Prepared in cooperation with the U.S. Department of Agriculture—Forest Service

Two-Dimensional Simulation of the June 11, 2010, Flood of the Little Missouri River at Albert Pike Recreation Area, Ouachita National Forest, Arkansas

Scientific Investigations Report 2012–5274

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

Cover, Little Missouri River near Camp Area C at Albert Pike Recreation Area, Arkansas (photograph by Daniel M. Wagner, U.S. Geological Survey).

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SALLY JEWELL, Secretary

U.S. Geological Survey
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U.S. Geological Survey, Reston, Virginia: 2013

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Acknowledgments

Data collection and analysis following the June 11, 2010, flood of the Little Missouri River was a collective effort by employees from the U.S. Geological Survey (USGS) Water Science Centers in Arkansas, Missouri, and Texas; the U.S. Geological Survey Office of Surface Water; and the U.S. Forest Service (USFS). Particularly noteworthy were the efforts of Walter F. Killion and Jonathan Gillip (USGS Arkansas), Paul Rydlund (USGS Missouri), and Robert Holmes (USGS Office of Surface Water).

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
square foot per second (ft^2/s)	0.09290	square meter per second (m^2/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)

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

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

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

Two-Dimensional Simulation of the June 11, 2010, Flood of the Little Missouri River at Albert Pike Recreation Area, Ouachita National Forest, Arkansas

By Daniel M. Wagner

Abstract

In the early morning hours of June 11, 2010, substantial flooding occurred at Albert Pike Recreation Area in the Ouachita National Forest of west-central Arkansas, killing 20 campers. The U.S. Forest Service needed information concerning the extent and depth of flood inundation, the water velocity, and flow paths throughout Albert Pike Recreation Area for the flood and for streamflows corresponding to annual exceedence probabilities of 1 and 2 percent. The two-dimensional flow model Fst2DH, part of the Federal Highway Administration's Finite Element Surface-water Modeling System, and the graphical user interface Surface-water Modeling System (SMS) were used to perform a steady-state simulation of the flood in a 1.5-mile reach of the Little Missouri River at Albert Pike Recreation Area. Peak streamflows of the Little Missouri River and tributary Brier Creek served as inputs to the simulation, which was calibrated to the surveyed elevations of high-water marks left by the flood and then used to predict flooding that would result from streamflows corresponding to annual exceedence probabilities of 1 and 2 percent. The simulated extent of the June 11, 2010, flood matched the observed extent of flooding at Albert Pike Recreation Area. The mean depth of inundation in the camp areas was 8.5 feet in Area D, 7.4 feet in Area C, 3.8 feet in Areas A, B, and the Day Use Area, and 12.5 feet in Lowry's Camp Albert Pike. The mean water velocity was 7.2 feet per second in Area D, 7.6 feet per second in Area C, 7.2 feet per second in Areas A, B, and the Day Use Area, and 7.6 feet per second in Lowry's Camp Albert Pike. A sensitivity analysis indicated that varying the streamflow of the Little Missouri River had the greatest effect on simulated water-surface elevation, while varying the streamflow of tributary Brier Creek had the least effect. Simulated water-surface elevations were lower than those modeled by the U.S. Forest Service using the standard-step method, but the comparison between the two was favorable with a mean absolute difference of 0.58 feet in Area C and 0.32 feet in Area D. Results of a HEC-RAS model of the Little Missouri River watershed upstream from the U.S. Geological Survey streamflow-gaging station near Langley showed no difference in mean depth in the areas in common between the models, and a difference in mean velocity of only 0.5 foot per second. Predictions of flooding that would result from streamflows corresponding to annual exceedence probabilities of 1 and 2 percent indicated that the extent of inundation of the June 11, 2010, flood exceeded that of the 1 percent flood, and that for both the 1 and 2 percent floods, all of Areas C and D, and parts of Areas A, B, and the Day Use Area were inundated. Predicted water-surface elevations for the 1 and 2 percent floods were approximately 1 foot lower than those predicted by the U.S. Forest Service using a standard-step model.

Introduction

During the evening of June 10 and the early morning hours of June 11, 2010, as much as 7 inches of rain fell on the upper Little Missouri River watershed in the Ouachita National Forest of west-central Arkansas (National Weather Service, 2010), resulting in a substantial flood at Albert Pike Recreation Area (hereafter referred to as"Albert Pike") (fig. 1) that killed 20 campers and caused extensive damage to campgrounds (Holmes and Wagner, 2011).

The magnitude and annual exceedence probabilities (AEP) of the flood were previously determined by the U.S. Geological Survey (USGS) for USGS streamgage 07360200, Little Missouri River at Langley (fig. 1); the magnitude of the flood was also determined for the Little Missouri River above Long Creek, the Little Missouri River at Albert Pike Recreation Area, and for tributaries Long, Brier, and Blaylock Creeks (fig. 1) (Holmes and Wagner, 2011). The U.S. Department of Agriculture—Forest Service (USFS) had conducted its own investigation of the flood (Marion, 2012), which included: (1) measurements of land-surface boundary roughness in the study area; (2) slope/area indirect measurements of peak streamflow of the Little Missouri River at Camp Areas C and D at Albert Pike; (3) estimates of streamflows corresponding to AEPs of 1 and 2 percent for the Little Missouri River at Camp Areas C and D at Albert Pike using a regional regression model; and (4) standard-step models of water-surface elevation at 8 cross sections

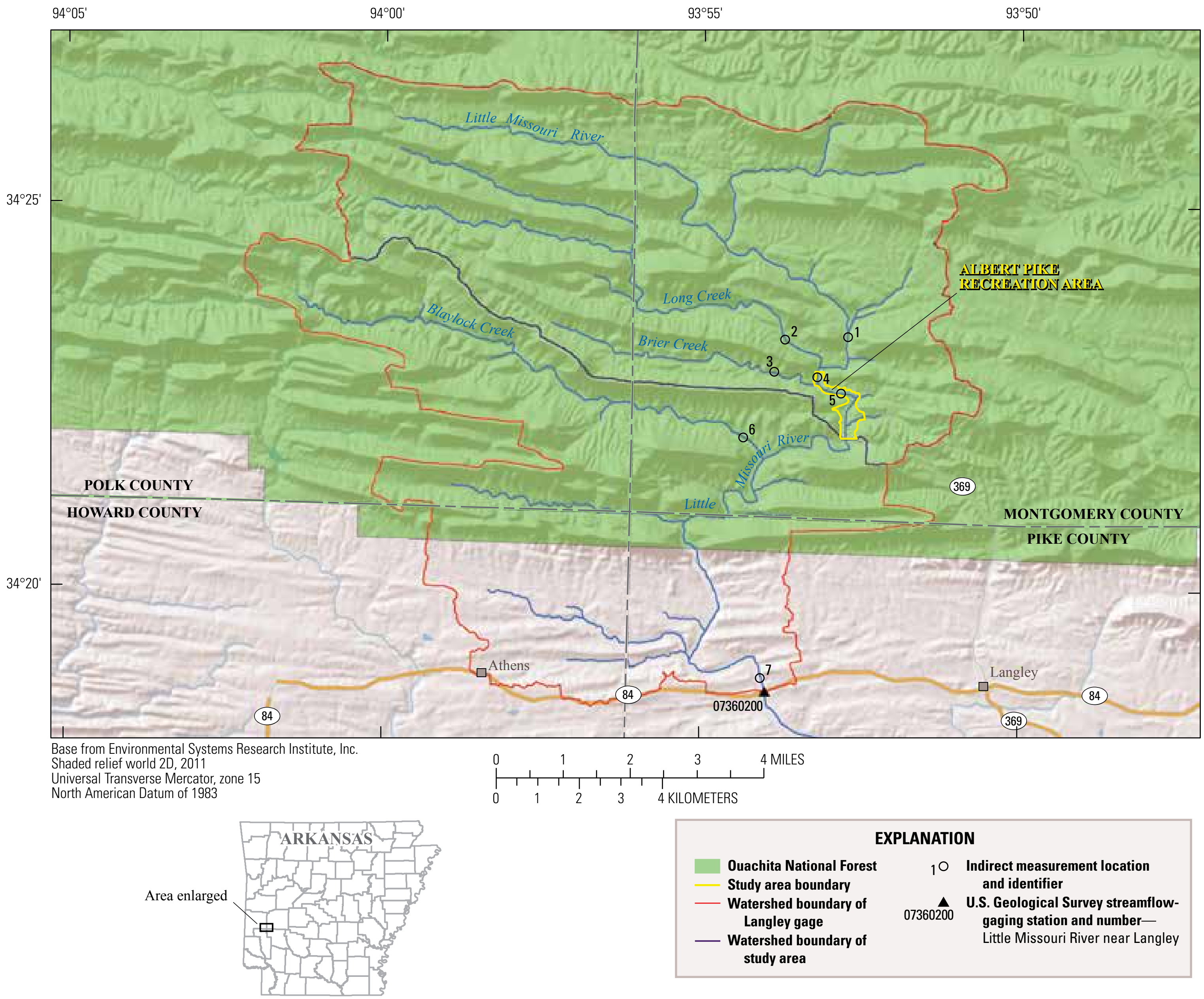


Figure 1. Location of the Little Missouri River watershed and the study area.

in Camp Area C and 10 cross sections in Camp Area D at Albert Pike for the peak of the flood and for streamflows corresponding to AEPs of 1 and 2 percent.

To better understand the flood, the USFS needed information concerning the extent and depth of flood inundation, the water velocity, and flow paths throughout Albert Pike. This information was also needed for streamflows corresponding to AEPs of 1 and 2 percent (100- and 50-year recurrence intervals, respectively). To address these needs, the USGS conducted a study in cooperation with the USFS.

The hydraulic characteristics of streams can be used to estimate how they convey water during specific floodflows. One- and two-dimensional flow models are often used to establish the hydraulic characteristics necessary for design of bridges and other hydraulic structures, to determine velocity distribution in streams and around flow obstructions, and to delineate the area inundated by floods (Musser and Dyar, 2007; Wagner, 2007; Huizinga, 2008). At Albert Pike, an abrupt bend in the channel of the Little Missouri River, bathhouses that obstructed flow in the camp areas, and the desire to know the two-dimensional flow paths created conditions that were best simulated using a two-dimensional flow model.

Purpose and Scope

The purpose of this report is to present the results of a two-dimensional flow simulation of the June 11, 2010, flood (hereafter referred to as “the flood”) and predictions of flooding that could result from streamflows corresponding to AEPs of 1 and 2 percent in a 1.5-mile (mi) reach of the upper Little Missouri River (hereafter referred to as “the study area”) that flows through Albert Pike and part of the privately-owned Lowry’s Camp Albert Pike that is located immediately downstream from the Albert Pike Recreation Area (fig. 2).

