis of rainfall totals indicated that September was the wettest September in Minnesota's modern climate record that extends back to 1891 (Minnesota Department of Natural Resources State Climatology Office, 2010b). The largest contribution to the new state-wide record came from southern Minnesota where monthly totals as high as 10 in. were common. During September 22–24, heavy rain developed over southern Minnesota, helped in part by deep tropical-origin moisture from former tropical cyclones (National Oceanic and Atmospheric Administration, 2010a). Moisture from the remnants of tropical storm Georgette in the eastern Pacific Ocean and Hurricane Karl in the Gulf of Mexico moved northward into the region and enhanced rainfall rates over southern Minnesota. This moisture, along with instability, was brought northward by low pressure in the central Plains. The first low pressure on September 22 developed in Kansas and moved into northwest Iowa, uplifting the first surge of moist and unstable air across the area. Widespread heavy-rain producing storms developed and moved steadily from west to east over southern Minnesota, in an axis north of the surface **warm front** (National Oceanic and Atmospheric Administration, 2010a). A second low pressure system lifted northward into Minnesota on September 23, providing an even larger tropical moisture surge, which resulted in sustained heavy rainfall in southern Minnesota. The City of Amboy in Blue Earth County received 10.68 in. of rain between September 22 and 24, and Zumbro Falls in Wabasha County received 8.50 in. of rain in the same period (Minnesota Department of Natural Resources State Climatology Office, 2010c; fig. 2).

A map of estimated rainfall totals prepared from National Oceanic and Atmospheric Administration (NOAA)/NSSL NMQ/Q2 system (National Oceanic and Atmospheric Administration, 2010b) shows rainfall totals ranging from 3 in. to more than 10 in. for September 22–24 across southern Minnesota (fig. 2). Total rainfall amounts for six NWS precipitation stations from September 22–24 ranged from 5.75 in. at Pipestone in Pipestone County to 10.68 in. at Amboy in Blue Earth County (table 1). The 100-year (annual exceedance probability of 0.01, or 1 percent) 72-hour rainfall for southern Minnesota is about 7 in. (Huff and Angel, 1992). Rainfall at precipitation stations for Amboy in Blue Earth County, Owatonna in Steele County, Winnebago in Faribault County, Zumbro Falls in Wabasha County, and Zumbrota in Goodhue County exceeded the 100-year 72-hour rainfall amount for southern Minnesota (table 1). A graph of daily cumulative rainfall (fig. 3) at selected NWS precipitation stations illustrates the rainfall patterns. Distribution of rainfall amounts (fig. 2) and rainfall patterns (fig. 3) show that the most severely affected communities were located along a defined line of heavy rainfall through southern Minnesota.

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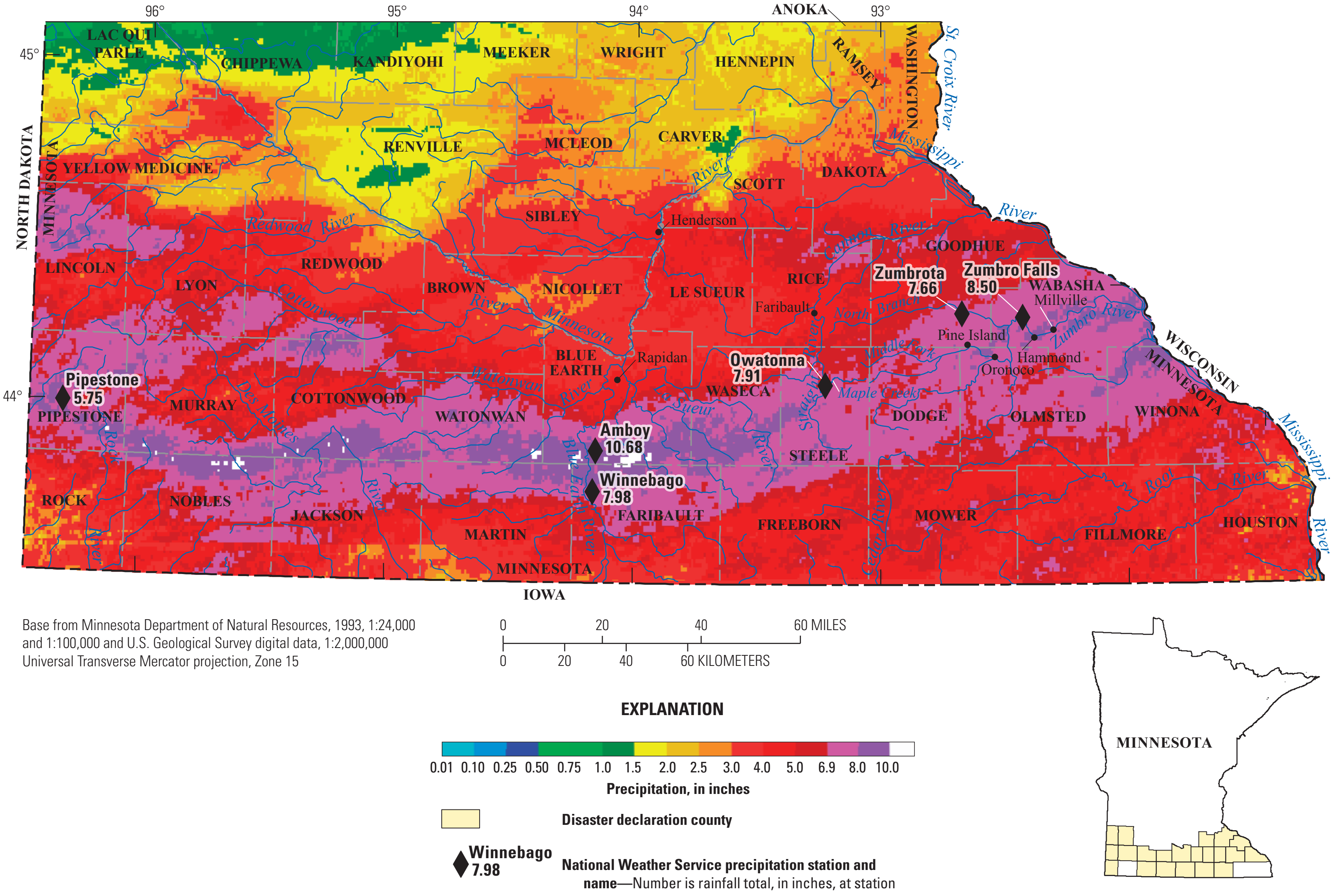
[3] Terms in **bold type** are defined in the Glossary at the back of the report.



Base from Minnesota Department of Natural Resources, 1993, 1:24,000 and 1:100,000 and U.S. Geological Survey digital data, 1:2,000,000 Universal Transverse Mercator projection, Zone 15

Figure 2. Distribution of rainfall totals September 22–24, 2010, and rainfall totals for the National Weather Service stations.

Table 1. Total rainfall for September 22–24, 2010, and 72-hour duration rainfalls for selected annual exceedance probabilities at selected National Weather Service (NWS) precipitation stations in Minnesota.

[Total rainfall from Minnesota Department of Natural Resources State Climate Office (2010c). Annual exceedance probabilities from Huff and Angel (1992). NWS, National Weather Service]

Station name (location shown in fig. 2)	County	NWS station identifier	Total rainfall (inches)	72-hour duration rainfall (inches) for selected annual exceedance probabilities[1]				
				0.20	**0.10**	**0.04**	**0.02**	**0.01**
Amboy, Minn.	Blue Earth	210157	10.68	4.06	4.77	5.67	6.43	7.08
Owatonna, Minn.	Steele	216287	7.91	4.06	4.77	5.67	6.43	7.08
Pipestone, Minn.	Pipestone	216565	5.75	3.96	4.57	5.50	5.93	7.13
Winnebago, Minn.	Faribault	219046	7.98	4.06	4.77	5.67	6.43	7.08
Zumbro Falls, Minn.	Wabasha	219231	8.50	4.35	4.97	5.74	6.30	6.83
Zumbrota, Minn.	Goodhue	219249	7.66	4.35	4.97	5.74	6.30	6.83

[1] The annual exceedance probability is the probability that a given event will be exceeded or equaled in any given year. For example, the annual exceedance probability of the 100-year rainfall is 0.01. In other words, there is a 1-percent chance that the rainfall would be exceeded or equaled in any given year.

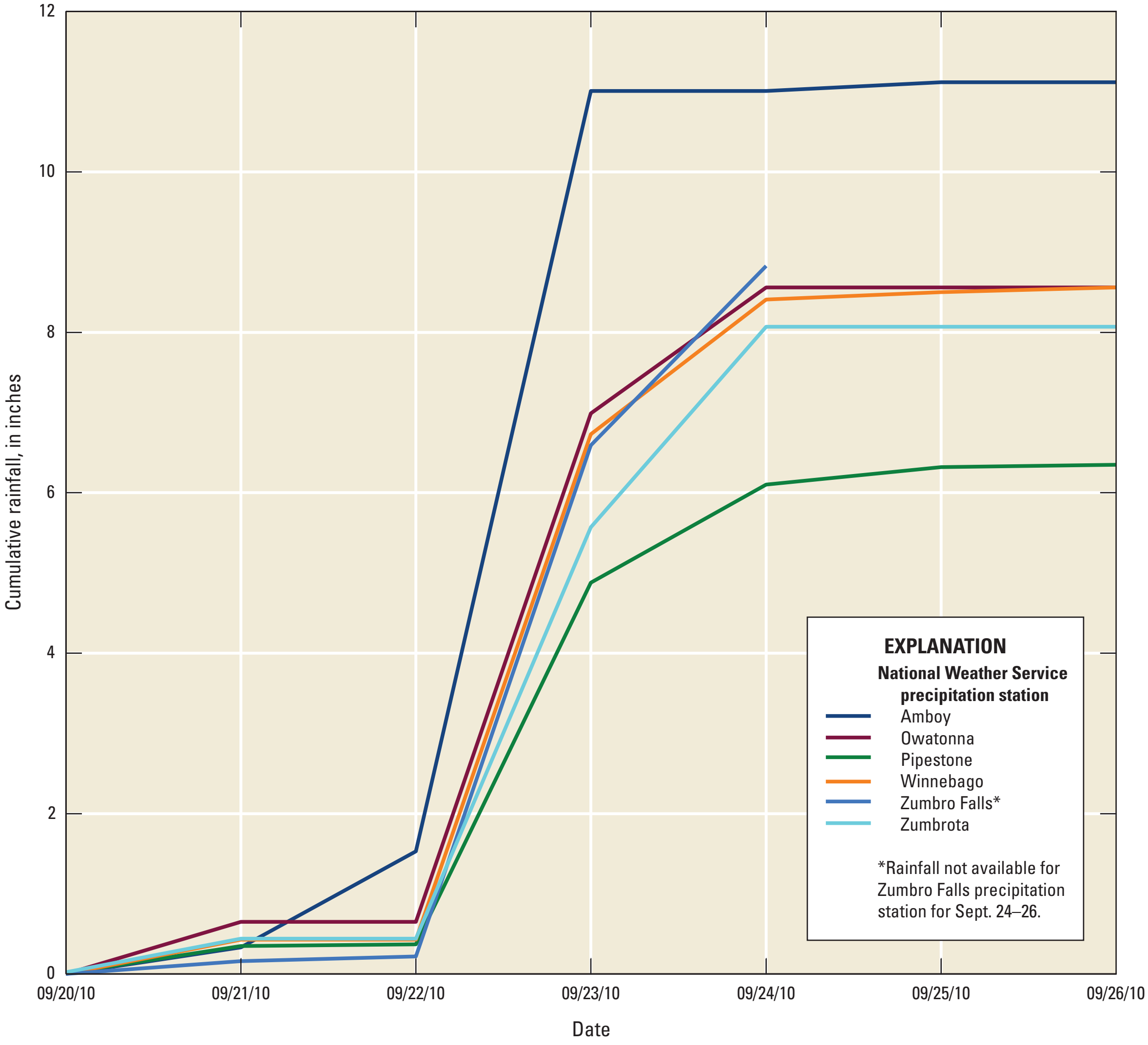


Figure 3. Cumulative daily rainfall for selected National Weather Service precipitation stations during September 20–26, 2010, in southern Minnesota.

Methods

The methods used to compute magnitudes and annual exceedance probabilities of peak streamflows and to collect high-water-mark data are described in this section of the report. Methods used to create flood-peak inundation maps and water-surface profiles also are described.

Computing the Magnitudes of Peak Streamflows

Peak streamflows documented in this study were determined at 27 USGS and 5 MDNR streamgages (fig. 4) by use of a stage-to-discharge rating curve (or rating curve, the relation between streamgage height and streamflow) unique to each streamgage. Stage-discharge relations at streamgages are developed by relating paired measurements of stage (gage height) and streamflow over the range of streamflows that occur. Paired measurements used to develop a rating are determined most commonly by direct measurement of stage (observed/recorded) and streamflow (velocity meter) at the streamgage (Rantz and others, 1982); or, if direct measurement is not possible, by indirect hydraulic methods (Benson and Dalrymple, 1967). The rating curve is developed using available stage/streamflow measurements and controlling hydraulic features of the channel. The rating curve can be extrapolated slightly beyond the highest measurement of stage/streamflow, depending on available information about channel geometry and hydraulic conditions.