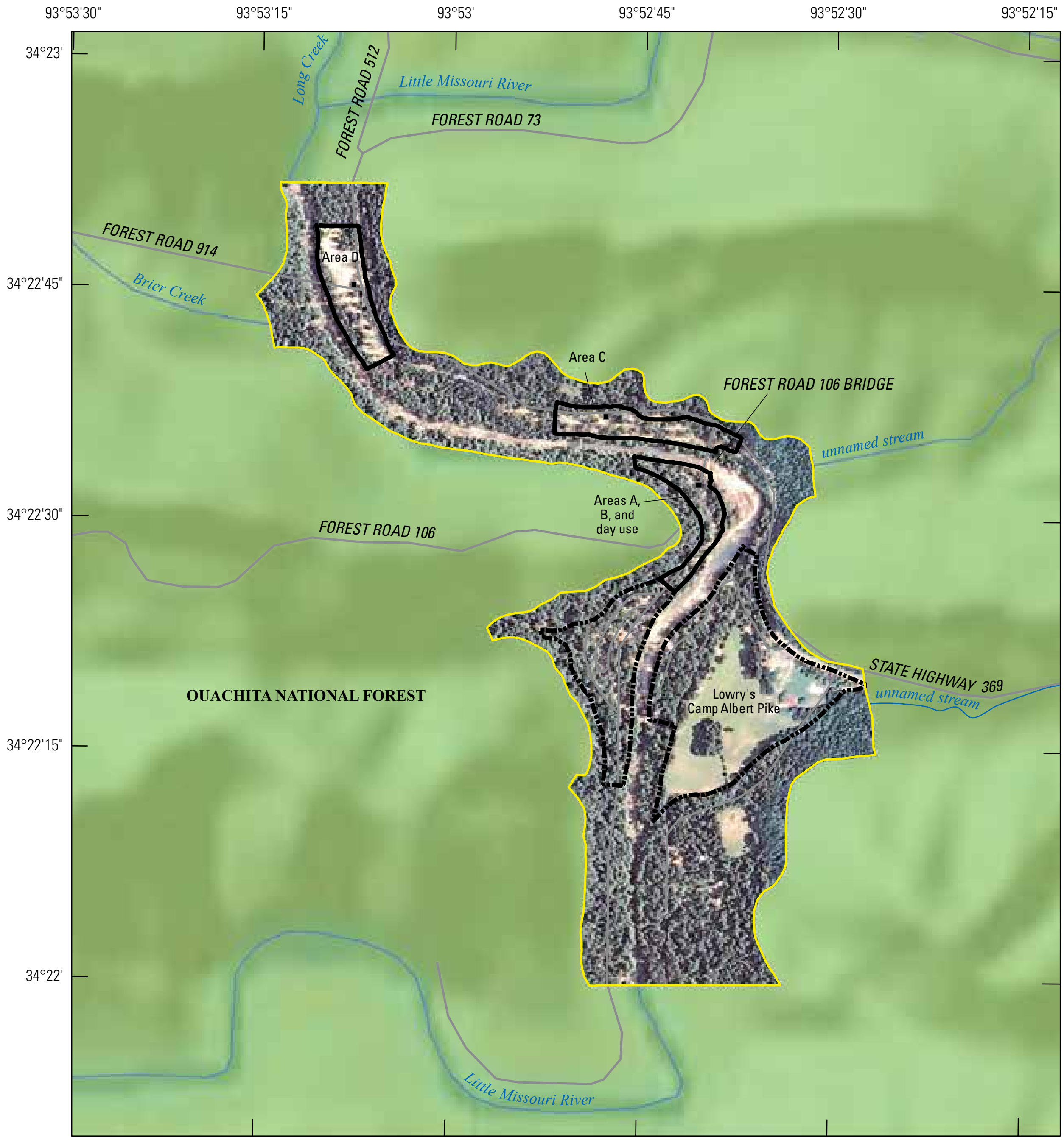
The flow model Fst2DH, part of the Federal Highway Administrations’s Finite Element Surface-water Modeling System, (Froehlich, 2002) was used to perform a depth-averaged, two-dimensional, steady-state flow simulation of the flood. Peak streamflows of the Little Missouri River at Camp Area D at Albert Pike (Marion, 2012) and tributary Brier Creek (Holmes and Wagner, 2011) served as streamflow inputs to the model. The model was calibrated to the surveyed elevations of high-water marks left by the flood. The calibrated model then was used to predict the extent of flooding that would result from streamflows corresponding to AEPs of 1 and 2 percent. The simulated extent and depth of flood inundation, water-surface elevation, water velocity, and flow paths are presented for the three floods. Model results are presented for Albert Pike and part of Lowry’s Camp Albert Pike and compared with the results of the previous investigations in the study area.

Description of the Study Area

The study area is located within the rugged southern part of the Ouachita Mountains physiographic province (Fenneman, 1938). The Ouachita Mountains are characterized by steep, rocky, forested hillslopes; narrow stream valleys; and bedrock, boulder, and gravel stream channels with steep gradients. The topography of the Ouachita Mountains and their proximity to abundant moisture from the Gulf of Mexico result in streams that experience higher peak flows than those of similarly sized drainage areas in other parts of the United States (Crippen and Bue, 1977; O’Connor and Costa, 2003). In the study area, the overbank areas are characterized by dense timber and brush and campgrounds with large trees, parking lots, bathroom buildings, and cabins (fig. 3; Holmes and Wagner, 2011, figs. 14–17, 20–21). Steep hillsides occur along the channel or behind the campground areas and are covered with dense timber, large boulders, and vertical rock faces (fig. 3).

The study area encompasses 0.25 square miles (mi^2) and includes a 1.5-mi reach of the Little Missouri River, Albert Pike, part of Lowry’s Camp Albert Pike, and the adjacent lowlands and lower hillslopes (fig. 2). The northern boundary of the study area is downstream from the confluence of the Little Missouri River and tributary Long Creek (fig. 2) and approximately 300 ft upstream from camp area D at Albert Pike (camp areas at Albert Pike are hereafter referred to as “Area A,” “Area B,” “Area C,” or “Area D”). Tributary Brier Creek joins the Little Missouri River within the study area, across the river from Area D (fig. 2). The downstream boundary of the study area is approximately 0.5 mi downstream from the Day Use Area at Albert Pike (fig. 2), and approximately 8.5 mi upstream from USGS streamflow gaging station 07360200, Little Missouri River near Langley, Ark. (hereafter referred to as “the Langley gage”) (fig. 1). The size of the Little Missouri River watershed at the downstream boundary of the study area is 36.0 mi^2.

The camp areas at Albert Pike are located adjacent to the Little Missouri River. Areas C and D are located along Forest Road 73, while Areas A, B, and the Day Use Area are accessed from Forest Road 106 (FR106) (fig. 2). Area D, the upstream-most camp area (fig. 2), encompasses 5.6 acres and is equipped with full recreational vehicle (RV) hookups. Seventeen of the 20 fatalities that occurred during the June 11, 2010, flood were campers in Area D. Area C, 0.25 mi downstream from Area D (fig. 2), encompasses 4.7 acres and was under construction at the time of the flood. Areas A, B, and the Day Use Area occupy a contiguous parcel of 3.6 acres across the river from Area C, at a sharp bend in the Little Missouri River (fig. 2). FR106 passes between Areas A and B (fig. 2), and the Day Use Area is located at the southern end of the parcel, just upstream from Lowry’s Camp Albert Pike (fig. 2).



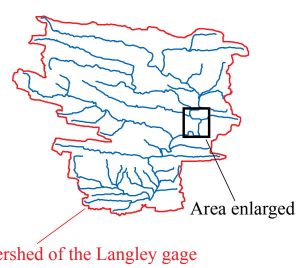


Figure 2. Features of the Little Missouri River and surrounding area near Albert Pike Recreation Area and Lowry's Camp Albert Pike, Arkansas.

A. **Areas A and B**

B. **Area C**

C. **Area D**

D. **Lowry's Camp Albert Pike**

Figure 3. The Little Missouri River at Albert Pike Recreation Area and Lowry's Camp Albert Pike, Arkansas.

Methods

Ground Survey

Within a few days of the flood, the study area was surveyed using a total station surveying instrument as part of the previous investigation of the flood (Holmes and Wagner, 2011) (fig. 4). The purpose of the initial ground survey was to obtain high-water mark elevations, water-surface slope, stream-channel cross-sectional geometry, and stream-channel and land-surface boundary roughness for use in the computation of peak streamflows by the slope-area indirect measurement technique (Holmes and Wagner, 2011). A second ground survey using a total station surveying instrument was conducted in March 2011 (fig. 4) to collect additional land-surface and high-water mark elevations in the study area for use in the two-dimensional flow simulation of the flood.

Prior to beginning the ground surveys, survey control points (fig. 4) were established in the study area and georeferenced to assign real-world coordinates to the survey data. Location and elevation of the control points were determined using static and real-time kinematic global positioning systems (GPS). On account of the dense canopy and high ridges in the forest surrounding Albert Pike, points were occupied for two 8-hour sessions to establish their vertical and horizontal positions.

Determination of Boundary Roughness in the Study Area

Manning's coefficients of boundary roughness (hereafter referred to as *n*-values) were assigned to the main channel of the Little Missouri River and the camp areas at Albert Pike as part of the previous investigations of the flood by the USGS (Holmes and Wagner, 2011) and the USFS (Marion, 2012). In both investigations, *n*-values that took into account all types of land-cover present (that is trees, grass, and pavement in the camp areas; bedrock and boulders in the main channel; and trees and other vegetation within the bankfull channel width) were determined using field observations, comparative photographs from known channel roughness measurements (Arcement and Schneider, 1989; Barnes, 1967; Chow, 1959), and various theoretical roughness equations. To be consistent with the previous investigations, these *n*-values were used in the model as the initial boundary roughness for the main channel and camp areas at Albert Pike. For the remainder of the study area, *n*-values were assigned based on: (1) field observations, (2) areas of similar roughness in the previous investigations, and (3) comparison with photographs of areas with known channel roughness (Barnes, 1967; Chow, 1959). To account for longitudinal changes in roughness (fig. 3), the main channel of the Little Missouri River was divided into five subreaches, with each subreach assigned a unique *n*-value.

Determination of Peak Streamflows in the Study Area

As part of the previous investigations of the flood (Holmes and Wagner, 2011; Marion, 2012), peak streamflows were determined at four locations on the Little Missouri River: (1) above Long Creek (site 1, fig. 1); (2) at Area C at Albert Pike (site 5, fig. 1); (3) at Area D at Albert Pike (site 4, fig. 1); and (4) at the streamflow gage near Langley (site 7, fig. 1). Peak streamflows also were determined at one location on each of three tributary streams: (1) Long Creek (site 2, fig. 1); (2) Brier Creek (site 3, fig. 1); and (3) Blaylock Creek (site 6, fig. 1) (Holmes and Wagner, 2011). The slope-area indirect measurement technique (Dalrymple and Benson, 1967) and the USGS Slope-Area Computation computer program (SAC), version 97–01 (Fulford, 1994) were used to compute the peak streamflows (table 1).

Streamflows corresponding to AEPs of 1 and 2 percent for the Little Missouri River at Areas C and D at Albert Pike (Marion, 2012) (table 1) and for tributary Brier Creek (table 1) were computed using the USGS regional regression model for Arkansas Region B (Hodge and Tasker, 1995), which includes the southern Ouachita Mountains and the study area. Watershed characteristics used in the regional regression model (drainage area, mean elevation, channel length, and shape factor) were determined from a 10-meter (m) digital elevation model (U.S. Geological Survey, 2010) using ArcGIS version 9.3 (Environmental Systems Research Institute, Inc., 2008) (table 1). Watershed characteristics also were determined for the Little Missouri River at the Langley gage and then provided for comparison because it is the nearest gaging location to the study area (fig. 1, table 1).

Development of the Model of the June 11, 2010, Flood

The Fst2DH 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). The model domain is subdivided into elements in the shape of triangles or quadrilaterals. The network of elements in the model domain is known as a "mesh" (fig. 5). The position and geometry of elements in the mesh are defined by node points at the element vertices, midside points, and, for nine-node quadrilaterals, at their centers. Solution variables are defined at the nodes, and continuous approximations of quantities are made within elements using interpolation functions and the point values at the nodes (Froehlich, 2002). The model can simulate longitudinal and lateral variations in water-surface elevation and velocity and can accommodate buildings and other flow obstructions (Froehlich, 2002).

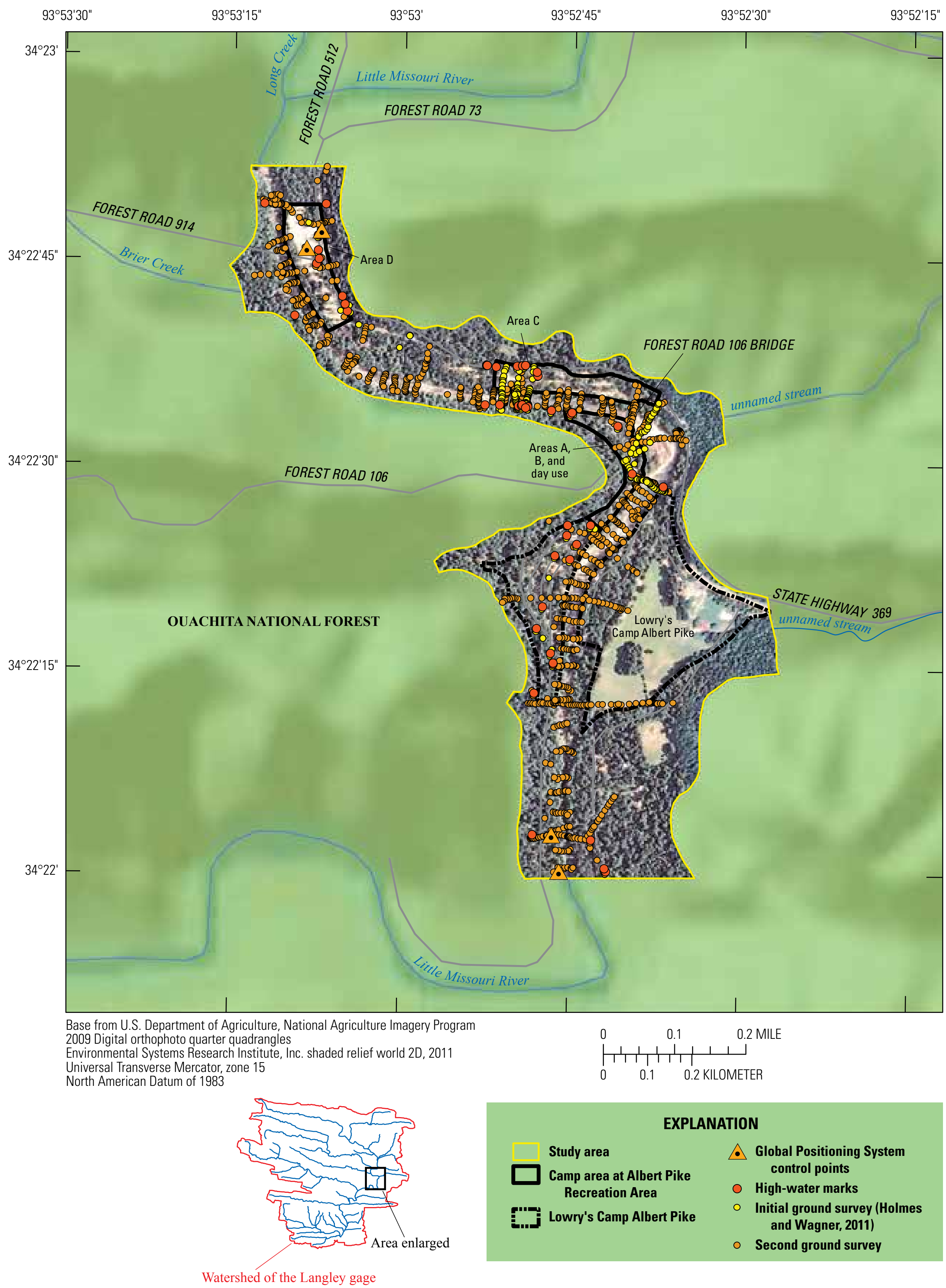


Figure 4. Location of survey control points, surveyed points, and surveyed high-water marks in the vicinity of Albert Pike Recreation Area and Lowry's Camp Albert Pike, Arkansas.

Table 1. Watershed characteristics, peak streamflows of the June 11, 2010, flood, and peak streamflows of floods corresponding to annual exceedence probabilities of 1 and 2 percent for gaged and ungaged sites on the Little Missouri River and for tributaries Long and Brier Creeks in the vicinity of Albert Pike Recreation Area, Arkansas.

[mi², square miles; ft, feet; mi, miles; AEP, annual exceedence probability; yr, year; ND, not determined]

Site	Site identifier (fig. 1)	Watershed characteristics				June 11, 2010, peak streamflow[3]	Streamflow corresponding to an AEP of 1 percent	Streamflow corresponding to an AEP of 2 percent
		Drainage area (mi^2)	Average elevation (ft)	Length (mi)[1]	Shape factor[2]	Streamflows expressed in units of cubic feet per second (ft^3/s)		
07360176 Little Missouri River above Long Creek near Albert Pike[4]	1	18.2	ND	ND	ND	28,200	ND	ND
07360178 Long Creek near Langley[4]	2	10.7	ND	ND	ND	13,000	ND	ND
07360180 Little Missouri River at Albert Pike Recreation Area (Area D)[4]	4	[5]30.4	[5]1,444	[5]12.0	[5]0.21	[5]35,600	[5, 6]27,900 [7](14,300–54,100)	[5, 6]23,700 [7](12,400–45,400)
07360183 Brier Creek near Langley[4]	3	3.32	1,378	6.24	0.085	6,530	[6]3,570 [7](1,750–6,850)	[6]3,060 [7](1,500–5,870)
07360187 Little Missouri River at Albert Pike (Area C)4	5	[5]34.0	[5]1,437	[5]12.9	[5]0.24	40,100	[5, 6]31,700 [7](16,200–61,900)	[5, 6]27,000 [7](14,000–51,800)
07360200 Little Missouri River near Langley	7	68.4	1,309	21.5	0.15	70,800	38,100 [8](27,300–65,700)	31,700 [8](23,500–51,500)

[1]Computed by digitizing the distance from the upstream-most discernible channel thalweg to the channel thalweg at the site location.

[2]Shape factor is defined as the drainage area (A) divided by the square of the stream length (L), or A/L^2, and is dimensionless (Hodge and Tasker, 1995).

[3]All peak streamflows for the June 11, 2010, flood were determined using the slope-area indirect measurement technique (Dalrymple and Benson, 1967).

[4]Ungaged site with no continuous-record streamflow gaging station. Site assigned a U.S. Geological Survey station identification number.

[5]Provided by U.S. Forest Service (Marion, 2012).

[6]Estimated using regional regression model for Arkansas Region B (Hodge and Tasker, 1995).

[7]90 percent confidence interval.

[8]95 percent confidence interval.

The graphical user interface Surface-Water Modeling System, version 10.1.11 (hereafter referred to as “SMS”) (Aquaveo, LLC, 2010), was used to digitize the model domain, construct the model mesh, assign roughness coefficients to the mesh elements, assign boundary conditions to the model, execute the model, and evaluate model output. Required user-provided model inputs were land-surface elevations, land-cover types and their associated *n*-values, streamflows, a water-surface elevation at the downstream model boundary, and various model control parameters.

Land-surface elevations of the study area were obtained from a 10-m digital elevation model (U.S. Geological Survey, 2010) supplemented with land-surface elevations obtained during the ground surveys. The elevations of the nodes in the model mesh (fig. 6) were interpolated from the elevation data set using the linear method available in SMS.

Land-cover types (fig. 7, table 2) were assigned to the mesh elements based on field observations and analysis of orthophotographs. Initial Manning’s *n*-values were assigned to the various land-cover types based on stream-channel and land-surface boundary roughness determined during previous investigations of the flood (Holmes and Wagner, 2011; Marion, 2012), published Manning’s *n*-values (Barnes, 1967; Chow, 1959), and previously calibrated models of similar river reaches (Huizinga, 2008). The roughness of the main channel of the Little Missouri River varied throughout the study area (fig. 3); therefore, the main channel was divided into five subreaches, each assigned a unique *n*-value (fig. 7; table 2). A depth-averaged *n*-value was used for areas of dense timber and brush and a field of tall grasses (table 2), where the effect of the physical features causing the roughness decreased when flow depth increased. For these land-cover types, a “lower depth” *n*-value was applied when the water depth over a mesh element was less than the assigned lower depth, and an “upper depth” *n*-value was applied when the water depth was greater than the assigned upper depth. When the water depth over a mesh element was between the assigned upper and lower depths, the *n*-value applied to the element was interpolated linearly between the two (Froehlich, 2002).

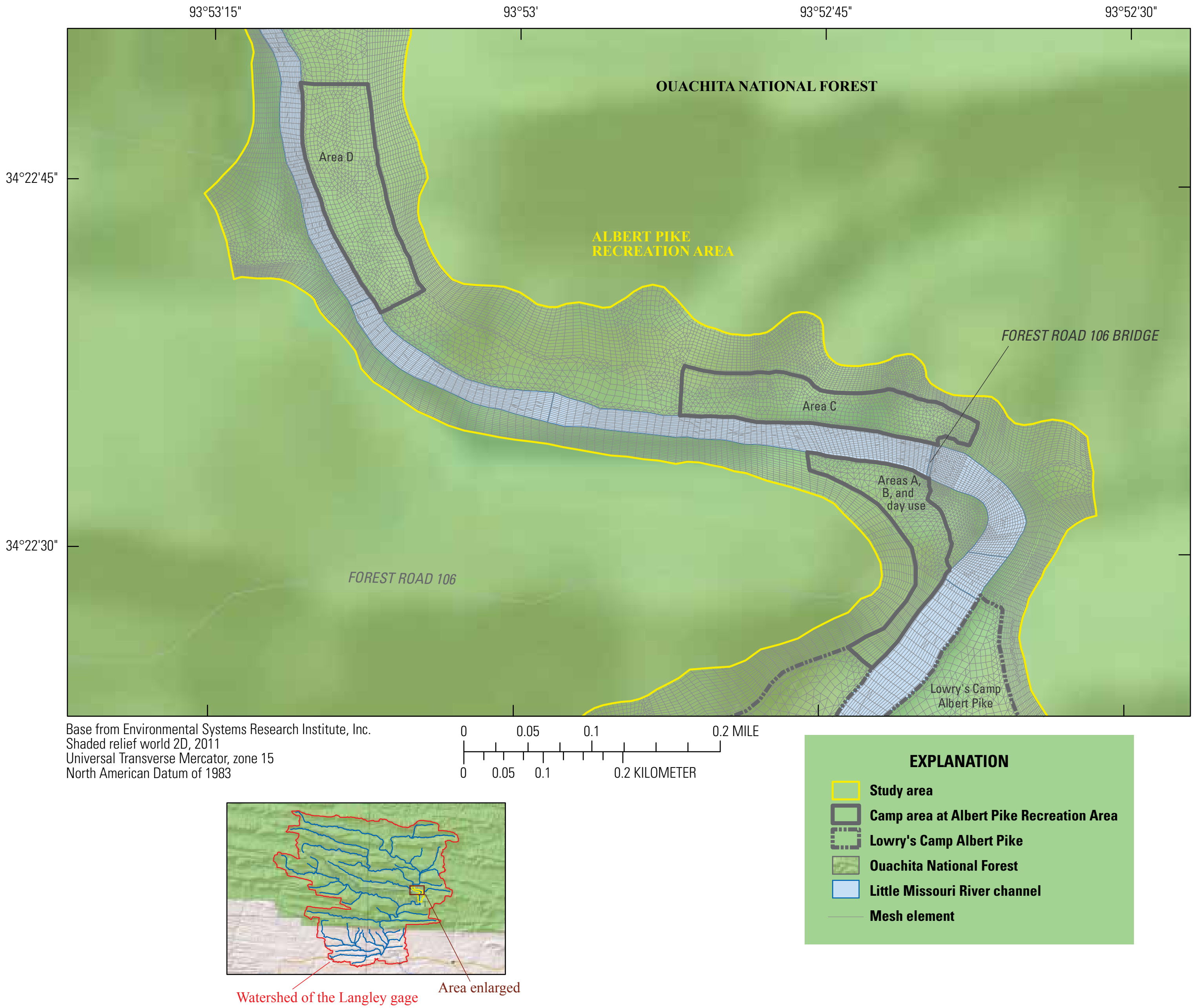


Figure 5. Elements in the finite-element mesh used to represent the land surface in part of the study area at Albert Pike Recreation Area, Arkansas.