Flood-peak gage heights were obtained either from electronic data recorders or from surveyed high-water marks near streamgages (where recorders or stage sensors malfunctioned or if streamgages were not available). For example, at the Zumbro River at Zumbro Falls, the USGS streamgage failed to record the flood-peak gage height after becoming inundated with water, so high-water marks near the streamgage were surveyed. The stage-discharge relation at each streamgage was used to compute peak streamflow from the flood-peak gage height. Direct or indirect streamflow measurements served as flood-event data points for rating-curve verification and extrapolation.

In cases where no nearby streamgages were available or if the equipment was damaged during a flood at a streamgage, one of three methods was used to compute peak streamflow: (1) the slope-area method, (2) the drainage-area ratio method, or (3) use of the Hydrologic Engineering Center River Analysis System (HEC–RAS) water-surface profile model (U.S. Army Corps of Engineers, 2010). For the Zumbro River at Zumbro Falls (USGS streamgage 05374000), where equipment was damaged, the slope-area method (Dalrymple and Benson, 1968) was used to measure peak streamflow. For Turtle Creek (USGS/MDNR streamgage 05352810/39054001), near the community of Owatonna, streamflow was computed by extrapolating the stage-discharge rating curve and using the slope-area method to compute the additional streamflow that had flooded over the roadway. In the slope-area method, streamflow is computed on the basis of a uniform-flow equation involving channel characteristics, water-surface profiles, and a roughness coefficient (Rantz and others, 1982). Computations were done with the USGS slope-area computation program (Fulford, 1995) and surveyed channel geometry and high-water-mark data.

Peak streamflow was estimated for the community of Faribault using the drainage-area ratio method (Ries, 2007). In addition to Faribault, peak streamflows for the communities of Oronoco, Hammond, and Millville also were estimated using this method. In the drainage-area ratio method, the streamflow of the ungaged site is estimated using streamflow from a streamgage or from streamflow that was measured upstream or downstream from the ungaged site and from the ratio between the drainage area of the ungaged site and the drainage area of the gaged site. Normally, the method is applied only if the drainage area ratio is between 0.5 and 1.5 (Ries, 2007), but the ratios can be set differently for each State if information is available to support changing them. The equation used to determine the drainage-area ratio estimates, modified from Ries (2007), is:

$$Q_u = (A_u / A_g)^b \text{ x } Q_g \tag{1}$$

where

Q_u is the estimated flow statistic for the ungaged site in **cubic feet per second**,

A_u is the drainage area for the ungaged site in square miles,

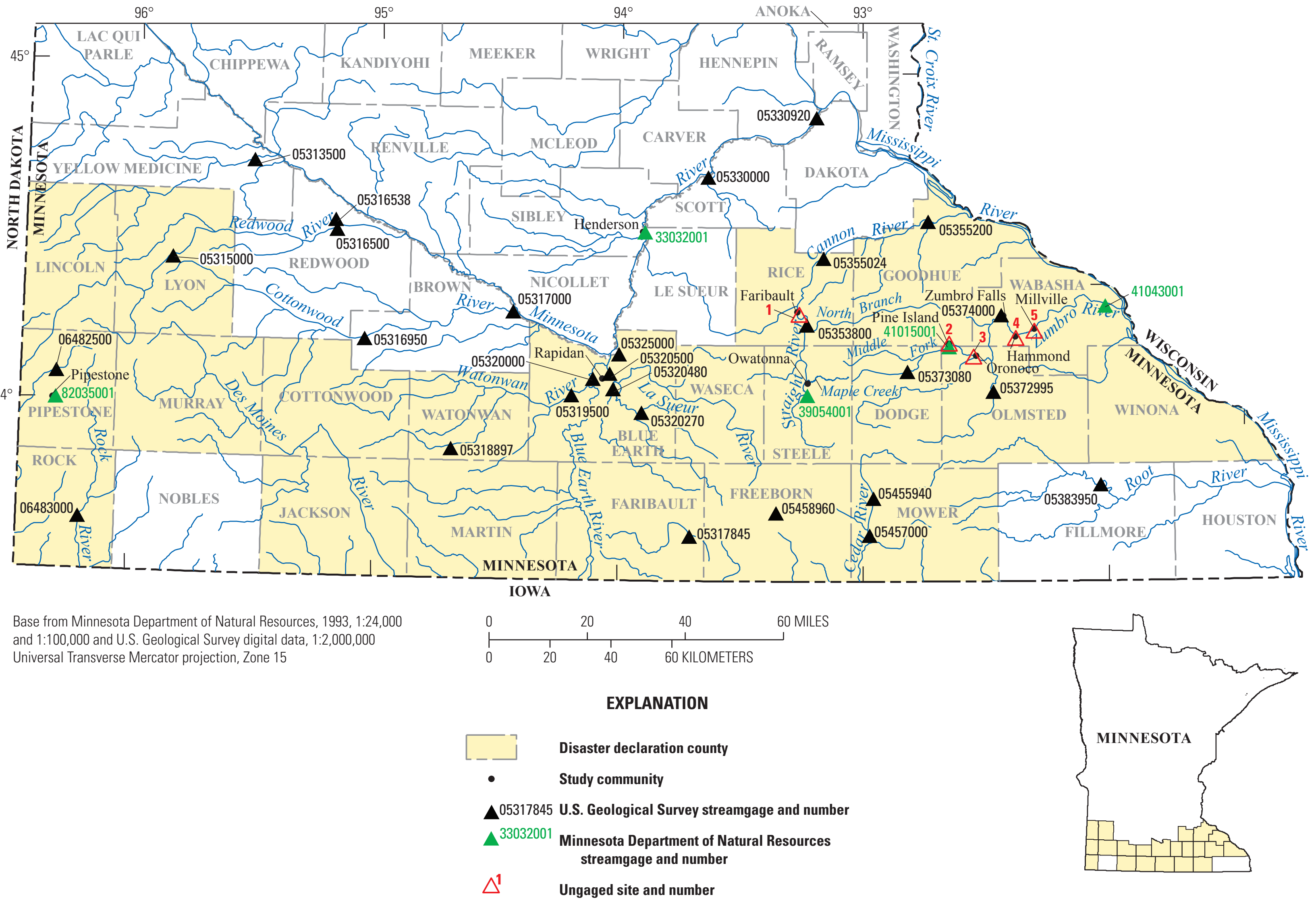
A_g is the drainage area for the upstream or downstream streamgage (or site upstream or downstream where streamflow was measured) in square miles,

Q_g is the streamflow for the streamgage (or site upstream or downstream where streamflow was measured) in cubic feet per second, and

b is the exponent of drainage area from the appropriate regression equation, or 1 where not defined.

A general description of the slope-area method can be found in Rantz and others (1982), and the drainage-area ratio method can be found in Ries (2007). Detailed descriptions can be found in Bodhaine (1968), Dalrymple and Benson (1968), Davidian (1984), and Matthai (1967). Because many factors associated with the indirect computation of streamflow (slope-area method and drainage-area ratio method) can have various levels of accuracy, and because the methods can depend considerably on engineering judgment, estimates may have large errors associated with them (Rantz and others, 1982; Ries, 2007).

For the community of Pine Island, streamflow was computed for the North Branch and the Middle Fork Zumbro River by the MDNR using the HEC–RAS version 4.1 water-surface profile model (U.S. Army Corps of Engineers, 2010). The steady-flow component of the modeling system was used to



Base from Minnesota Department of Natural Resources, 1993, 1:24,000
and 1:100,000 and U.S. Geological Survey digital data, 1:2,000,000
Universal Transverse Mercator projection, Zone 15

Figure 4. Locations of selected U.S. Geological Survey and Minnesota Department of Natural Resources streamgages and ungaged sites.

calculate water-surface elevations for steady gradually varied flow for a range of streamflows. A stage-discharge rating curve then was plotted using the computed elevations for the range of streamflows. Using this rating curve for a given stage, the computed peak streamflow was determined from known elevations/stages at the height of flooding.

Estimating Annual Exceedance Probabilities of Peak Streamflows

The annual exceedance probability for a particular streamflow is the probability of that streamflow being equaled or exceeded in any given year. For example, a probability of 0.01 means there is a 1-percent chance of that streamflow magnitude being equaled or exceeded in any given year. The traditional concept of **recurrence interval** is related directly to the annual exceedance probability. By definition, the recurrence interval corresponding to a particular annual exceedance probability is equal to 1 divided by the annual exceedance probability (American Society of Civil Engineers, 1953; Hodgkins and others, 2007). For example, the annual exceedance probability of 0.01 corresponds to the 100-year flood or 100-year recurrence interval.

Annual exceedance probabilities associated with peak streamflows for 32 active streamgages and 5 ungaged locations were estimated to indicate the relative magnitude of the September 2010 floods. Streamflows for selected annual exceedance probabilities (0.10, 0.04, 0.02, 0.01, and 0.002) were estimated by using one of three methods: (1) the procedure presented by the Interagency Advisory Committee on Water Data (1982), commonly called the Bulletin 17B procedure, (2) regional regression equations for rural conditions (Lorenz and others, 2009), or (3) the Expected Moments Algorithm (Cohn and others, 1997). Users of the Bulletin 17B procedure and regional regression equations for rural conditions calculate flood probabilities by fitting systematic annual peak-streamflow data to a log-Pearson type III (LPIII) distribution. The Expected Moments Algorithm is a generalization of the procedures in Bulletin 17B and was designed to better accommodate historical peak-flow data (known peak flows outside the period of continuous streamflow data collection) and left-censored data (peak flows less than what can be measured at the streamgage).

Streamflow magnitudes associated with selected annual exceedance probabilities then can be used to estimate the range of annual exceedance probabilities for a particular flood. The upper and lower bounds for the range of probabilities are determined by comparing a particular peak streamflow (in this case, the peak streamflow from the 2010 flood) directly to streamflow magnitudes associated with the selected annual exceedance probabilities.

Collection of High-Water-Mark Data

High-water marks were identified and flagged by the USGS and MDNR in the four communities of Faribault, Owatonna, Pine Island, and Zumbro Falls along six streams: North Branch, Middle Fork Zumbro River, Zumbro River, Cannon River, Straight River, and Maple Creek (fig. 1, appendix 1). The high-water marks were identified and flagged during October and November 2010 after floodwaters receded. High-water marks were identified and flagged on both sides of each stream at spacings of approximately 500 to 1,000 feet (ft), in accordance with standard USGS methods (Benson and Dalrymple, 1967). Commonly, stain lines on buildings, trees, or other structures were used to identify the highest level reached by the flooding waters. High-water marks were mapped and photographed, and site diagrams with associated information were recorded. The quality of the high-water marks was subjectively rated in the field as excellent, good, fair, or poor by the high-water-mark crews. Ratings were based on the clarity of the mark and visual or hand-level comparison to nearby marks.

High-water marks were surveyed during November using a Real-Time Kinematic Global Positioning System (RTK–GPS). Quality-assurance procedures included setting up the RTK–GPS base station at a high location (roof of county court house, municipal building, school, and so forth) for maximum satellite reception and radio coverage, and locating a minimum of two control points with multiple repeated readings (Vertical Second Order Class I; preferred) (Fitzpatrick and others, 2008). The preferred method of surveying a high-water mark was to set the RTK–GPS rover on the high-water mark and collect fixed-point data. If tree cover or building interference did not allow a fixed solution on the high-water mark, data for an intermediate survey point were collected a short distance away. In this case, the elevation of the desired high-water mark was determined by extending the elevation of the high-water mark to the intermediate survey point by using a hand level or string level. The difference in horizontal position between the intermediate point and the desired high-water mark was entered into the RTK–GPS unit using an estimated **azimuth** and distance to adjust the surveyed intermediate horizontal position to the actual high-water mark. The high-water marks were surveyed to an expected accuracy of 0.1 ft. The datum used was the North American Vertical Datum of 1988 (NAVD 88). High-water-mark descriptions, locations (latitude and longitude), and quality ratings are presented in appendix 1.

Flood-Peak Inundation Maps

Flood-peak inundation maps were produced by use of geographic information system (GIS) software and associated programs (Morlock and others, 2008; Fitzpatrick and others, 2008; Fowler and others, 2010). These maps show the maximum extent of floodwaters in and around a community. GIS layers of the high-water-mark elevations (NAVD 88) and locations (latitude and longitude) in North American Datum of 1983 (NAD 83) were used in conjunction with **LiDAR**-based 1-meter land-surface elevation data files. LiDAR, an acronym for "light detection and ranging," is remote sensing technology that is based on discrete light pulses and measured travel times. It is used to generate highly accurate three-dimensional representations of the Earth's surface, termed "digital elevation models" (DEMs) (National Oceanic and Atmospheric Administration, 2008). These DEMs were used to develop the inundation maps, which then were superimposed on the corresponding National Agricultural Imagery Program aerial imagery (U.S. Department of Agriculture, 2009).

A GIS application was used to produce a plane representing the flood-peak water surface. The application duplicates the high-water-mark elevation data points across the **flood plain** perpendicular to the direction of the flood flow (Moon Kim, U.S. Geological Survey, written commun., January 2011). Elevations between high-water marks are proportional interpolations of the high-water-mark data and were positioned to generate a flood surface sloping with the water flow. A triangular irregular network (TIN) surface was created with the data points (TIN-generated surfaces pass exactly through the data-point elevations), forming the estimated flood surface. The flood-peak inundation areas are available in a GIS format that provides the extent of the flood peak. This format allows the GIS data to be overlain on maps and aerial photographs, and to be used for various GIS applications, such as FEMA's Hazards U.S. Multi-Hazards (HAZUS–MH) program (Federal Emergency Management Agency, 2010b) to estimate flood damages.