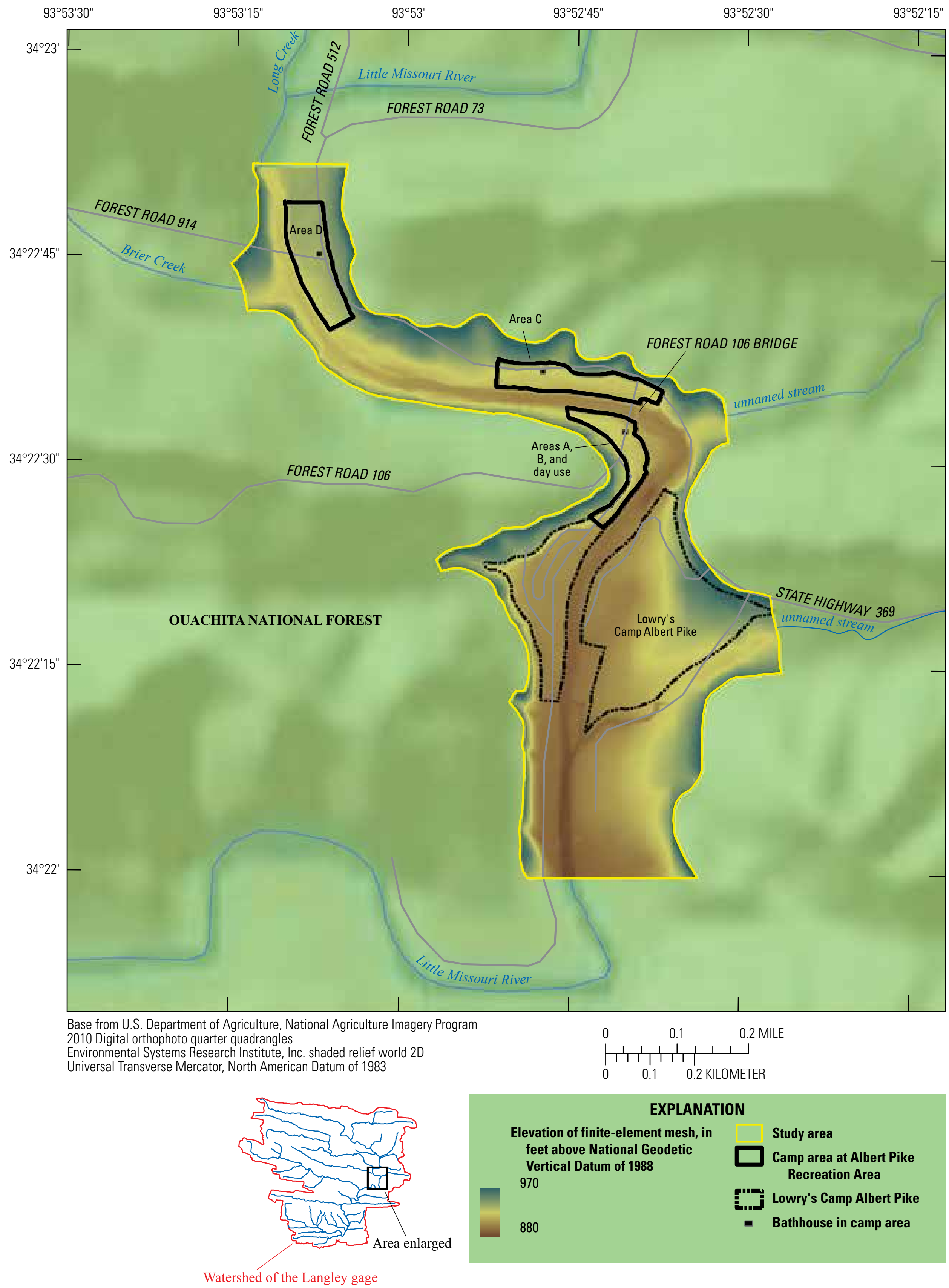


Figure 6. Elevation of the finite-element mesh used to represent the land surface at Albert Pike Recreation Area and Lowry's Camp Albert Pike, Arkansas.

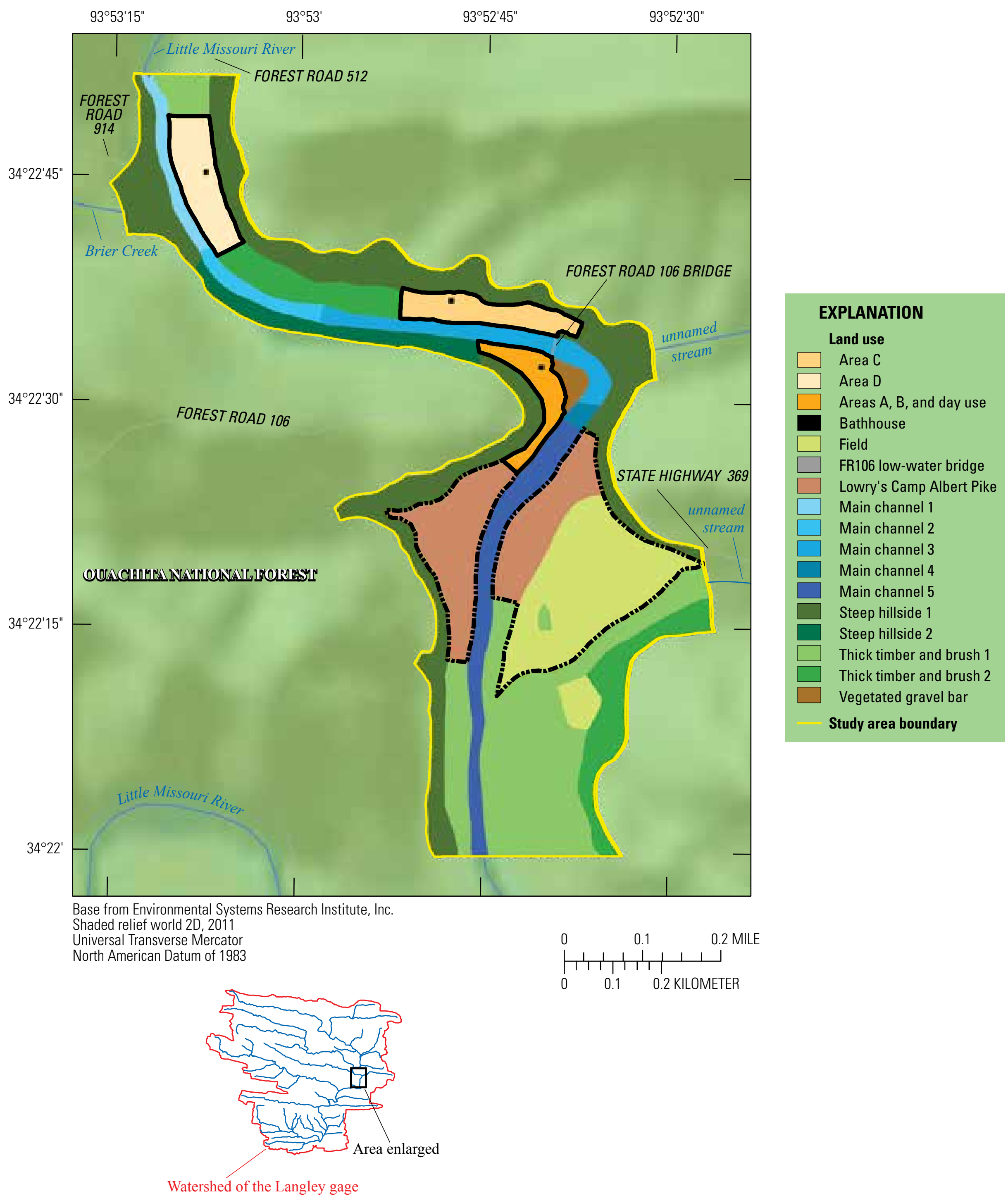


Figure 7. Land-cover types at Albert Pike Recreation Area and Lowry's Camp Albert Pike, Arkansas.

Table 2. Land-cover types and associated Manning's *n*-values used in the development of the model of the June 11, 2010, flood of the Little Missouri River at Albert Pike Recreation Area, Arkansas.

Land-cover type	Lower depth		Upper depth	
	Manning's *n*	Depth (feet)	Manning's *n*	Depth (feet)
Channel				
Main channel 1	0.060	10	0.060	15
Main channel 2	0.070	10	0.070	15
Main channel 3	0.053	10	0.053	15
Main channel 4	0.060	10	0.060	15
Main channel 5	0.057	10	0.057	15
FR106 bridge	0.045	6	0.045	8
Vegetated gravel bar	0.040	3	0.040	8
Camp areas				
Area C	0.035	3	0.035	8
Area D	0.045	3	0.045	8
Areas A, B & Day Use Area	0.035	3	0.035	8
Lowry's Camp Albert Pike	0.058	6	0.058	10
Overbank and hillslopes				
Dense timber and brush 1	0.120	6	0.075	12
Dense timber and brush 2	0.073	6	0.073	12
Field	0.035	2	0.030	3
Steep hillside 1	0.076	6	0.076	12
Steep hillside 2	0.070	6	0.070	12

Table 3. Model-control parameters used in the model of the June 11, 2010, flood of the Little Missouri River at Albert Pike Recreation Area, Arkansas.

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

Parameter	Initial value	Final value
Water depth convergence[1] (ft)	0.5	0.001
Unit flow convergence[2] (ft^2/s)	10	0.005
Depth tolerance for drying[3] (ft)	0.2	0.2
Storativity depth[4] (ft)	3.0	3.0
Kinematic eddy viscosity[5] (ft^2/s)	300	20

[1]Maximum allowable change of water-surface elevation at a node between successive model iterations.

[2]Maximum allowable change in flow rate per unit width (ft) between model iterations.

[3]Minimum depth of water over the node of lowest elevation in an element necessary to rewet the element if it has gone dry in the previous iteration.

[4]A node goes dry when the computed water-surface elevation at the node falls below its assigned elevation minus the storativity depth.

[5]Accounts for lateral shear stress in turbulent flow.

FR106 crosses the Little Missouri River on a small bridge between Areas B and C at Albert Pike (fig. 2). Because the bridge was inundated to a depth of more than 10 ft, pressure flow through the bridge was considered very small in comparison to the total flow over the bridge deck, and the bridge was represented in the model as a weir. Elements in the model mesh used to represent the bridge were assigned the dimensions and elevation of the bridge deck obtained during the ground survey.

User-defined model-control parameters (table 3) (Froehlich, 2002) included water-depth convergence, unit-flow convergence, depth tolerance for drying, storativity depth, and kinematic eddy viscosity. Water-depth convergence is the maximum allowable change of water-surface elevation at a node between successive model iterations. Unit-flow convergence is the maximum allowable change in flow rate per unit width (feet) between model iterations. The depth tolerance for drying is the minimum depth of water over the node of lowest elevation in an element necessary to rewet the element if it has gone dry in the previous iteration. The storativity depth is subtracted from the land-surface elevation of each node in the mesh; a node goes dry when the computed water-surface elevation at the node falls below its assigned elevation minus the storativity depth. Kinematic eddy viscosity accounts for lateral shear stress resulting from turbulent flow. In addition to these model control parameters, semislip conditions were enabled in the model to account for tangential shear stress on the edges of the flooded extent.

Peak streamflows of the Little Missouri River and tributary Brier Creek served as the streamflow inputs to the model. Two options were considered for the Little Missouri River input: (1) the combined total of the peak streamflows of the Little Missouri River above Long Creek and tributary Long Creek (Holmes and Wagner, 2011) (table 1); and (2) the peak streamflow of the Little Missouri River at Area D at Albert Pike (Marion, 2012) (table 1). Because of the unknown timing of the peaks of Long Creek and the main stem of the Little Missouri River, the peak streamflow provided for the Little Missouri River at Area D at Albert Pike (35,600 ft^3/s) (Marion, 2012) was selected as the main streamflow input to the model. The peak streamflow for tributary Brier Creek (6,530 ft^3/s) (Holmes and Wagner, 2011) was included in the model as a second streamflow input. Two small, unnamed tributary streams also drained to the model reach (fig. 2). The total drainage area of these tributaries (1.9 mi^2) accounted for only 5.3 percent of the total drainage area of the model reach (36.0 mi^2). The peak streamflows of these tributaries were assumed to be minor in comparison to the peak streamflows of the Little Missouri River and Brier Creek and were not included in the simulation.

In addition to boundary roughness and streamflow inputs, the Fst2DH model requires that a target water-surface elevation be assigned to the downstream boundary of the model. The elevation used was 905.6 ft, which is the average elevation of two high-water marks located near the boundary (fig. 4).

Calibration of the Model of the June 11, 2010, Flood

The simulation of a flow scenario using Fst2DH required an iterative process called spindown (Huizinga, 2008) that involved initializing the model with the desired streamflow input and a water-surface elevation at the downstream model boundary that was equal to the highest land-surface elevation in the model. This created a flat water surface and ensured that all elements in the model exhibited a positive depth of flow, promoting numerical stability. After the model converged on an initial solution, the downstream water-surface elevation was reduced incrementally until convergence was achieved at the target water-surface elevation.

Once the target water-surface elevation was reached, *n*-values for the various land-cover types were varied in small increments to adjust simulated water-surface elevations to within 0.5 ft of the surveyed elevations of high-water marks of excellent or good quality and 1.0 ft of high-water marks of fair quality. The final *n*-values were comparable to those used in the study area in the previous investigations of the flood and to those of similar land-cover types referenced in Barnes (1967) and Chow (1959).

Model-control parameters were then adjusted. First, the kinematic eddy viscosity was reduced incrementally to 20 square feet per second (ft^2/s) (table 3), which is within the range of acceptable values for natural streams (Froelich, 2002). The depth tolerance for drying was left unchanged at 0.2 ft (table 3). Because of the steep terrain in the study area, many elements along the edges of the flooded extent exhibited a large range in elevation between their lowest and highest nodes. To prevent those elements from being turned off when only small sections of them were dry, the storativity depth was left at the initial setting of 3.0 ft. Mesh elements along the edges of the flooded extent that the model solution indicated were dry, but remained wet because of the relatively high storativity depth, were manually turned off. The final solution was then improved by incrementally decreasing the water depth convergence and unit flow convergence parameters to very small values (table 3).

For comparison of model output with the results of the previous investigations in the study area, the water-surface elevation, velocity, and depth were observed at 23 cross sections in the study area (fig. 8). Locations and names of the 8 cross sections in Area C and the 10 cross sections in Area D corresponded to those of cross sections in the USFS investigation (Marion, 2012). The names of the remaining five cross-sections, XS-1, XS-2, XS-3, XS-4, and XS-5, correspond to those of cross sections used in the indirect measurement of peak streamflow of the Little Missouri River at Area C at Albert Pike (Holmes and Wagner, 2011; measurement summary available at http://water.usgs.gov/osw/floods/reports/index.html#2010).

Development of the Models of Floods Corresponding to Annual Exceedence Probabilities of 1 and 2 Percent

Predictions of flooding that would result from streamflows corresponding to AEPs of 1 and 2 percent (table 1) were achieved by using the calibrated model of the June 11, 2010, flood as an initial model solution and continuing the spin-down process. Streamflow inputs for the Little Missouri River at Area D at Albert Pike and tributary Brier Creek were reduced incrementally from the June 11, 2010, values until those corresponding to AEPs of 1 percent were reached. The water-surface elevation at the downstream model boundary was then reduced incrementally until a water-surface elevation representative of an AEP of 1 percent was reached. The process was repeated for streamflows of the Little Missouri River and Brier Creek corresponding to AEPs of 2 percent.

Water-surface elevations at the downstream model boundary corresponding to AEPs of 1 and 2 percent were computed using the water-surface slope between cross section C04 (fig. 8) and the downstream model boundary from the calibrated model of the flood. Cross-section C04 was chosen because the average simulated water-surface elevation at the cross section (921.98 ft) closely matched the water-surface elevation simulated using a standard step model (922.0 ft) (Marion, 2012). The difference between the simulated water-surface elevations at cross-section C04 and the downstream model boundary (905.6 ft) yielded a fall of 16.38 ft over a stream-wise distance of 4,150 ft (a water-surface slope of 0.0039 ft/ft). The fall in water-surface elevation was then subtracted from the water-surface elevations corresponding to the 1 and 2 percent AEPs (920.6 ft and 919.7 ft, respectively) at cross-section C04 that were predicted using a standard step model (Marion, 2012), yielding water-surface elevations of 904.2 ft for the 1 percent AEP and 903.3 ft for the 2 percent AEP.

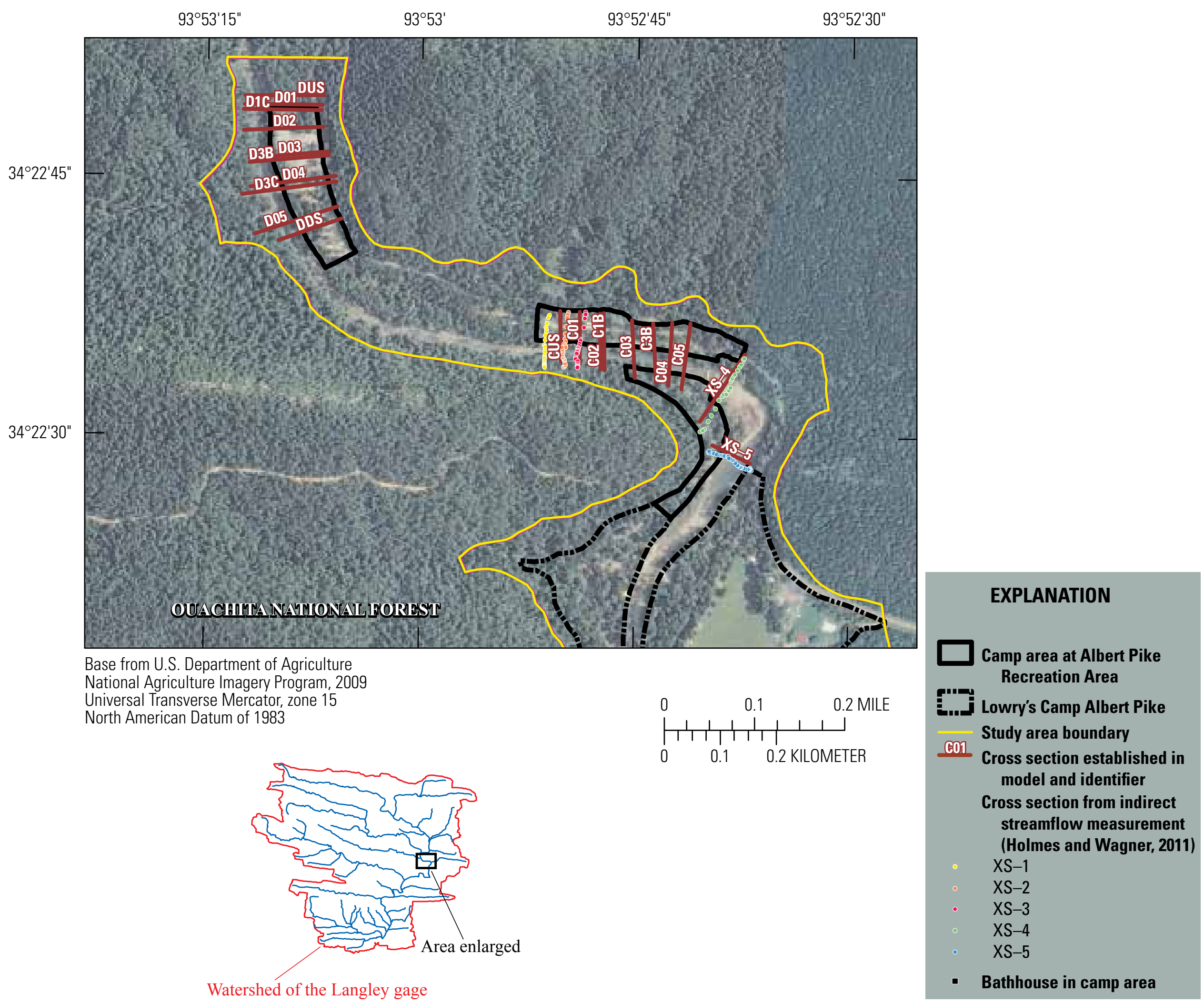


Figure 8. Location of cross sections in the study area at Albert Pike Recreation Area, Arkansas.

Two-Dimensional Simulation

Simulation of the June 11, 2010, Flood

Peak streamflows determined for the flood at Albert Pike and at the Langley gage were considerably higher than those experienced during other floods in recent history. Peak streamflow determined at the Langley gage was 70,800 ft^3/s, the highest peak streamflow in 22 years of record (Holmes and Wagner, 2011). Based on discussions with a longtime Lowry's Camp Albert Pike resident (Holmes and Wagner, 2011), the flood appears to have been the largest since May 13, 1968 (Gilstrap, 1970).

The simulation of the flood extent (fig. 9) replicated the observed extent of flooding in all of the camp areas. Simulated water-surface elevations (fig. 10) ranged from 940.0 ft at the upstream model boundary to 905.6 ft at the downstream model boundary. Generally, the simulated water-surface elevations in the study area were within 0.5 ft of the surveyed elevations of high-water marks of excellent or good quality and within 1.0 ft of the surveyed elevations of high-water marks of fair quality (table 4). The simulated water-surface elevation at the location of high-water mark 11 on the upstream wall of the bathhouse in Area C (924.58 ft) was 1.90 ft higher than the surveyed elevation of the high-water mark (922.68 ft) (table 4) because of run-up on the upstream wall of the bathhouse. This compares favorably with the velocity head of 2.02 ft computed at XS-3 in the indirect measurement of peak streamflow of the Little Missouri River at Area C (Holmes and Wagner, 2011; measurement summary available at http://water.usgs.gov/osw/floods/reports/index.html#2010).