Flood-Peak Water-Surface Profiles

Standard USGS methods were used to develop flood-peak water-surface profiles from the high-water-mark elevations and locations (Benson and Dalrymple, 1967; Lumia and others, 1986). Flood profiles were produced for seven stream reaches by plotting high-water-mark elevations by mile of stream as measured upstream on the centerline of the **thalweg** from the downstream boundary of each study reach. The water surface between high-water marks was estimated by linear interpolation. A linear interpolation between high-water marks is an approximation of the actual water surface. The river-mile location of the high-water marks was calculated by the GIS-based programs.

Floods of September 2010 in Southern Minnesota

The magnitudes and estimated annual exceedance probabilities of peak streamflows for the floods of September 2010 are presented in this section of the report. Flood-peak inundation maps and flood-peak water-surface profiles also are presented.

Magnitudes and Estimated Annual Exceedance Probabilities of Peak Streamflows

The magnitudes (flood-peak gage-height data and peak-streamflow data) and estimated annual exceedance probabilities from the September 2010 floods are presented for 32 active streamgages (table 2) and 5 ungaged sites (table 3). Locations of streamgages and ungaged sites are shown in figure 4. New peak-of-record streamflows were observed at 12 active streamgages. Most streams rose and fell rapidly beginning on September 23 (fig. 5). Large streams took longer to peak; the Straight River near Faribault peaked on September 24, whereas the Minnesota River near Jordan peaked on September 30. For 3 of the 31 active streamgages (USGS streamgage 05330920, USGS/MDNR streamgage 05326450/33032001, and MDNR streamgage 82035001), annual exceedance probabilities could not be estimated using the Bulletin 17B procedure or from regional regression equations either because the period of record was less than the minimum required 10 years of peak-flow data or because one or more basin characteristics were beyond the range used for development of models from regression analysis (Lorenz and others, 2009). For two USGS streamgages (05383950 and 05455940) and five ungaged sites, annual exceedance probabilities were obtained by use of regional regression equations for rural conditions (Lorenz and others, 2009). For two USGS streamgages (05318897 and 05355024), annual exceedance probabilities were determined by use of the Expected Moments Algorithm (Cohn and others, 1997). For the streamgages and ungaged sites where annual exceedance probabilities could be computed (34 of 37 sites), the estimated annual exceedance probabilities were less than 0.2 percent for 7 streamgages, and between 0.2 and 1 percent for 9 locations (5 streamgages and 4 ungaged sites; tables 2 and 3).

Table 2. Flood-peak gage heights, peak streamflows, and annual exceedance probabilities of peak streamflows during the floods of September 2010 at selected U.S. Geological Survey and Minnesota Department of Natural Resources streamgages in Minnesota.

[mi^2, square miles; ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; ft^3/s, cubic feet per second; %, percent; USGS, U.S. Geological Survey; >, greater than; <, less than; MDNR, Minnesota Department of Natural Resources; --, data not available]

Streamgage number (shown on fig. 4)	Stream and community	Agency	Drainage area (mi^2)	Gage vertical datum (ft, NGVD 29)	Period of record (water years)[1]	Length of record of annual peaks (years)
05313500	Yellow Medicine River near Granite Falls, Minn.	USGS	664	961.20	1931–38, 1940–2010	79
05315000	Redwood River near Marshall, Minn.	USGS	259	1,188.23	1940–2010	71
05316500	Redwood River near Redwood Falls, Minn.	USGS	629	972.33	1910–14, 1931–2010	85
[5]05316538	Ramsey Creek near Redwood Falls, Minn.	USGS	64	Undetermined[6]	1991–93, 1995–2010	19
[5]05316950	Cottonwood River near Springfield, Minn.	USGS	777	1,000.00	1969, 1973–2010	38
05317000	Cottonwood River near New Ulm, Minn.	USGS	1,300	796.83	1910–13, 1931–2010	84
[5]05317845	East Branch Blue Earth River near Walters, Minn.	USGS	30	Undetermined[6]	1979–2010	32
[5]05318897	South Fork Watonwan River near Ormsby, Minn.	USGS	107	Undetermined[6]	1979–2010	32
05319500	Watonwan River near Garden City, Minn.	USGS	851	905.05	1940–45, 1953, 1965, 1969, 1977–2010	43
05320000	Blue Earth River near Rapidan, Minn.	USGS	2,410	808.80	1910, 1912–46, 1948, 1950–2010	98
05320270	Little Cobb River near Beauford, Minn.	USGS	130	975.00	1996–99, 2001–10	14
[5]05320480	Maple River near Rapidan, Minn.	USGS	338	838.27	1972–2010	39
05320500	Le Sueur River near Rapidan, Minn.	USGS	1,110	775.76	1940–45, 1949–2010	68
05325000	Minnesota River at Mankato, Minn.	USGS	14,900	747.92	1903–2010	108
05326450/ [9]33032001	Minnesota River at Henderson, Minn.	USGS/ MDNR	15,800	700.00	2010	1
05330000	Minnesota River near Jordan, Minn.	USGS	16,200	690.00	1935–2010	76
05330920	Minnesota River at Fort Snelling, Minn.	USGS	16,900	680.00	2004–10	7
05352810/ [9]39054001	Turtle Creek near Owatonna, Minn.	USGS/ MDNR	40	Undetermined[6]	2009–10	2
05353800	Straight River near Faribault, Minn.	USGS	435	1,034.58	1966–78, 1980–2010	44
[5]05355024	Cannon River at Northfield, Minn.	USGS	929	902.79	1980–2010	31
05355200	Cannon River at Welch, Minn.	USGS	1,340	699.16	1911–13, 1931–87, 1992–2010	80
05372995	South Fork Zumbro River at Rochester, Minn.	USGS	303	950.00	1951–2010	60
[5]05373080	Milliken Creek near Concord, Minn.	USGS	22	Undetermined[6]	1979–2010	32

Peak flow for period of record prior to September 2010			Peak flow for September 2010			Annual exceedance probability[2] for September 2010 peak streamflow	Estimated streamflow of .01 (1%) annual exceedance probability
Date	Gage height (feet above gage datum)	Streamflow (ft^3/s)	Date	Gage height (feet above gage datum)	Streamflow (ft^3/s)		
4/10/1969	14.90	17,200	9/28/2010	9.42	6,070	0.04–0.10	[3]13,000
5/9/1993	17.00	[4]6,380	9/25/2010	17.09	4,580	0.02–0.04	[3]6,480
6/18/1957	15.92	19,700	9/27/2010	12.97	8,000	0.04–0.10	[3]15,300
6/17/1993	25.94	920	9/24/2010	24.41	800	>0.10	[3]1,550
4/8/1969	31.55	18,300	9/24/2010	32.89	12,100	0.04–0.10	[3]20,000
4/10/1969	19.15	28,700	9/26/2010	18.95	19,600	0.02–0.04	[3]27,400
9/15/2004	20.54	1,440	9/23/2010	18.28	747	0.04–0.10	[3]966
9/26/2005	18.25	2,360	9/24/2010	19.93	[7]3,180	0.02–0.04	[8]4,240
4/7/1965	18.89	19,000	9/25/2010	18.01	16,100	0.005–0.01	[3]15,200
4/9/1965	21.36	43,100	9/26/2010	15.97	27,000	0.01–0.02	[3]30,000
9/18/2004	11.93	1,630	9/25/2010	16.00	[7]5,300	<0.002	[3]2,000
4/12/2001	13.79	5,540	9/24/2010	18.30	[7]12,800	<0.002	[3]6,320
4/8/1965	22.10	24,700	9/26/2010	21.35	[7]30,500	0.002–0.005	[3]21,800
4/10/1965	29.09	94,100	9/27/2010	28.25	84,600	0.005–0.01	[3]79,200
--	--	--	9/28/2010	40.08	72,000	Undetermined[10]	Undetermined[10]
4/11/1965	33.89	117,000	9/30/2010	33.07	74,700	0.01–0.02	[3]84,800
3/24/2010	706.78	68,900	10/2/2010	705.57	65,300	Undetermined[10]	Undetermined[10]
--	--	--	9/24/2010	15.20	[7, 11]5,400	<0.002	[3]3,500
6/12/2004	11.31	6,080	9/24/2010	14.88	[7]12,200	<0.002	[3]8,360
4/12/2001	905.40	8,370	9/24/2010	907.59	[7]16,600	<0.002	[8]12,400
4/8/1965	14.01	36,100	9/25/2010	14.37	20,500	0.02–0.04	[3]25,200
7/6/1978	[12]23.36	30,500	9/24/2010	17.08	12,100	0.04–0.10	[3]26,900
6/13/2001	15.80	4,080	9/23/2010	15.95	[7]4,620	0.01–0.02	[3]5,700

Table 2. Flood-peak gage heights, peak streamflows, and annual exceedance probabilities of peak streamflows during the floods of September 2010 at selected U.S. Geological Survey (USGS) and Minnesota Department of Natural Resources (MDNR) streamgages in Minnesota.—Continued

[mi², square miles; ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; ft³/s, cubic feet per second; >, greater than; <, less than; %, percent; USGS, U.S. Geological Survey; MDNR, Minnesota Department of natural Resources; --, data not available]

Streamgage number (shown on fig. 4)	Stream and community	Agency	Drainage area (mi²)	Gage vertical datum (ft, NGVD 29)	Period of record (water years)[1]	Length of record of annual peaks (years)
41015001	Middle Fork Zumbro River at Pine Island, Minn.	MDNR	128	1,005.72	2007–08, 2010	2
[5]05374000	Zumbro River at Zumbro Falls, Minn.	USGS	1,150	811.26	1910–17, 1930–80, 1985–88, 1990–2010	85
05374900/ [15]41043001	Zumbro River at Kellogg, Minn.	USGS/ MDNR	1,400	669.47	1976–90, 2009–10	17
05383950	Root River near Pilot Mound, Minn.	USGS	565	Undetermined[6]	2003–2010	8
[5]05455940	Cedar River at Lansing, Minn.	USGS	160	Undetermined[6]	2007–2010	4
05457000	Cedar River near Austin, Minn.	USGS	399	1,162.10	1910–14, 1945–2010	71
[5]05458960	Bancroft Creek at Bancroft, Minn.	USGS	29	1,240.00	1986–2010	25
[9]82035001	Pipestone Creek at Pipestone, Minn.	MDNR	30	1,697.23	1999–2006, 2010	8
[5]06483000	Rock River at Luverne, Minn.	USGS	419	Undetermined[6]	1912–14, 1969, 1972–2001, 2003–10	42

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

[2] The annual exceedance probability is the probability that a given event magnitude will be equaled or exceeded in any given year and is the reciprocal of the recurrence interval. The recurrence interval is the average interval of time within which the given flood will be equaled or exceeded once (American Society of Civil Engineers, 1953, p. 1,221). The annual exceedance probability for a recurrence interval of 10 years is 0.10 (10%); for 25 years, 0.04 (4%); for 50 years, 0.02 (2%); for 100 years, 0.01 (1%); 200 years, 0.005 (0.5%) and 500 years 0.002 (0.2%).

[3] Streamflow computed from Bulletin 17B (Interagency Advisory Committee on Water Data, 1982).

[4] Streamflow affected to unknown degree by regulation or diversion.

[5] U.S. Geological Survey crest-stage or peak-stage gage.

[6] Elevation from vertical datum has not been established.

[7] New streamflow peak stage of record.

[8] Streamflow computed from Expected Moments Algorithm (Cohn and others, 1997).

[9] Minnesota Department of Natural Resources streamgage. Streamgage was installed by USGS technicians for the MDNR streamgage program and was assigned a USGS streamgage number.

[10] Recurrence-interval flows have not been established. One or more basin characteristics are beyond the range used for development of models from regression analysis.

[11] Streamflow computed using the slope-area method (Dalrymple and Benson, 1968).

[12] Gage height at different site and (or) datum.

[13] Streamflow computed by using Hydrologic Engineering Center River Analysis System water-surface profile model (U.S. Army Corps of Engineers, 2010).

[14] Streamflow from regional regression equations in Lorenz and others (2009).

[15] Minnesota Department of Natural Resources streamgage from 2009–10.

[16] Streamflow is an estimate.

Peak flow for period of record prior to September 2010			Peak flow for September 2010			Annual exceedance probability[2] for September 2010 peak streamflow	Estimated streamflow of .01 (1%) annual exceedance probability
Date	Gage height (feet above gage datum)	Streamflow (ft³/s)	Date	Gage height (feet above gage datum)	Streamflow (ft³/s)		
--	--	--	9/23/2010	23.45	[13]13,500	0.002–0.01	[14]11,300
7/22/1951	30.80	35,900	9/24/2010	35.82	[7, 11]53,000	<0.002	[3]33,900
9/23/1986	16.07	22,300	9/25/2010	691.25	[7]54,900	<0.002	[3]26,300
9/16/2004	23.85	21,900	9/24/2010	19.40	12,900	>0.10	[14]43,100
6/12/2008	20.55	8,660	9/24/2010	20.99	[7]9,950	0.002–0.01	[14]7,410
9/16/2004	23.26	20,000	9/24/2010	19.83	12,900	0.02–0.04	[3]17,000
6/14/2001	8.81	1,070	9/23/2010	8.34	964	0.04–0.10	[3]1,460
3/15/2010	17.85	607	9/24/2010	21.37	[7]1,630	Undetermined[10]	Undetermined[10]
5/8/1993	14.20	[16]35,400	9/24/2010	12.69	14,700	0.02–0.04	[3]26,500

Table 3. Peak streamflows and estimated annual exceedance probabilities during the floods of September 2010, at selected ungaged locations in Minnesota.

[mi^2, square miles; ft^3/s, cubic feet per second; <, less than; %, percent; --, none]

Site number (shown on fig. 4)	Stream and community	County	Drainage area at site (mi^2)	Peak flow (ft^3/s) for given annual exceedance probability[1]				Peak flow during September flood		
				0.10	0.04	0.02	0.01	Peak flow (ft^3/s)	Estimated annual exceedance probability[1]	Comment
1	Straight River at Faribault, Minn.	Rice	460	[2]5,650	[2]8,140	[2]10,300	[2]12,700	[3]12,900	<0.01	Peak flow 2% greater than 100-year flood.
2	North Branch River at Pine Island, Minn.	Goodhue	58	[2]3,460	[2]4,760	[2]5,790	[2]6,930	[4]6,500	0.01–0.02	--
3	Middle Fork Zumbro River at Oronoco, Minn.	Olmsted	206	[2]7,580	[2]10,400	[2]12,600	[2]15,100	[3]21,700	<0.01	Peak flow 44% greater than 100-year flood.
4	Zumbro River at Hammond, Minn.	Wabasha	1,160	[2]21,400	[2]29,000	[2]34,700	[2]40,900	[3]52,000	<0.01	Peak flow 27% greater than 100-year flood.
5	Zumbro River at Millville, Minn.	Wabasha	1,200	[2]21,900	[2]29,600	[2]35,400	[2]41,800	[3]53,800	<0.01	Peak flow 29% greater than 100-year flood.

[1] The annual exceedance probability is the probability that a given event magnitude will be equaled or exceeded in any given year (the reciprocal of the recurrence interval). The recurrence interval is the average interval of time within which the given flood will be equaled or exceeded once (American Society of Civil Engineers, 1953, p. 1,221). The annual exceedance probability for a recurrence interval of 10 years is 0.10 (10%); for 25 years, 0.04 (4%); for 50 years, 0.02 (2%); and for 100 years, 0.01 (1%).

[2] Streamflow from Lorenz and others (2009).

[3] Streamflow estimated using drainage-area ratio method (Ries, 2007).

[4] Streamflow computed using Hydrologic Engineering Center River Analysis System water-surface profile model (U.S. Army Corps of Engineers, 2010).

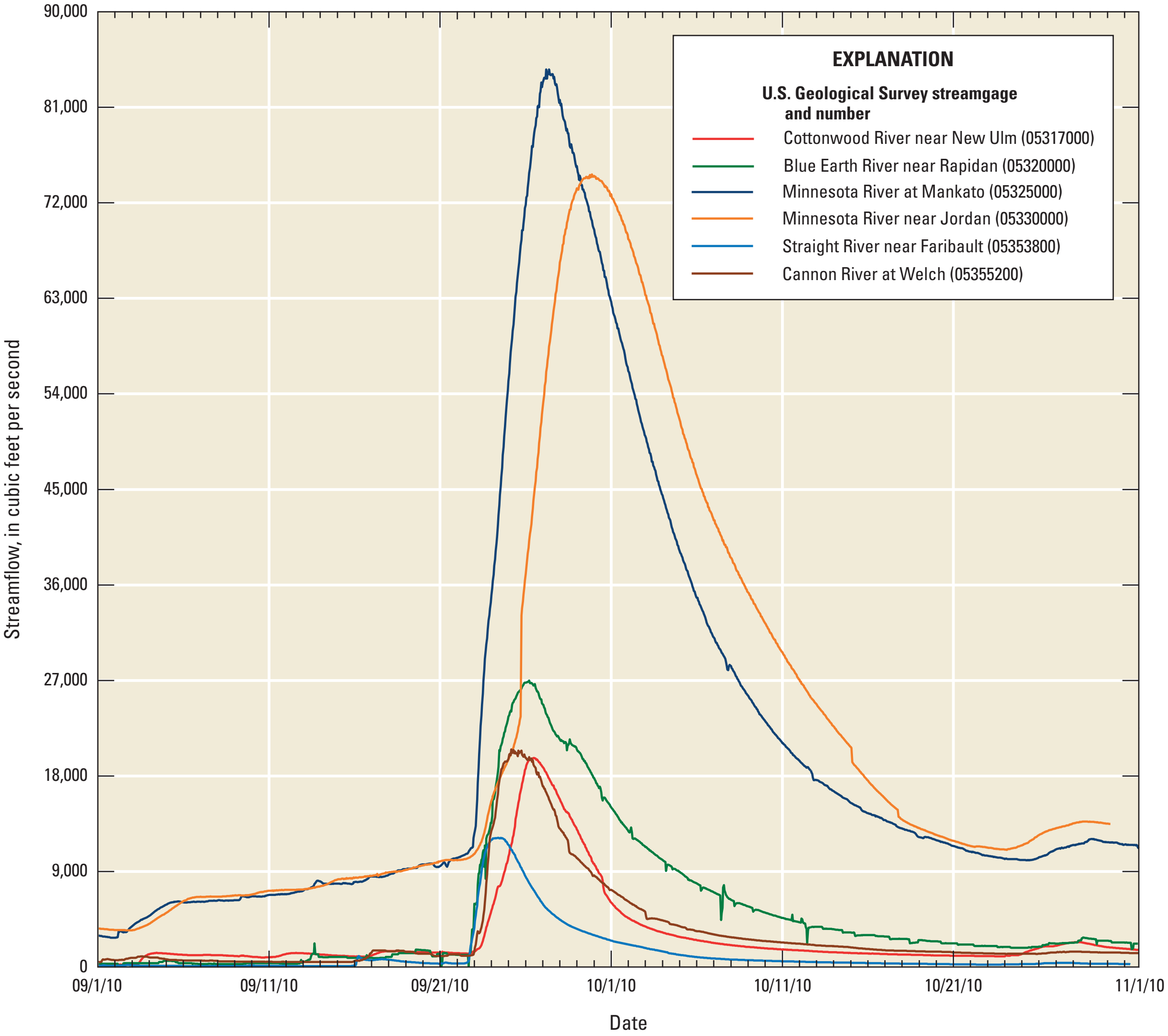


Figure 5. Hydrographs showing selected U.S. Geological Survey streamgages in southern Minnesota for September through October 2010 (locations of streamgages shown on figure 4).

Flood-Peak Inundation Maps and Water-Surface Profiles

Flood-peak inundation maps and flood-peak water-surface profiles were produced for the four communities of Faribault (Cannon and Straight Rivers), Owatonna (Straight River and Maple Creek), Pine Island (North Branch and Middle Fork Zumbro River), and Zumbro Falls (Zumbro River). Personnel from the USGS and MDNR flagged and surveyed 43 high-water marks along a total of 11 stream miles in October and November 2010 in the four most severely affected communities. A descriptive table of high-water marks used in the inundation mapping is listed in appendix 1.

A flood-peak inundation map was generated for each community showing the maximum extent and height of floodwaters in and around the community; the four maps are presented in appendix 2. Inundation maps also contain locations and elevations of high-water marks used to develop the map. The maps were checked by USGS surveying and high-water-mark personnel, and the high-water marks were compared spatially to check for mathematical or other errors. If a data point was too high or too low when compared to neighboring points, the point in question was removed from the inundation map. For example, high-water marks PI1 and PI7 (appendix 1) in the community of Pine Island were removed from the inundation map because they did not compare well spatially with high-water mark PI2. High-water mark PI2 was a well-defined seed line and was rated good quality by field personnel. In contrast, PI1 was based on a homeowner's recollection of the high-water mark, and PI7 was based on a debris line; both received poor quality ratings by field personnel.

Seven flood-peak water-surface profiles are provided in appendix 3. Flood-peak profiles show how the flood-peak inundation surface and slope varied along the stream reach through each of the four communities. Locations of street crossings and important landmarks were added to the profiles to provide additional context.

Description of Flood Damages and Effects

Heavy rainfall on a landscape already wet from antecedent conditions caused widespread record flooding in southern Minnesota in September 2010. Power outages, evacuations, and major transportation disruptions affected thousands of southern Minnesota residents and caused damage in excess of 64 million dollars to homes, businesses, and infrastructure (Bruce Gordon, Minnesota Department of Public Safety, written commun., February 2011).

Flooding was most extensive in the communities of Faribault, Owatonna, Pine Island, and Zumbro Falls as local rivers, creeks, and ditches rose rapidly during September 22 through 25, 2010. In addition to these communities, but to a lesser degree, the communities of Hammond, Henderson, Millville, Oronoco, Pipestone, and Rapidan (fig. 1) also had extensive flooding and damages. Zumbro Falls, a town with a population of 177 located adjacent to the Zumbro River, was inundated by record streamflow in the early hours of September 25. The previous records for stage and streamflow, set in 1951 for the Zumbro River at Zumbro Falls (streamgage 05374000; fig. 4), with a river stage of 30.8 ft and associated streamflow of 35,900 cubic feet per second (ft^3/s), were exceeded by 5 ft in stage (35.82 ft) and more than 17,000 cubic feet per second (53,000 ft^3/s) in streamflow (table 2). The annual exceedance probability for the 2010 flood at this streamgage was less than 0.2 percent (greater than a 500-year recurrence interval). In the downtown area of Zumbro Falls, 58 homes and 20 of the 26 businesses were classified as destroyed. Downstream from Zumbro Falls, the banks of the Zumbro River suffered massive bank failure at Kellogg (USGS/MDNR streamgage 05374900/41043001; fig. 4, table 2), endangering several homes when 40 ft of nearby homeowners' yards eroded away when the saturated banks collapsed. The community of Pine Island also experienced major flooding. In Pine Island, more than 100 homes were affected, with damage varying from water in basements to water over the main floor structure. Additionally, more than 20 businesses were damaged and numerous roads and culverts were washed out.

In southwestern Minnesota, Pipestone Creek at Pipestone (MDNR streamgage 82035001), peaked on September 24 at stages and streamflow that exceeded the previous records (table 2). The city's wastewater system was overwhelmed with water. At the height of the flood, the city's main lift station was pumping 3,000 gallons of water per minute, compared to 1,100 gallons per minute during typical operations (Pipestone County Star Online, 2010). The communities of Faribault and Owatonna on the Straight River also had record streamflows. Upstream from Faribault, the Straight River (USGS streamgage 05353800) peaked on September 24 at approximately twice the previous record streamflow (12,200 ft^3/s on September 24, 2010, compared to 6,080 ft^3/s on June 12, 2004) (table 2). Streamflow on the Straight River near Faribault had an annual exceedance probability of less than 0.2 percent. Farther upstream from Faribault on the Straight River, the community of Owatonna also received extensive flooding. More than 200 homes around Owatonna were evacuated or affected by the flooding and more than 70 county roads and city streets were closed at the height of flooding (Minnesota State Emergency Operations Center, 2010).

The following is a summary of damage assessment compiled after September 2010:

- More than 600 dwellings were affected with 101 properties suffering major damage, 280 suffering minor damage, and 80 properties classified as destroyed (Bruce Gordon, Minnesota Department of Public Safety, written commun., February 2011).
- The Shady Lake Dam failed in Olmsted County near the town of Oronoco (Minnesota State Emergency Operations Center, 2010).
- More than 200 evacuations and water rescues were made during the flooding.
- More than 100 Minnesota National Guard Soldiers and Airmen supported relief missions.
- More than 360 Red Cross Staff and volunteers provided 242 overnight stays at 11 shelters, distributed approximately 2,400 clean-up kits, and provided more than 23,000 meals to residents, emergency workers, and clean-up volunteers; donations from the Red Cross were estimated at more than 800 thousand dollars (American Red Cross Southeast Minnesota Chapter, 2010).
- Food and drinking-water distribution points were set up in the affected counties.
- Levee damage occurred along the Blue Earth River in Mankato (Blue Earth County) (Minnesota State Emergency Operations Center, 2010).
- Main electric transmission lines were damaged.
- Transportation disruptions were widespread. Highway 169 (Blue Earth County) between Mankato and Henderson was closed for 2 weeks because of high water and road damage. In Steele County, more than 70 county roads and city streets were closed at the height of flooding (Minnesota State Emergency Operations Center, 2010).

- Ten school districts reported flood-related facility damage totaling an estimated 960 thousand dollars (Minnesota State Emergency Operations Center, 2010).

On October 13, 2010, President Obama declared that a major disaster existed in southern Minnesota (Federal Emergency Management Agency, 2010a). The disaster declaration brought much needed additional assistance for residents and businesses. This declaration made Public Assistance requested by the Governor available to State and eligible local governments, and certain private nonprofit organizations on a cost-sharing basis for emergency work and the repair or replacement of facilities damaged by the severe flooding in Blue Earth, Cottonwood, Dodge, Faribault, Freeborn, Goodhue, Jackson, Lincoln, Lyon, Martin, Mower, Murray, Olmsted, Pipestone, Rice, Rock, Steele, Wabasha, Waseca, Watonwan, and Winona Counties. Direct Federal assistance also was authorized. Finally, this declaration made Hazard Mitigation Grant Program assistance requested by the Governor available for hazard-mitigation measures statewide.