Comparison of the simulated water-surface elevations at the cross sections in Areas C and D with those modeled by the USFS (Marion, 2012) was, in general, favorable. In Area D, the simulated water-surface elevations ranged from

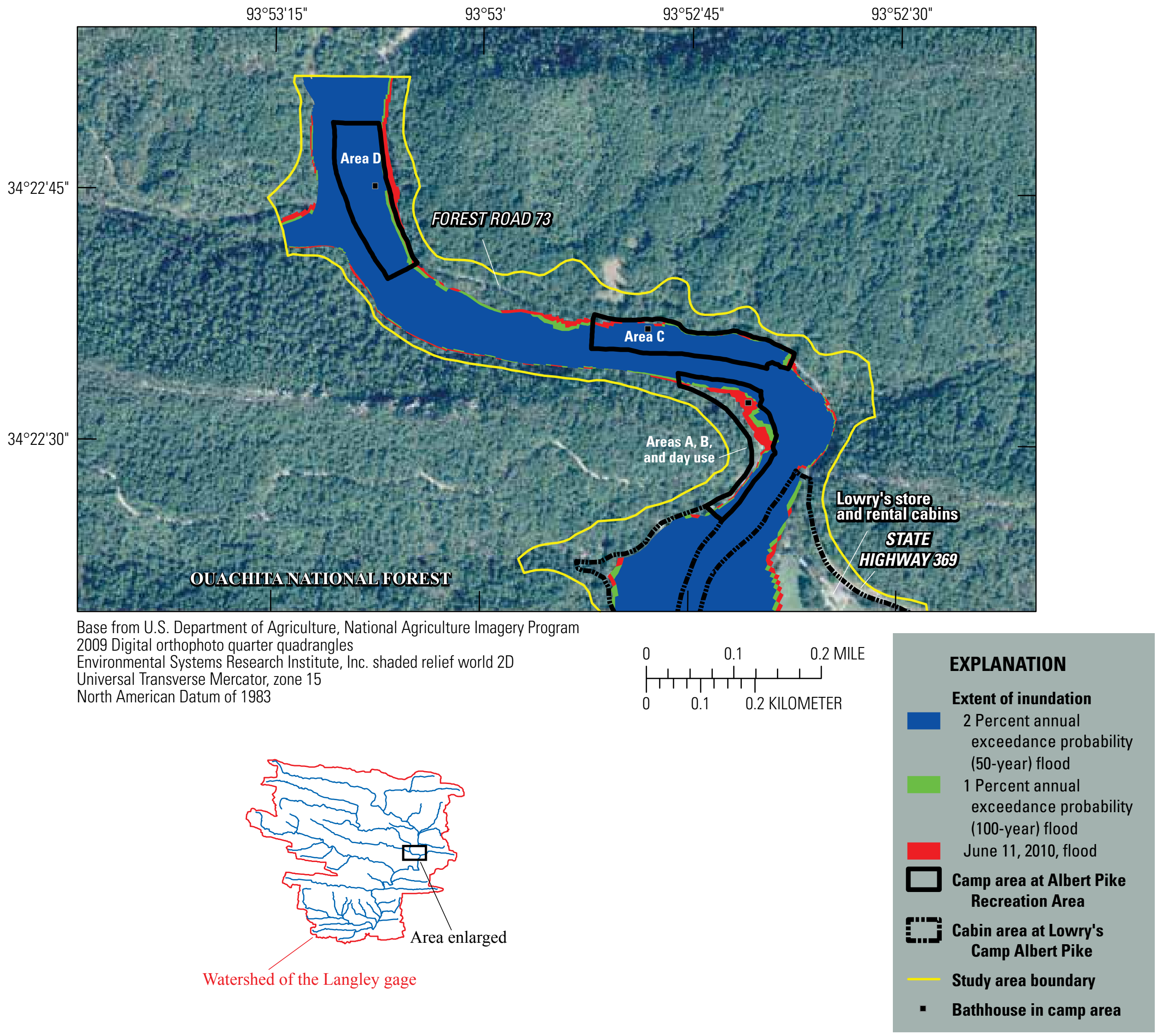


Figure 9. The study area showing the simulated extent of inundation of the June 11, 2010, flood of the Little Missouri River at Albert Pike Recreation Area, Arkansas, and the predicted extents of inundation of floods corresponding to annual exceedence probabilities of 1 and 2 percent.

+0.7 to -1.1 ft of those modeled by the USFS (Marion, 2012) (table 5), with a mean absolute difference of 0.32 ft. In Area C, the comparison was not as good; simulated water-surface elevations ranged from 0 to -1.1 ft of the water-surface elevations modeled by the USFS (Marion, 2012) (table 6), with a mean absolute difference of 0.58 ft. The difference was greater at the four upstream cross sections (CUS, C01, C1B, and C02; mean absolute difference of 0.93 ft) than at the four downstream cross sections (C03, C3B, C04, and C05; mean absolute difference of 0.23 ft). The greater differences at the four upstream cross sections were attributed to variability between the elevations of high-water marks used in the USFS investigation and those used in the two-dimensional simulation. The mean elevations of high-water marks used by the USFS at cross-sections CUS and C01 were 925.12 ft and 925.01 ft, respectively (Marion, 2012). The mean of the elevations of high-water marks 9, 10, 15, 16, and 17 (table 4), which were located between cross-sections CUS and C01, was 924.18 ft, nearly 1 ft lower than the elevation of the high-water marks used by the USFS (note that the elevations of high-water marks 9, 10, 15, 16, and 17 range from 923.56 ft to 925.03 ft). At the four downstream cross sections in Area C, the agreement between models was better because the elevations of high-water marks used in the USFS investigation were near to those of high-water marks used to calibrate the two-dimensional simulation. For example, a high-water mark elevation of 922.84 ft was used by the USFS at cross-section C03 (Marion, 2012); the elevations of high-water marks 20 and 21 (table 4), located near cross-section C03, were 922.65 ft and 922.30 ft, respectively.

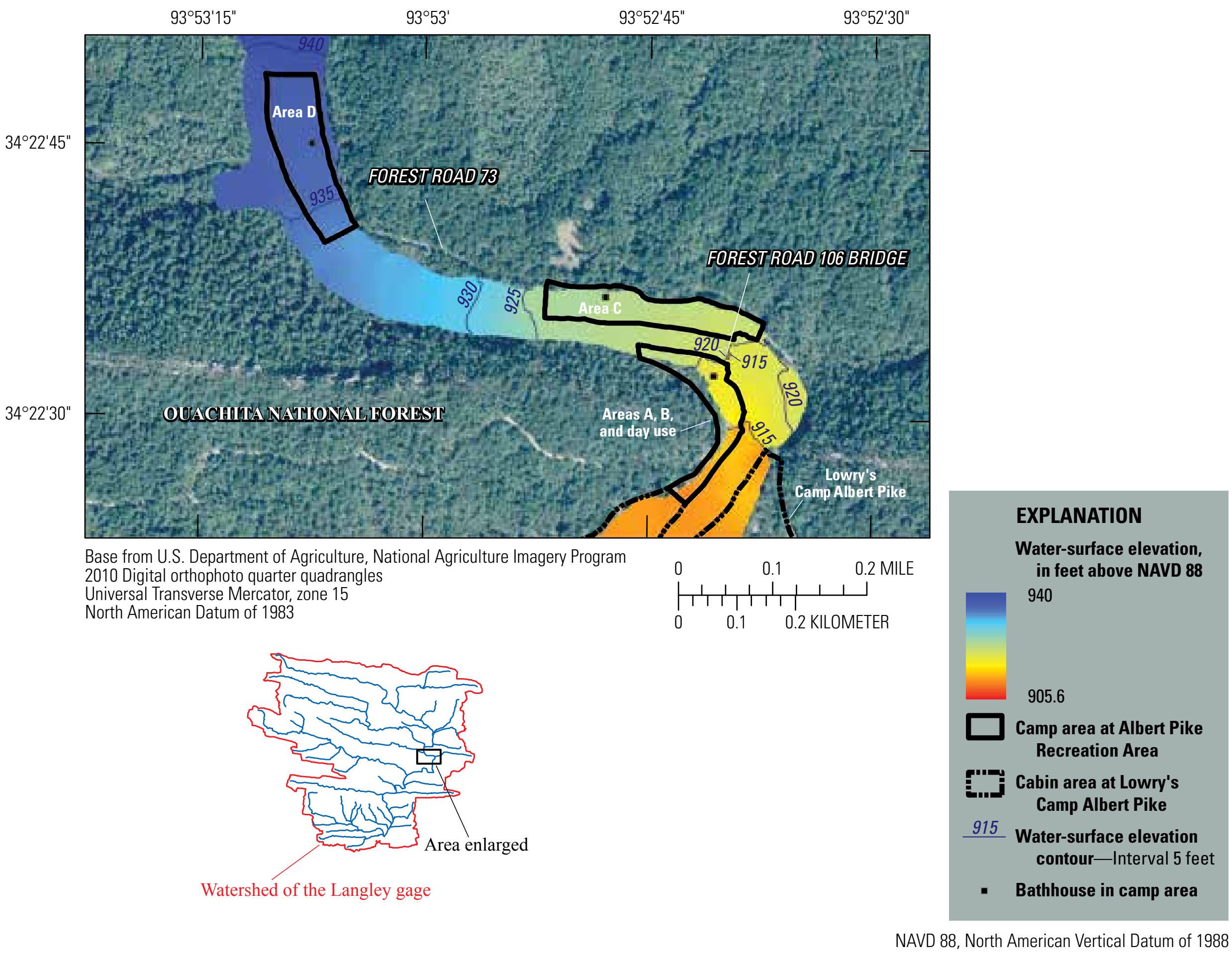


Figure 10. Simulated water-surface elevations of the June 11, 2010, flood of the Little Missouri River at Albert Pike Recreation Area, Arkansas.

Simulated depth of inundation was as much as 31 ft in the main channel of the Little Missouri River at the swimming area (fig. 11). In the camp areas, the mean depth of inundation (calculated as the mean of the depth at all nodes in each respective area) was 8.5 ft in Area D, 7.4 ft in Area C, 3.8 ft in Areas A, B, and the Day Use Area, and 12.5 ft in Lowry's Camp Albert Pike. With the exception of cross-sections D3C, D04, C1B, C02, and C05, simulated maximum depths compared favorably with those in the USFS investigation (Marion, 2012) (tables 5, 6). Comparison with the results of a HEC-RAS model of the Little Missouri River watershed upstream from the Langley gage for the area in common with the two-dimensional model indicated that the mean water depth was 11.0 ft in the HEC-RAS model, and 10.8 ft in the two-dimensional model (Westerman and Clark, 2013).