Summary

During September 22–24, 2010, heavy rainfall ranging from 3 inches to more than 10 inches caused severe flooding across southern Minnesota. The floods were exacerbated by wet antecedent conditions, where summer rainfall totals were as high as 20 inches, exceeding the historical average by more than 4 inches. Widespread flooding that occurred as a result of the heavy rainfall caused evacuations of hundreds of residents, and damages in excess of 64 million dollars to residences, businesses, and infrastructure. In all, 21 counties in southern Minnesota were declared Federal disaster areas.

The 72-hour rainfall amounts in September 2010 had an annual exceedance probability of less than 1 percent (recurrence interval greater than 100 years) at several National Weather Service precipitation stations. Given the severity of the flooding, the U.S. Geological Survey (USGS), in cooperation with the Federal Emergency Management Agency and the Minnesota Department of Natural Resources (MDNR), Division of Ecological and Water Resources, conducted a study to document the meteorological and hydrological conditions leading to the flood; compile flood-peak gage heights, streamflows, and annual exceedance probabilities at selected USGS and MDNR streamgages and ungaged sites; construct flood-peak inundation maps and flood-peak water-surface profiles; and summarize flood damages and effects.

Peak-of-record streamflows were recorded at nine USGS and three MDNR streamgages as a result of the heavy rainfall. Flood-peak gage heights, peak streamflows, and annual exceedance probabilities were tabulated for 27 USGS and 5 MDNR streamgages and 5 ungaged sites. Flood-peak streamflows had annual exceedance probabilities estimated to be less than 0.2 percent (recurrence interval greater than 500 years) at 7 streamgages and less than 1 percent (recurrence interval greater than 100 years) at 5 streamgages and 4 ungaged sites. The USGS and MDNR flagged and surveyed 43 high-water marks along a total of 11 stream miles in October and November 2010 in 4 communities of Faribault along the Cannon and Straight Rivers, Owatonna along the Straight River and Maple Creek, Pine Island along the North Branch and Middle Fork Zumbro River, and Zumbro Falls along the Zumbro River. The nearby communities of Hammond, Henderson, Millville, Oronoco, Pipestone, and Rapidan also received extensive flooding and damage but were not surveyed for high-water marks.

Flood-peak inundation maps and water-surface profiles for the four most severely affected communities were constructed in a geographic information system by combining high-water-mark data with the highest resolution digital elevation model data available. The flood maps and profiles show the extent and height of flooding through the communities and can be used for flood response and recovery efforts by local, county, State, and Federal agencies.

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Glossary

The following definitions, except where otherwise noted, are from Langbein and Iseri (1960).

annual exceedance probability The probability that a given event magnitude will be exceeded or equaled in any given year. The annual exceedance probability is directly related to the recurrence interval. For example, there is a 1-percent chance that the 100-year peak flow will be exceeded or equaled in any given year. A flood probability of 0.01 has a recurrence interval of 100 years. The recurrence interval corresponding to a particular flood probability is equal to one divided by the flood probability.

azimuth The angle measured on the horizon between the meridian (north-south line) and the plane of the vertical circle through a celestial body (typically Polaris or Ursae Minoris in the northern hemisphere) or other object (Bureau of Land Management, 2011).

cubic feet per second A unit expressing rates of discharge. One cubic foot per second is equal to the discharge of a stream of rectangular cross section, 1 foot wide and 1 foot deep, flowing water an average velocity of 1 foot per second.

flood peak The highest value of the stage or discharge attained by a flood; thus, peak stage or peak discharge. “Flood crest” has nearly the same meaning, but because it connotes the top of the flood wave, it is properly used only in referring to stage—thus, “crest stage,” but not “crest discharge.”

flood plain A strip of relatively smooth land bordering a stream, built of sediment carried by the stream and dropped in the slack water beyond the influence of the swiftest current. It is called a living flood plain if it is overflowed in times of highwater, but a fossil flood plain if it is beyond the reach of the highest flood.

flood profile A graph of elevation of the water surface of a river in flood, plotted as ordinate, against distance, measured in the downstream direction, plotted as abscissa. A flood profile may be drawn to show elevation at a given time or crests during a particular flood.

gage height The water-surface elevation referred to some arbitrary gage datum. Gage height is often used interchangeably with the more general term “stage,” although gage height is more appropriate when used with a reading on a gage.

high-water mark The highest stage reached by a flood that has been maintained for a sufficient period to leave evidence on the landscape (Benson and Dalrymple, 1967).

LiDAR Remote-sensing technology that uses laser pulses to measure the distance from the laser to topographic and bathymetric surfaces (Skinner, 2009).

recurrence interval (return period) The average interval of time within which the given flood will be equaled or exceeded once. The recurrence interval is directly related to the flood probability. The recurrence interval corresponding to a particular flood probability is equal to 1 divided by the flood probability. For example, a 100-year recurrence interval has a flood probability of 0.01.

stream A general term for a body of flowing water. In hydrology the term is generally applied to the water flowing in a natural channel as distinct from a canal.

streamflow The discharge that occurs in a natural channel. Although the term “discharge” can be applied to the flow of a canal, the word “streamflow” uniquely describes the discharge in a surface stream course.

streamgage A gaging station where a record of discharge of a stream is obtained. Within the U.S. Geological Survey this term is used only for those gaging stations where a continuous record of gage-height is obtained.

thalweg The area of maximum water velocity within a channel flow (Charlton, 2009).

warm front A transition zone between a mass of warm air and the colder air it is replacing (National Weather Service, 2005).

Appendix 1. High-Water-Mark Descriptions in the Communities of Faribault, Owatonna, Pine Island, and Zumbro Falls, Floods of September 2010, Minnesota

Table 1–1. High-water-mark descriptions in the communities of Faribault, Owatonna, Pine Island, and Zumbro Falls, floods of September 2010, Minnesota.

[Vertical coordinate data are referenced to the North American Vertical Datum of 1988 (NAVD 1988). Horizontal coordinate data are referenced to the North American Datum of 1983. Approximate quality ratings of high-water marks: Excellent, ± 0.02 foot; Good, ± 0.05 foot; Fair, ± 0.1 foot; and Poor, greater than 0.10 foot (Lumia and others, 1986); for bank of nearest stream, “right” and “left” refer to an observation looking in the downstream direction]

Community name	Elevation (feet above NAVD 88)	Latitude	Longitude	High-water-mark description	High-water-mark quality	Nearest stream	Bank of nearest stream	High-water-mark identifier
Faribault	969.1	44°18′10.5″	93°17′23.3″	Seed line on bridge abutment	Good	Cannon River	Left	FB5
Faribault	968.9	44°18′20.3″	93°16′51.7″	Seed line on picnic shelter	Good	Cannon River	Left	FB4
Faribault	968.9	44°18′11.5″	93°16′48.4″	Seed line on storm drain	Good	Cannon River	Right	FB6
Faribault	968.8	44°18′31.6″	93°16′21.1″	Seed line on temporary structure	Good	Cannon River	Right	FB2
Faribault	968.8	44°18′33.9″	93°16′21.1″	Seed line on bridge	Good	Cannon River	Left	FB3
Faribault	968.9	44°18′27.9″	93°16′19.3″	Seed line on bridge	Good	Cannon River	Right	FB1
Faribault	977.5	44°17′32.9″	93°15′50.6″	Seed line on retaining wall	Good	Straight River	Right	FB9
Faribault	976.2	44°17′38.2″	93°15′54.8″	Debris line on concrete foundation	Poor	Straight River	Left	FB8
Faribault	975.2	44°17′49.7″	93°15′58.6″	Seed line on building	Good	Straight River	Left	FB10
Faribault	972.3	44°18′12.8″	93°15′57.8″	Mud line on tree	Poor	Straight River	Left	FB12
Faribault	970.4	44°18′27.4″	93°15′54.6″	Debris line on fence post	Poor	Straight River	Right	FB7
Owatonna	1,137.4	44°04′13.2″	93°14′32.0″	Seed line on retaining wall	Good	Straight River	Right	OW13
Owatonna	1,136.4	44°04′47.8″	93°14′7.3″	Debris line on ground	Good	Straight River	Left	OW4
Owatonna	1,136.5	44°04′49.1″	93°13′54.3″	Seed line on water tank	Good	Straight River	Right	OW12
Owatonna	1,135.0	44°05′10.9″	93°13′45.2″	Seed line on retaining wall	Good	Straight River	Right	OW2
Owatonna	1,134.8	44°05′11.3″	93°13′49.6″	Seed line on building	Good	Straight River	Left	OW3
Owatonna	1,134.5	44°05′12.5″	93°13′46.6″	Debris line on edge of sign post	Fair	Straight River	Right	OW1
Owatonna	1,134.7	44°05′15.0″	93°13′49.3″	Seed line on building and fence	Good	Straight River	Left	OW18
Owatonna	1,133.5	44°05′27.8″	93°13′48.3″	Mudline on building	Excellent	Straight River	Left	OW19
Owatonna	1,132.5	44°05′32.6″	93°13′40.4″	Seed line on precast concrete building	Good	Straight River	Right	OW16
Owatonna	1,132.8	44°05′34.7″	93°13′49.6″	Seed line on brick/block building	Good	Straight River	Left	OW15
Owatonna	1,127.6	44°06′35.0″	93°14′24.8″	Debris line on ground	Fair	Straight River	Left	OW11
Owatonna	1,126.9	44°06′35.0″	93°14′22.1″	Debris line on ground	Poor	Straight River	Right	OW10
Owatonna	1,127.0	44°06′35.6″	93°14′24.8″	Debris line on streambank	Fair	Straight River	Left	OW8
Owatonna	1,127.1	44°06′35.8″	93°14′21.7″	Debris line on ground	Poor	Straight River	Right	OW9
Owatonna	1,147.3	44°05′24.9″	93°12′30.2″	Debris line on tree	Poor	Maple Creek	Right	OW7
Owatonna	1,137.9	44°05′27.9″	93°12′58.6″	Debris line on chain-link fence	Fair	Maple Creek	Right	OW6

Table 1–1. High-water-mark descriptions in the communities of Faribault, Owatonna, Pine Island, and Zumbro Falls, floods of September 2010, Minnesota.—Continued

[Vertical coordinate data are referenced to the North American Vertical Datum of 1988 (NAVD 1988). Horizontal coordinate data are referenced to the North American Datum of 1983. Approximate quality ratings of high-water marks: Excellent, ± 0.02 foot; Good, ± 0.05 foot; Fair, ± 0.1 foot; and Poor, greater than 0.10 foot (Lumia and others, 1986); for bank of nearest stream, "right" and "left" refer to an observation looking in the downstream direction]

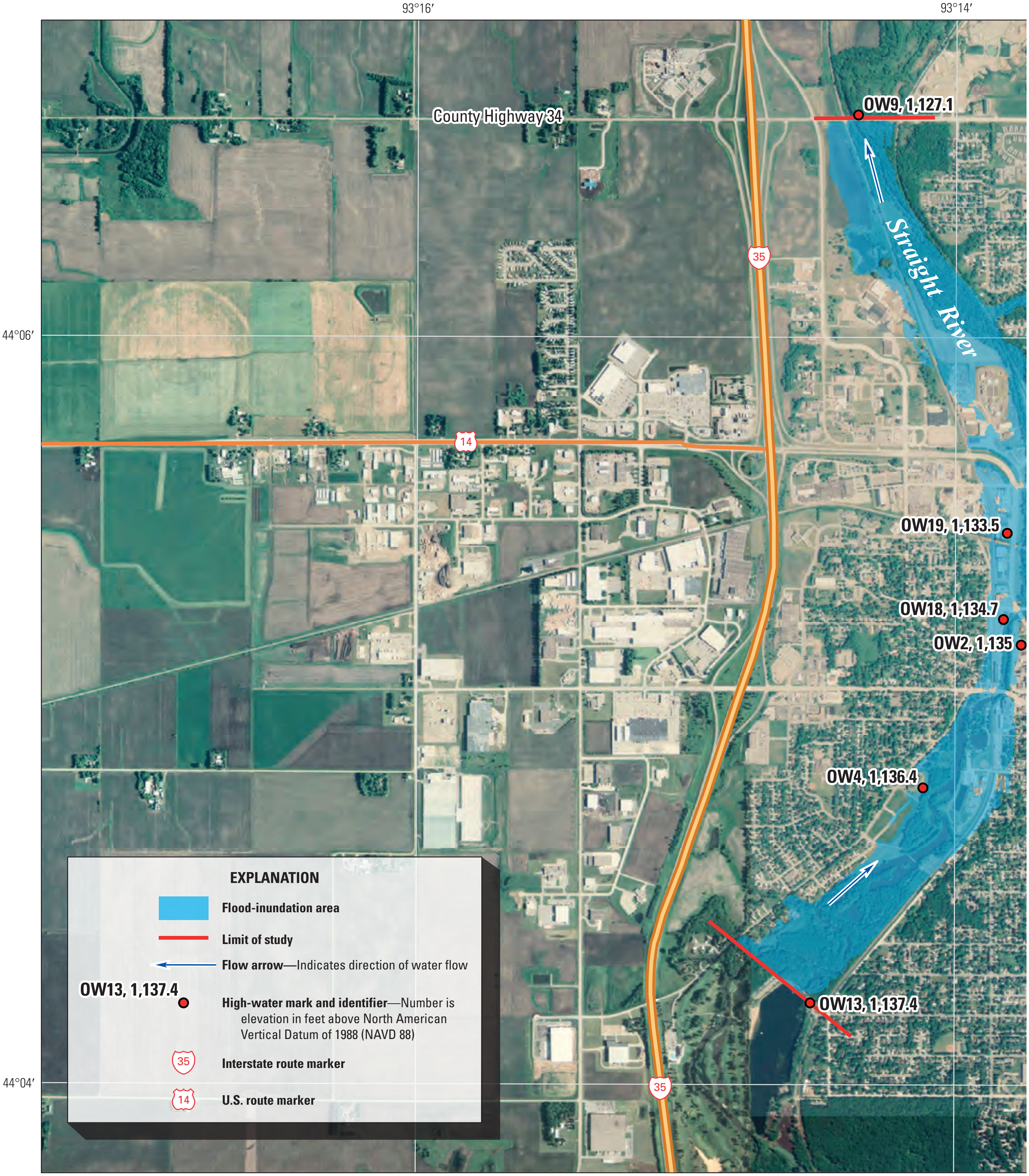
Community name	Elevation (feet above NAVD 88)	Latitude	Longitude	High-water-mark description	High-water-mark quality	Nearest stream	Bank of nearest stream	High-water-mark identifier
Owatonna	1,134.9	44°05′39.6″	93°13′23.4″	Seed line on fence	Fair	Maple Creek	Left	OW5
Pine Island	1,002.7	44°11′33.5″	92°38′54.4″	Mudline on bridge	Poor	Middle Fork Zumbro River	Right	PI9
Pine Island	996.7	44°11′55.4″	92°38′28.1″	Seedline on storage building	Good	Middle Fork Zumbro River	Left	PI2
Pine Island	995.5	44°11′57.2″	92°38′28.9″	Mudline on house/homeowner's mark	Poor	Middle Fork Zumbro River	Left	PI1
Pine Island	994.7	44°11′59.8″	92°38′21.2″	Debris line on tree	Poor	Middle Fork Zumbro River	Right	PI7
Pine Island	996.4	44°12′6.1″	92°38′32.0″	Seedline on school bus garage	Good	Middle Fork Zumbro River	Left	PI3
Pine Island	995.8	44°12′10.0″	92°38′23.4″	Seedline on pet shelter	Good	Middle Fork Zumbro River	Left	PI5
Pine Island	1,000.1	44°12′23.5″	92°39′5.2″	Debris line on tree	Poor	North Branch	Left	PI8
Pine Island	996.3	44°12′11.5″	92°38′40.3″	Water line on picnic shelter	Fair	North Branch	Left	PI4
Zumbro Falls	846.8	44°17′6.4″	92°25′53.6″	Mudline on house	Good	Zumbro River	Right	ZF6
Zumbro Falls	846.4	44°17′8.9″	92°25′47.3″	Mudline on bridge abutment	Good	Zumbro River	Left	ZF1
Zumbro Falls	845.2	44°16′59.1″	92°25′29.6″	Mudline on building	Good	Zumbro River	Left	ZF10
Zumbro Falls	845.2	44°16′58.1″	92°25′′45.2″	Mudline on house	Good	Zumbro River	Right	ZF11
Zumbro Falls	845.0	44°16′56.8″	92°25′20.8″	Mudline on house	Fair	Zumbro River	Left	ZF8
Zumbro Falls	844.9	44°17’00.6″	92°25′22.8″	Mudline on Fire Dept. building	Good	Zumbro River	Left	ZF7
Zumbro Falls	843.7	44°16′41.9″	92°25′26.5″	Mudline on building	Good	Zumbro River	Right	ZF9

Appendix 2. Flood-Peak Inundation Maps for Selected Communities, Floods of September 2010, Minnesota

Aerial photograph courtesy of MNGeo, Spatial Data Portal, 2009 National Agriculture Imagery Program, accessed January 2011, at *http://www.mngeo.state.mn.us/chouse/metadata/naip09.html.*

Figure 2–1. Approximate flood-peak extents and heights, flood of September 2010, for Cannon River and Straight River at Faribault, Minnesota.

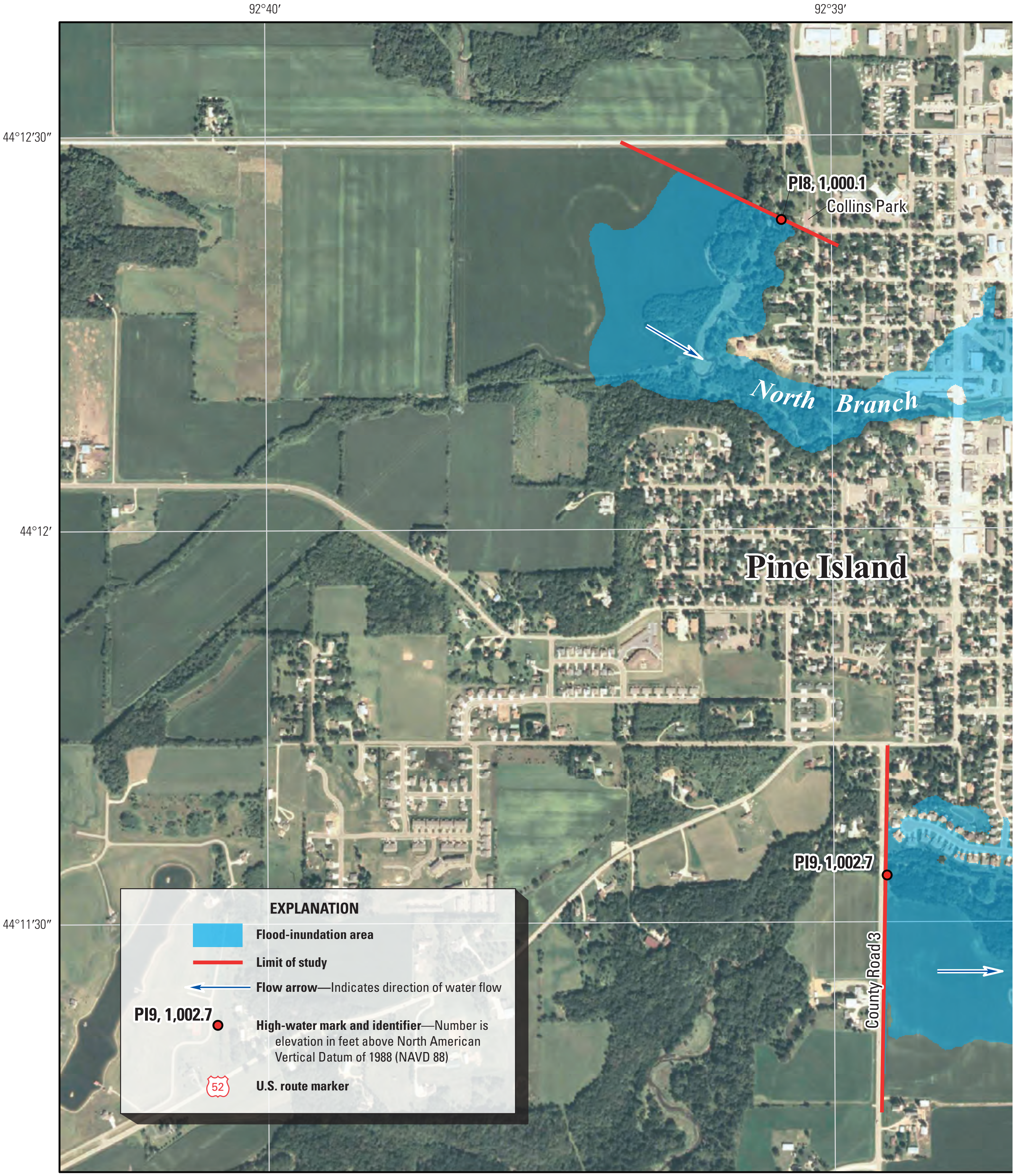

93°16′
93°15′
MINNESOTA
Cannon River Basin
Faribault
14th Street NE
FB3, 968.8
FB7, 970.4
FB12, 972.3
Straight River
FB10, 975.2
60
FB8, 976.2
FB9, 977.5
2nd Street NE
0
0.1
0.2
0.3
0.4
0.5 MILE
0
0.1
0.2
0.3
0.4
0.5 KILOMETER



Aerial photograph courtesy of MNGeo, Spatial Data Portal, 2009 National Agriculture Imagery Program, accessed January 2011, at *http://www.mngeo.state.mn.us/chouse/metadata/naip09.html.*

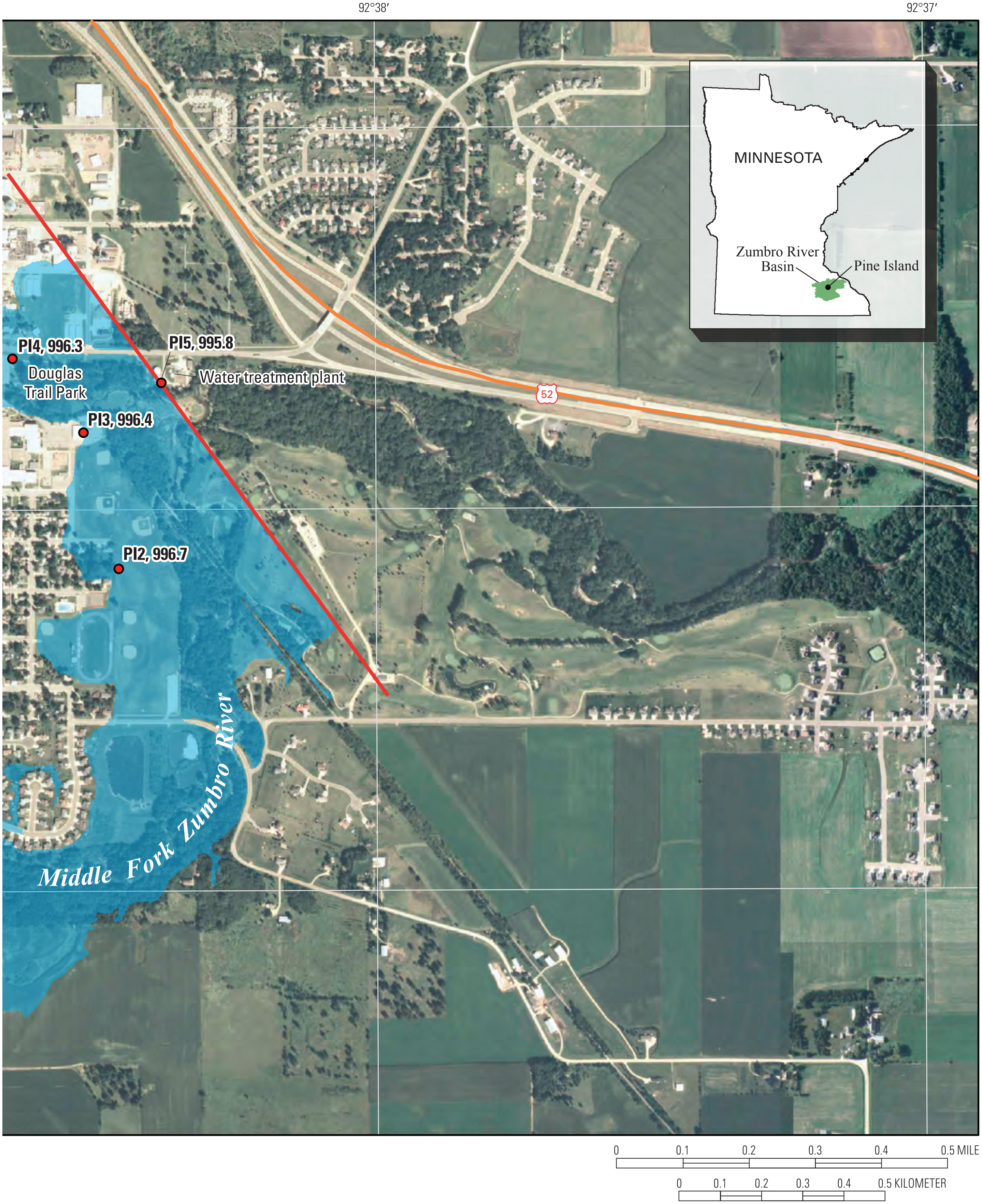
Figure 2–2. Approximate flood-peak extents and heights, flood of September 2010, for Straight River and Maple Creek at Owatonna, Minnesota.