The water velocity in the main channel was greater than 20 ft/s at the FR106 bridge and at the constriction in the main channel at cross-section XS-5, just upstream from the swimming area (figs. 8, 11). In the camp areas, the mean water velocity (calculated as the mean of the velocity magnitude at all nodes in each respective area) was 7.2 ft/s in Area D, 7.6 ft/s in Area C, 7.2 ft/s in Areas A, B, and the Day Use Area, and 7.6 ft/s in Lowry's Camp Albert Pike. In general, simulated water velocities at cross sections in Areas C and D (fig. 8) compared favorably with water velocities computed at those cross sections as part of the slope-area indirect measurements of peak streamflow of the Little Missouri River (Holmes and Wagner, 2011; Marion, 2012) (tables 5, 6). Simulated velocities at the cross sections in Area D generally were lower than those computed by the USFS at the same cross sections (Marion, 2012) (table 5). A possible explanation for the difference is that the relatively high roughness of the area of dense forest downstream from Area D decreased the magnitude of the velocity computed in Area D by the two-dimensional model, relative to that computed by Marion using the slope-area method. The comparison between velocities in Area C (table 6) was more favorable. Comparison with the results of a HEC-RAS model of the Little Missouri River watershed upstream from the Langley gage for the area in common with the two-dimensional model indicated that the mean stream velocity simulated by the HEC-RAS model was 5.7 ft/s, while the mean stream velocity simulated by the two-dimensional model was 6.2 ft/s (Westerman and Clark, 2013).

Table 4. High-water marks used to calibrate the simulation of the June 11, 2010, flood of the Little Missouri River at Albert Pike Recreation Area, Arkansas.

[NAVD 88, North American Vertical Datum of 1988]

Number	Location/ description	Quality	Observed water-surface elevation	Simulated water-surface elevation	Difference[1]
			Elevation (in feet above NAVD 88)		
1	Area D	fair	937.75	936.67	-1.08
2	Area D/kiosk	excellent	936.50	936.71	0.21
3	Area D/kiosk	excellent	936.19	936.01	-0.18
4	Area D/kiosk	excellent	935.98	935.99	0.01
5	Area D	fair	934.54	934.47	-0.07
6	Area D	fair	934.22	934.32	0.10
7	Area C	fair	925.36	924.40	-0.96
8	Area C	fair	925.15	924.40	-0.75
9	Area C	excellent	924.58	924.37	-0.21
10	Area C	fair	925.03	924.33	-0.70
11	Area C/bathhouse	excellent	922.68	924.58	1.90
12	Area C/bathhouse	good	922.42	923.33	0.91
13	Near trail upstream from Area B	excellent	926.30	926.48	0.18
14	Near trail upstream from Area B	fair	924.68	924.09	-0.59
15	Near trail upstream from Area B	excellent	924.00	924.05	0.05
16	Near trail upstream from Area B	excellent	923.75	924.24	0.49
17	Near trail upstream from Area B	fair	923.56	924.35	0.79
18	Near trail upstream from Area B	fair	923.32	923.97	0.65
19	Area B	fair	922.93	923.05	0.12
20	Area B	good	922.65	922.70	0.05
21	Area B	excellent	922.30	922.74	0.44
22	Area B/kiosk	fair	919.78	919.18	-0.60
23	Left bank, across river from Day Use Area	fair	915.35	915.42	0.07
24	Right bank at Day Use Area	fair	913.28	913.48	0.20
25	Lowry’s Camp Albert Pike	fair	912.62	911.96	-0.66
26	Lowry’s Camp Albert Pike	fair	912.19	911.79	-0.40
27	Lowry’s Camp Albert Pike	good	912.16	911.90	-0.26
28	Lowry’s Camp Albert Pike	good	912.14	911.98	-0.16
29	Lowry’s Camp Albert Pike	good	911.85	911.90	0.05
30	Lowry’s Camp Albert Pike	good	911.40	911.47	0.07
31	Lowry’s Camp Albert Pike	fair	911.28	911.99	0.71
32	Lowry’s Camp Albert Pike	good	910.30	910.45	0.15
33	Lowry’s Camp Albert Pike	fair	910.28	910.47	0.19
34	Lowry’s Camp Albert Pike	good	910.20	911.16	0.96
35	Lowry’s Camp Albert Pike	excellent	910.19	910.69	0.50
36	Lowry’s Camp Albert Pike	good	910.05	910.10	0.05
37	Lowry’s Camp Albert Pike	good	907.07	906.83	-0.24
38	Lowry’s Camp Albert Pike	fair	906.04	905.79	-0.25
39	Lowry’s Camp Albert Pike	good	906.32	905.64	-0.68
40	Lowry’s Camp Albert Pike	good	904.98	905.63	0.65

[1]Difference calculated as simulated water-surface elevation minus surveyed water-surface elevation.

Table 5. Simulated water-surface elevation, maximum depth, mean depth, and mean velocity for the June 11, 2010, flood at cross sections in Area D, Albert Pike Recreation Area, Arkansas.

[WSE, water-surface elevation; ft, feet; USFS, U.S. Department of Agriculture—Forest Service; D_{max}, maximum depth; V_{mean}, mean water velocity; ft/s, feet per second; MC, main channel]

Cross section	WSE (ft)	WSE (ft)[1] (USFS)	D_{max} (ft)	D_{max} (ft)[1] (USFS)	V_{mean}, Area D (ft/s)	V_{mean}, Area D (ft/s)[1] (USFS)	V_{mean}, MC (ft/s)	Vmean, MC (ft/s)[1] (USFS)
DUS	938.4	938.4	20.1	21.6	5.7	3.8	11.6	11.0
D01	937.7	937.8	20.6	20.5	5.8	4.7	11.5	11.9
D1C	937.5	938.0	20.7	20.9	5.9	8.2	10.9	9.7
D02	937.3	937.3	21.7	21.9	5.5	8.5	9.5	9.4
D03	936.6	936.6	22.3	21.8	6.1	10.9	10.1	8.0
D3B	936.6	936.5	21.6	21.3	5.7	10.8	9.7	8.1
D3C	936.5	936.5	22.0	20.5	5.4	7.7	9.2	8.4
D04	936.4	936.5	21.1	19.8	4.7	8.4	9.8	6.3
D05	935.9	935.2	22.9	23.1	6.6	8.1	10.0	10.8
DDS	935.0	934.3	22.9	22.3	7.7	8.2	10.6	11.4

[1]From U.S. Forest Service investigation (Marion, 2012).

Table 6. Simulated water-surface elevation, maximum depth, mean depth, and mean velocity for the June 11, 2010, flood of the Little Missouri River at cross sections in Area C, Albert Pike Recreation Area, Arkansas.

[WSE, water-surface elevation; ft, feet; USFS, U.S. Department of Agriculture—Forest Service; D_{max}, maximum depth; V_{mean}, mean water velocity; ft/s, feet per second; MC, main channel; NA, not applicable]

Cross section (fig. 8)	WSE (ft)	WSE (ft)[1] (USFS)	D_{max} (ft)	D_{max} (ft)[1] (USFS)	V_{mean}, Area C (ft/s)	V_{mean}, Area C (ft/s)[1] (USFS)	V_{mean}, MC (ft/s)	V_{mean}, MC (ft/s)[1] (USFS)	V_{mean}, Area B (ft/s)	V_{mean}, Area B (ft/s)[1] (USFS)
[2]XS-1	NA	NA	NA	NA	[2]9.3	NA	[2]11.1	NA	NA	NA
CUS	924.3	925.3	23.8	23.7	8.1	9.6	13.2	11.0	NA	NA
[2]XS-2	NA	NA	NA	NA	[2]9.0	NA	[2]12.1	NA	NA	NA
C01	924.1	924.7	23.9	24.3	7.6	9.3	12.2	11.3	NA	NA
[2]XS-3	NA	NA	NA	NA	[2]8.7	NA	[2]12.0	NA	NA	NA
C1B	923.2	924.3	22.5	24.8	7.6	9.2	11.2	9.9	NA	NA
C02	923.2	924.2	22.2	23.8	9.0	9.1	11.3	10.0	NA	NA
C03	922.9	923.3	22.6	23.1	10.1	10.8	10.8	9.1	NA	NA
C3B	922.4	922.5	22.4	22.7	10.1	8.7	12.7	10.6	6.7	4.2
C04	922.0	922.0	21.6	21.3	9.4	9.1	12.9	10.8	7.3	5.1
C05	921.2	921.6	20.5	21.4	9.1	9.1	14.1	10.2	8.9	6.3

[1]From U.S. Forest Service investigation (Marion, 2012).

[2]Cross-section data from indirect measurement of peak streamflow of Little Missouri River at Albert Pike Recreation Area (Area C) (Holmes and Wagner, 2011).

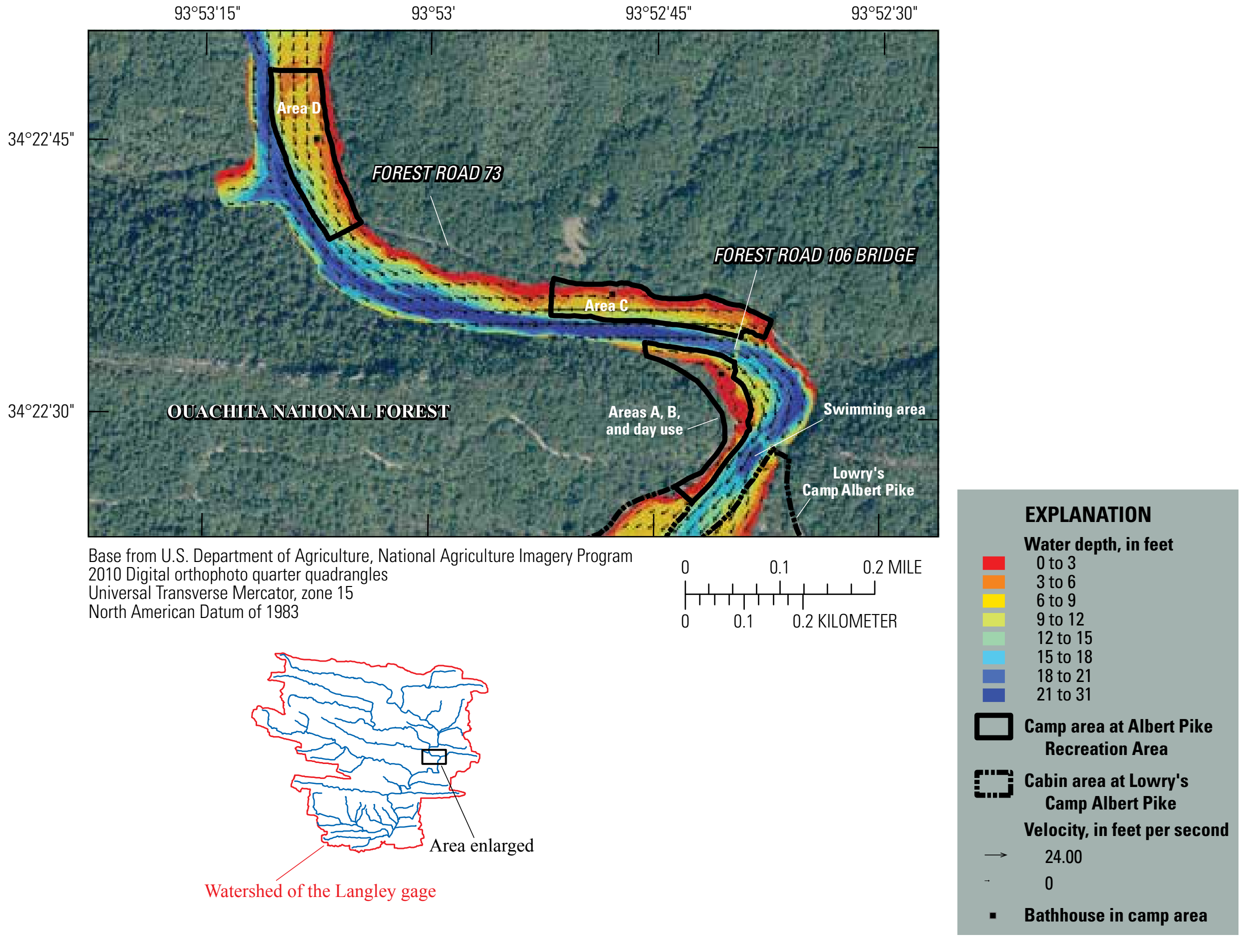


Figure 11. Simulated depth of inundation and magnitude and direction of velocity of the June 11, 2010, flood of the Little Missouri River at Albert Pike Recreation Area, Arkansas.