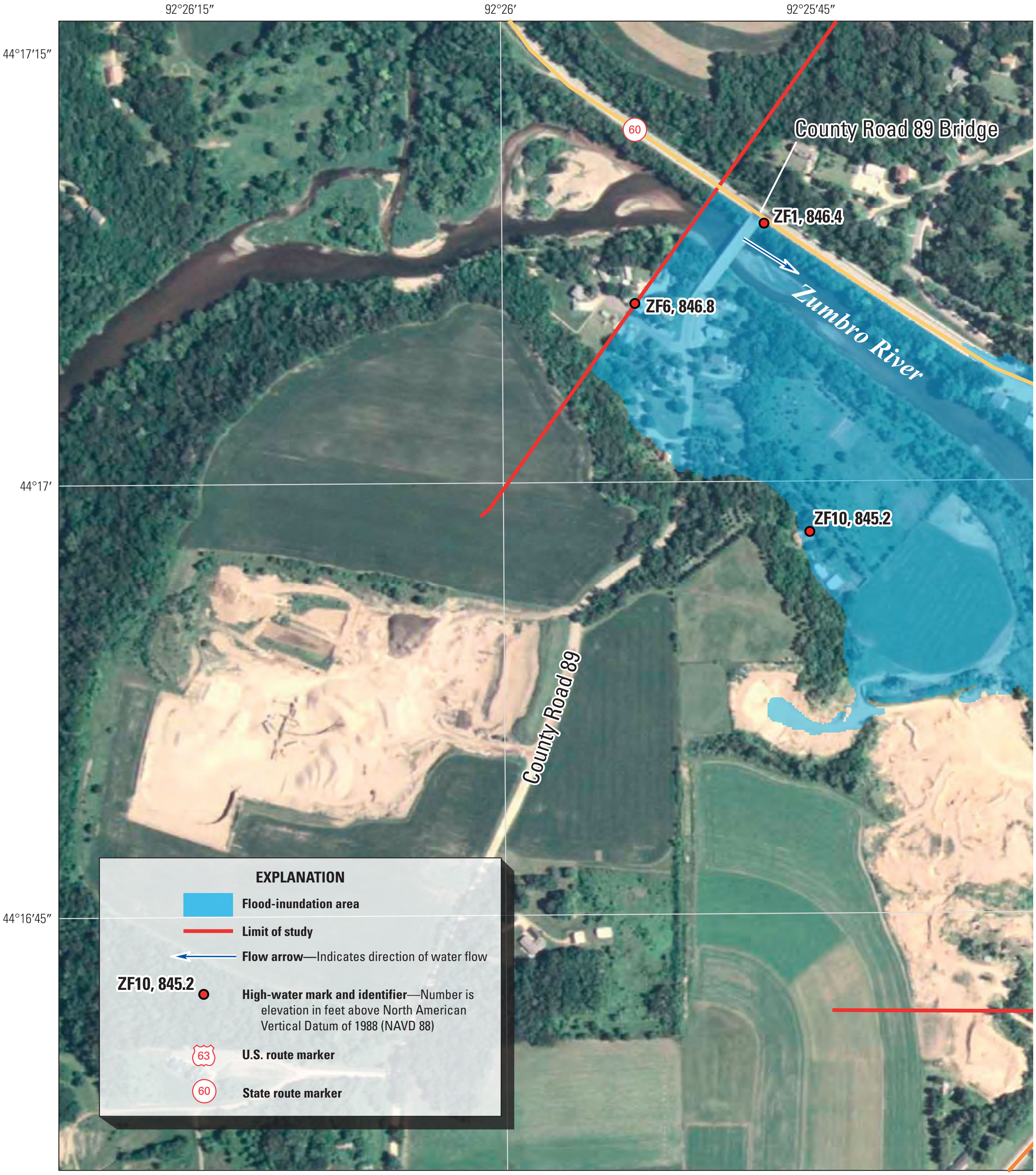

93°12′
MINNESOTA
Cannon River Basin
Owatonna
Maple Creek
OW5, 1,134.9
OW16, 1,132.5
OW6, 1,137.9
OW7, 1,147.3
Cherry Street
Owatonna
0
0.25
0.5
0.75
1 MILE
0
0.25
0.5
0.75
1 KILOMETER



Aerial photograph courtesy of MNGeo, Spatial Data Portal, 2009 National Agriculture Imagery Program, accessed January 2011, at *http://www.mngeo.state.mn.us/chouse/metadata/naip09.html.*

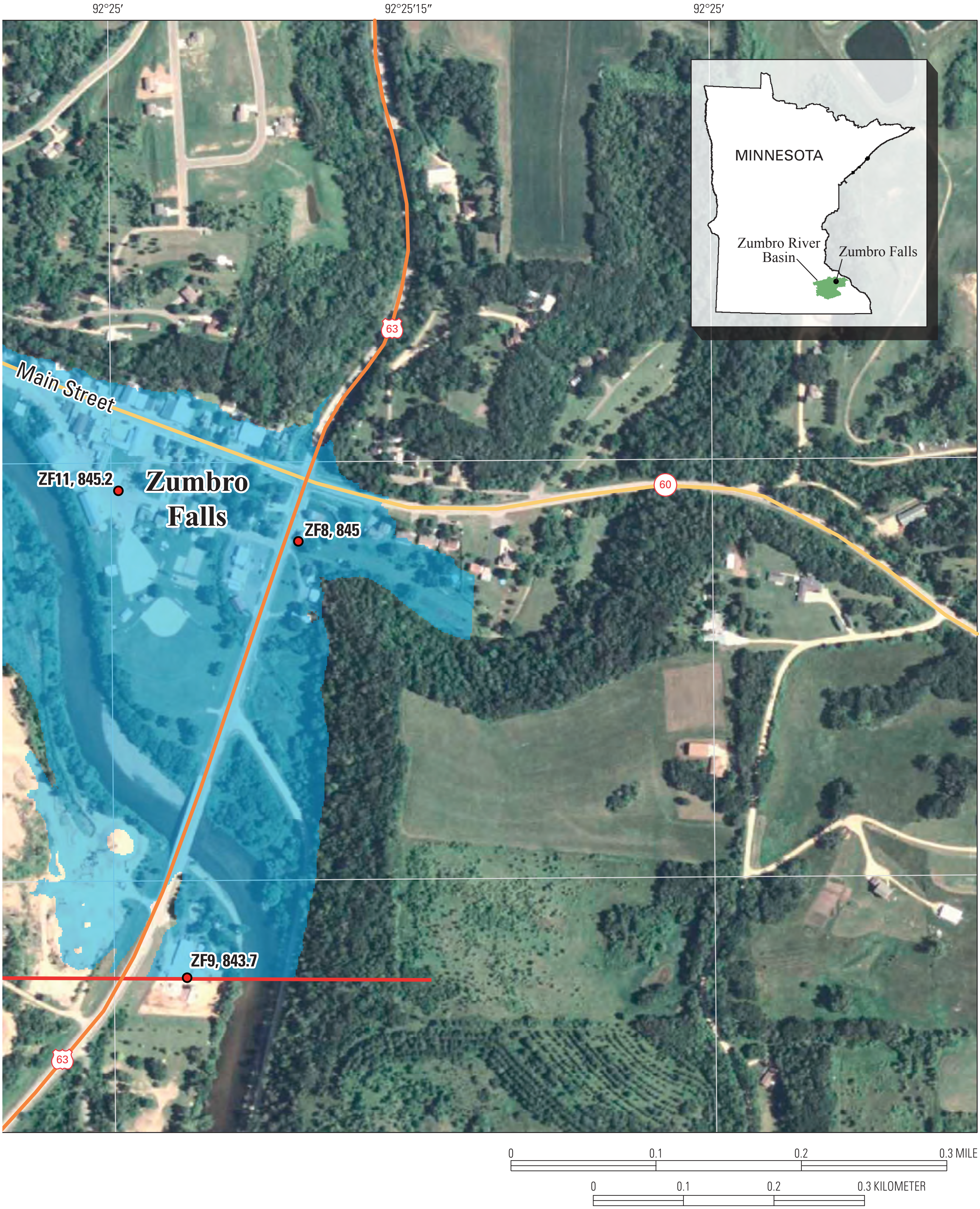
Figure 2–3. Approximate flood-peak extents and heights, flood of September 2010, North Branch and Middle Fork Zumbro River near Pine Island, Minnesota.


92°38′
92°37′
MINNESOTA
Zumbro River Basin
Pine Island
PI4, 996.3
PI5, 995.8
Douglas Trail Park
Water treatment plant
PI3, 996.4
PI2, 996.7
52
Middle Fork Zumbro River
0 0.1 0.2 0.3 0.4 0.5 MILE
0 0.1 0.2 0.3 0.4 0.5 KILOMETER



Aerial photograph courtesy of MNGeo, Spatial Data Portal, 2009 National Agriculture Imagery Program, accessed January 2011, at *http://www.mngeo.state.mn.us/chouse/metadata/naip09.html.*

Figure 2–4. Approximate flood-peak extents and heights, flood of September 2010, for Zumbro River at Zumbro Falls, Minnesota.


92°25′
92°25′15″
92°25′
MINNESOTA
Zumbro River Basin
Zumbro Falls
Main Street
63
60
ZF11, 845.2
Zumbro Falls
ZF8, 845
ZF9, 843.7
63
0
0.1
0.2
0.3 MILE
0
0.1
0.2
0.3 KILOMETER

Appendix 3. Flood-Peak Water-Surface Profiles for Selected Sites, Floods of September 2010, Minnesota

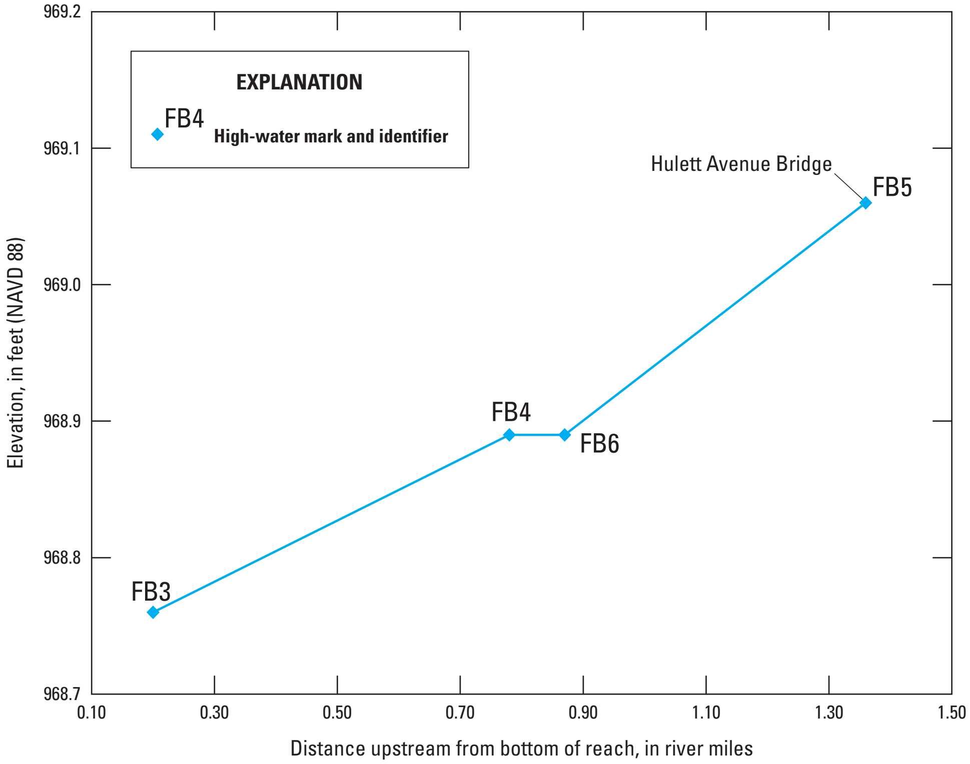


Figure 3–1. Flood-peak water-surface profile with selected high-water marks for the Cannon River at Faribault, Minnesota, for flood of September 2010. Elevation is referenced to North American Vertical Datum of 1988 (NAVD 88).

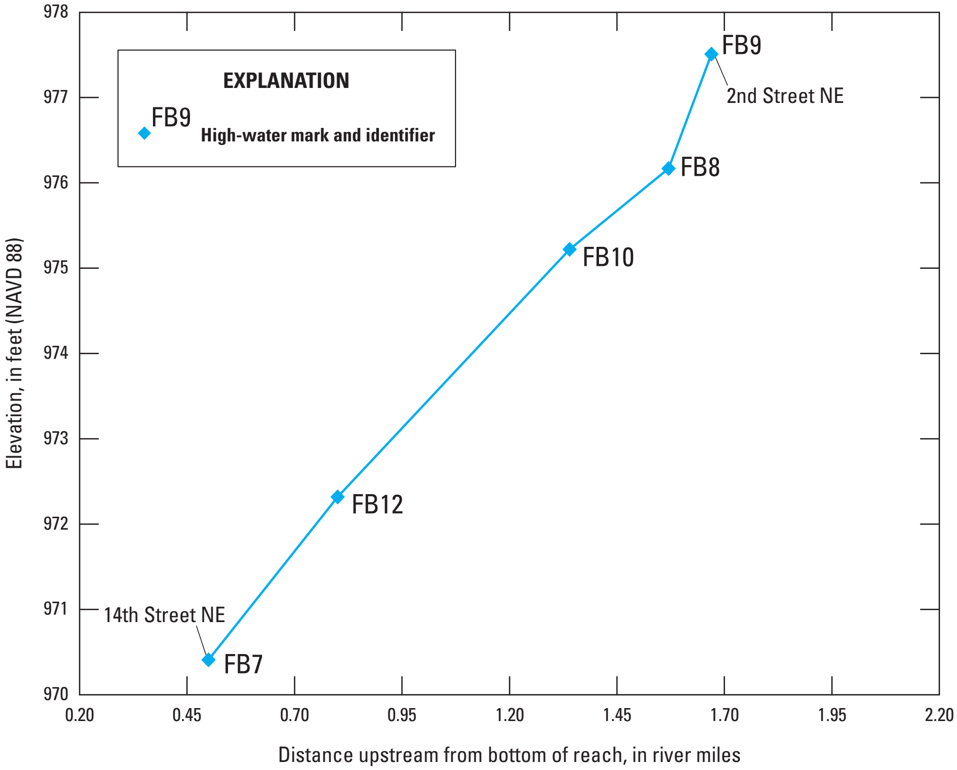


Figure 3–2. Flood-peak water-surface profile with selected high-water marks for the Straight River at Faribault, Minnesota, for flood of September 2010. Elevation is referenced to North American Vertical Datum of 1988 (NAVD 88).

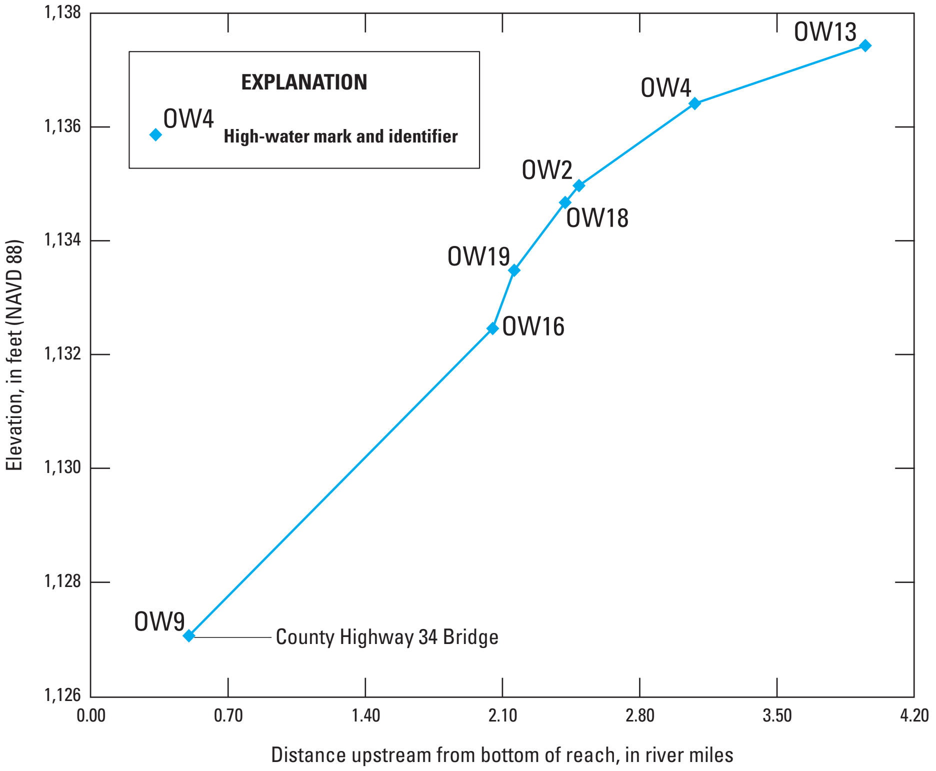


Figure 3–3. Flood-peak water-surface profile with selected high-water marks for Straight River at Owatonna, Minnesota, for flood of September 2010. Elevation is referenced to North American Vertical Datum of 1988 (NAVD 88).

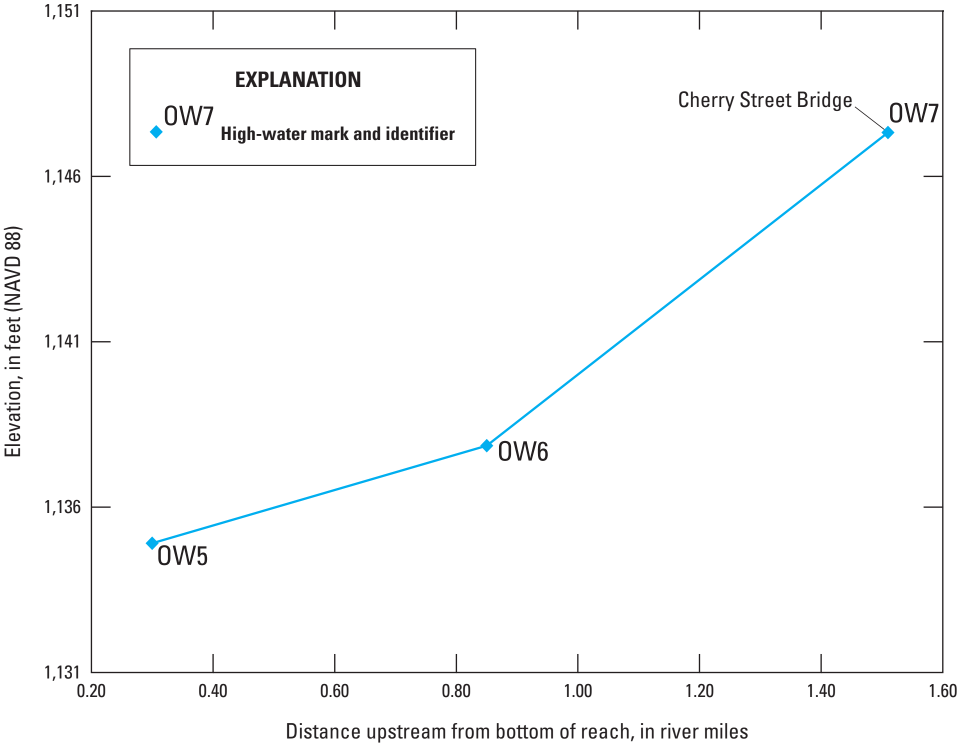


Figure 3–4. Flood-peak water-surface profile with selected high-water marks for Maple Creek at Owatonna, Minnesota, for flood of September 2010. Elevation is referenced to North American Vertical Datum of 1988 (NAVD 88).

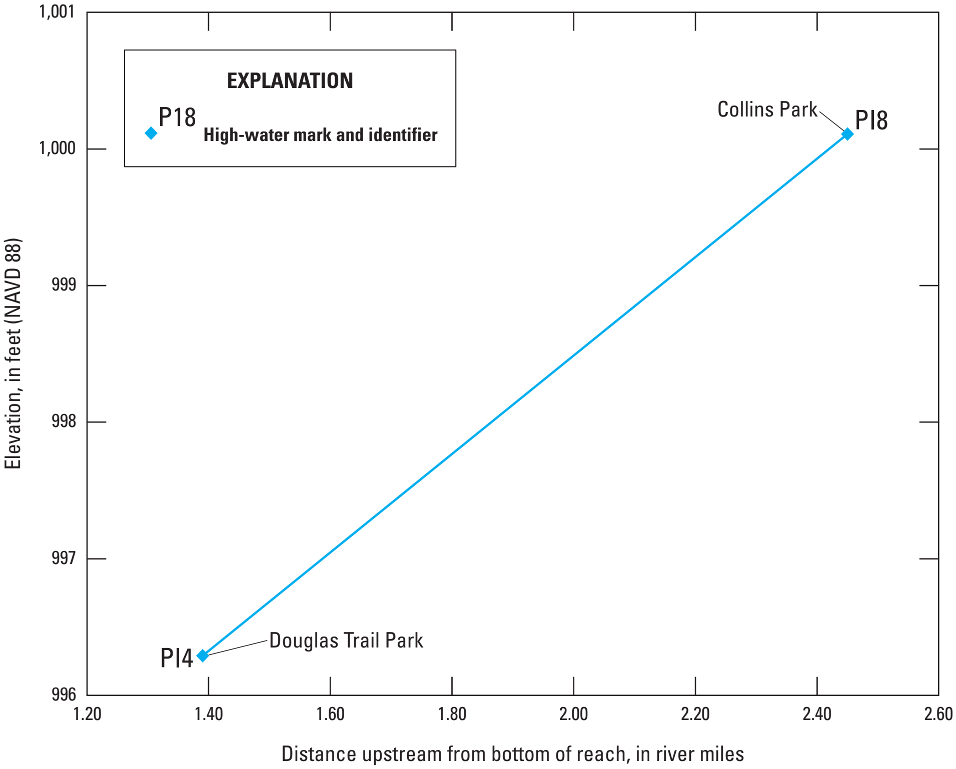


Figure 3–5. Flood-peak water-surface profile with selected high-water marks for the North Branch at Pine Island, Minnesota, for flood of September 2010. Elevation is referenced to the North American Vertical Datum of 1988 (NAVD 88).

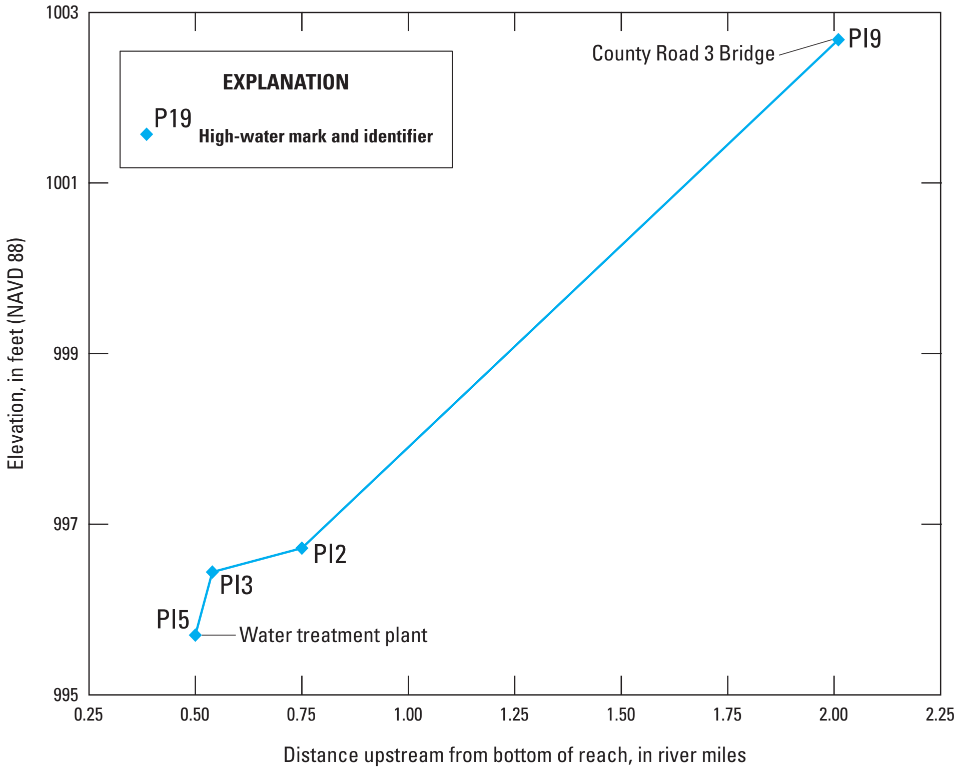


Figure 3–6. Flood-peak water-surface profile with selected high-water marks for the Middle Fork Zumbro River at Pine Island, Minnesota, for flood of September 2010. Elevation is referenced to North American Vertical Datum of 1988 (NAVD 88).

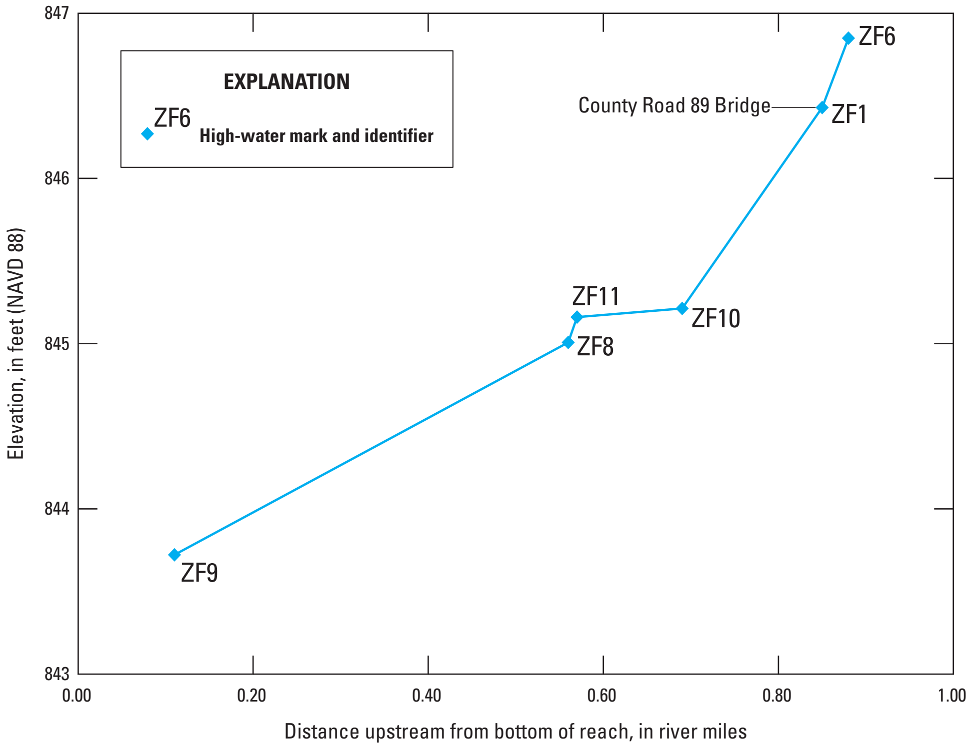


Figure 3–7. Flood-peak water-surface profile with selected high-water marks for the Zumbro River at Zumbro Falls, Minnesota, for flood of September 2010. Elevation is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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