A check for conservation of mass in the model was performed by establishing what is called a “flux line” near the middle of Area C. A flux line is a cross section, established in the model at a point downstream from all inputs, where the total streamflow is computed and logged in the model’s output file. Streamflow computed at the flux line was 43,727 ft^3/s, 3.8 percent greater than the sum of the inputs (42,130 ft^3/s). Given the steep water-surface slope in the study area, this difference was considered acceptable.

Model Sensitivity

A sensitivity analysis was conducted on the calibrated simulation of the June 11, 2010, flood. In the analysis, boundary roughness, streamflow inputs, and water-surface slope were varied within predetermined limits, and the calibrated model run with the varied inputs to examine their effect on the simulated water-surface elevation. For each model run, the root mean error, also known as the quadratic mean, of the differences between the observed and simulated water-surface elevations at all the high-water marks in the study area was computed as:

$$\text{root mean error} = \sqrt{[(1/n)(x_1^2+x_2^2+\ldots+x_n^2)]},$$

where n is the total number of high-water marks and x_1, x_2, x_n are the differences between the observed and simulated water-surface elevations at each high-water mark. The root mean errors for all model runs in the analysis (table 7) were then compared to the root mean error of the calibrated simulation of the flood (table 7) to determine which parameters had the greatest or least effect on model output.

The sensitivity of the model to changes in boundary roughness was evaluated by varying n-values in the study area by plus or minus (±) 10 percent. First, n-values for all land-cover types were varied simultaneously. Next, n-values for only the main channel of the Little Missouri River were varied. Finally, n-values for all other land-cover types, except the main channel of the Little Missouri River, were varied in aggregate.

Table 7. Root mean error of various model runs in sensitivity analysis.

Model run	Root mean error (feet)
Calibrated model	0.585
Decrease all *n*-values 10 percent	0.873
Increase all *n*-values 10 percent	0.844
Decrease main channel *n*-values 10 percent	0.671
Increase main channel *n*-values 10 percent	0.672
Decrease all but main channel *n*-values 10 percent	0.677
Increase all but main channel *n*-values 10 percent	0.663
Lower water surface elevation at downstream boundary 0.5 feet	0.618
Raise water surface elevation at downstream boundary 0.5 feet	0.596
Lower water surface elevation at downstream boundary 1.0 feet	0.666
Raise water surface elevation at downstream boundary 1.0 feet	0.664
Decrease Little Missouri River streamflow 5 percent	0.640
Increase Little Missouri River streamflow 5 percent	0.668
Decrease Little Missouri River streamflow 10 percent	0.808
Increase Little Missouri River streamflow 10 percent	0.844
Decrease Little Missouri River streamflow 15 percent	1.043
Increase Little Missouri River streamflow 15 percent	1.065
Decrease Brier Creek streamflow 5 percent	0.585
Increase Brier Creek streamflow 5 percent	0.591
Decrease Brier Creek streamflow 10 percent	0.590
Increase Brier Creek streamflow 10 percent	0.600
Decrease Brier Creek streamflow 15 percent	0.600
Increase Brier Creek streamflow 15 percent	0.615
Decrease Brier Creek streamflow 20 percent	0.615
Increase Brier Creek streamflow 20 percent	0.633
Decrease Brier Creek streamflow 25 percent	0.633
Increase Brier Creek streamflow 25 percent	0.656

Sensitivity to changes in the water-surface slope was evaluated by varying the water-surface elevation at the downstream boundary of the model. The water-surface elevation was varied ±0.5 ft and ±1.0 ft from the water-surface elevation of 905.6 ft used in the calibrated model.

Sensitivity to changes in streamflow inputs was evaluated by varying the streamflows for the Little Missouri River at Area D and Brier Creek, in ±5 percent increments, within the range of error associated with the rating of each streamflow measurement. For example, the Brier Creek measurement was rated poor; a poor indirect measurement could have an error of 25 percent or greater (Benson and Dalrymple, 1967). The measurement of the Little Missouri River at Area D (Marion, 2012) was not officially rated but was based on examination of the measurement diagnostics and comparison with the diagnostics of the measurement of the Little Missouri River at Area C (Holmes and Wagner, 2011). The measurement was considered to be of good-to-fair quality, which would represent a possible error of 10 to 15 percent (Benson and Dalrymple, 1967). The sensitivity analysis indicated that varying the streamflow of the Little Missouri River ±15 percent had the greatest effect on the simulated water-surface elevation (table 7), increasing the root mean error to over 1.0 ft. Varying the streamflow of Brier Creek ±5 percent had the least effect on the simulated water-surface elevation, increasing the root mean error 0–0.006 ft with respect to that of the calibrated model (table 7).

Model of the Flood Corresponding to an Annual Exceedence Probability of 1 Percent

The prediction of flooding that would result from a streamflow corresponding to an AEP of 1 percent indicated that all of Areas C, D, and the Day Use Area and parts of Areas A and B at Albert Pike would be inundated, and that the extent of inundation of the June 11, 2010, flood exceeded that of the 1-percent flood (fig. 9). Predicted water-surface elevations ranged from 939.0 ft at the upstream model boundary to 904.2 ft at the downstream model boundary (fig. 12). Predicted water-surface elevations at the cross sections in Areas D and C (fig. 8) were generally 1 ft lower than water-surface elevations modeled by the USFS using the standard step method (Marion, 2012) (table 8). The difference in water-surface elevations is likely because the water-surface slope used in the model of the 1 percent flood was computed using the water-surface elevation determined by the USFS at cross-section C04 for the June 11, 2010, flood (Marion, 2012) (table 6), where agreement between the two models was best; at cross-section C04, the water-surface elevations corresponding to the 1 percent AEP differ by only 0.4 ft (table 8).

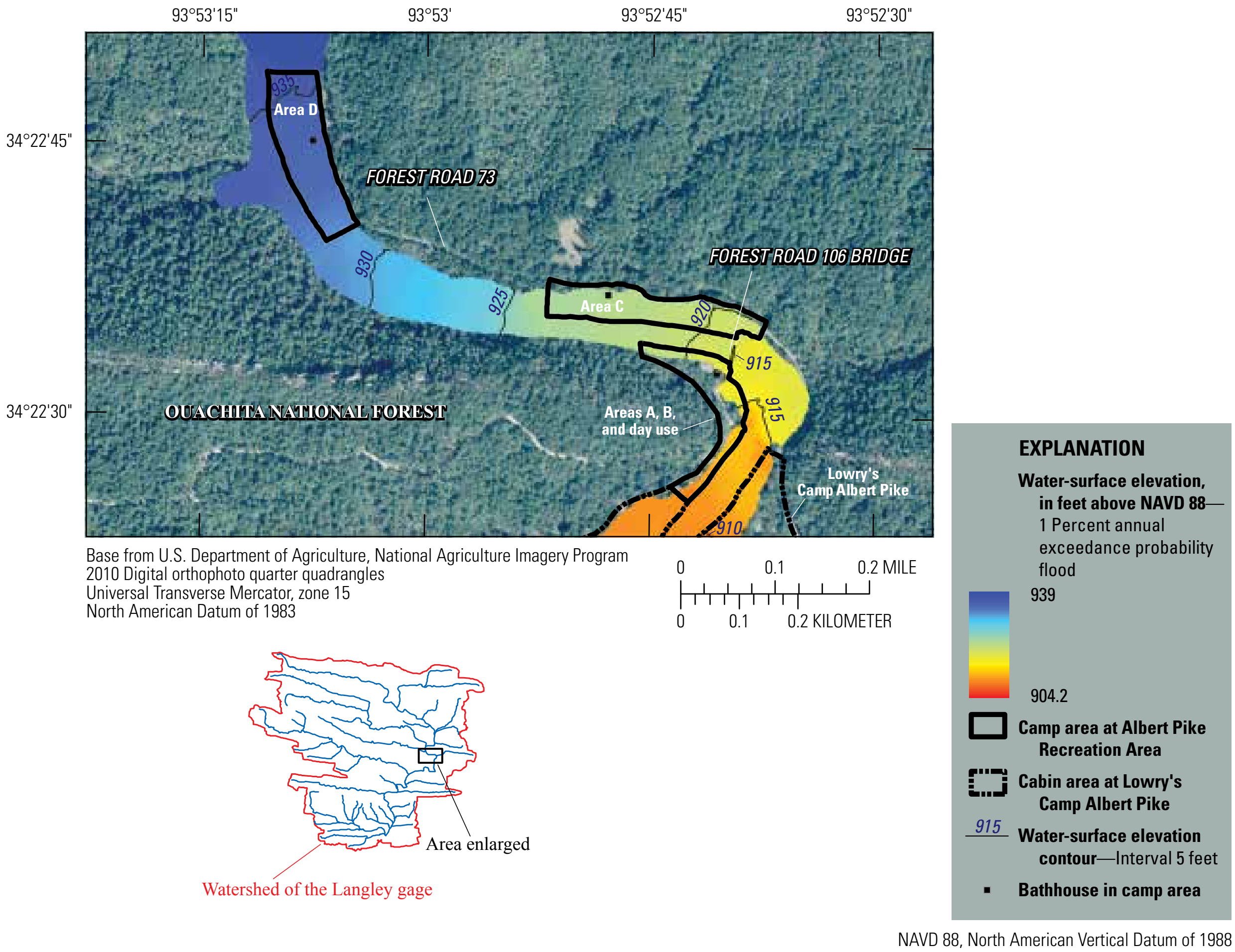


Figure 12. Predicted water-surface elevations of the streamflow of the Little Missouri River at Albert Pike Recreation Area, Arkansas, corresponding to an annual exceedence probability of 1 percent.

Table 8. Predicted water-surface elevation for the streamflow of the Little Missouri River corresponding to an annual exceedence probability of 1 percent at cross-sections in Areas C and D, Albert Pike Recreation Area, Arkansas, and water-surface elevations modeled by U.S. Forest Service using the standard step method (Marion, 2012).

[WSE, water-surface elevation; ft, feet; USFS, U.S. Department of Agriculture—Forest Service]

Cross section (fig. 8)	WSE (ft)	WSE (ft)[1] (USFS)	Cross section (fig. 8)	WSE (ft)	WSE (ft)[1] (USFS)
CUS	922.4	923.6	D01	935.5	936.5
C01	922.2	923.1	D1C	935.3	936.6
C1B	921.4	922.7	D02	935.0	936.0
C02	921.5	922.6	D03	934.0	935.3
C03	921.1	921.8	D3B	934.0	935.1
C3B	920.6	921.1	D3C	933.8	935.1
C04	920.2	920.6	D04	933.8	935.1
C05	919.4	920.1	D05	933.4	933.6
DUS	936.3	937.1	DDS	932.6	932.7

[1]From U.S. Forest Service investigation (Marion, 2012).

Predicted depth of inundation was as much as 25 ft in the main channel of the Little Missouri River at the swimming area (fig. 13). The mean depth of inundation in the camp areas (calculated as the mean of the depth at all nodes in each respective area) was 6.51 ft in Area D, 6.51 ft in Area C, 3.84 ft in Areas A, B, and the Day Use Area, and 6.90 ft in Lowry's Camp Albert Pike.

Predicted water velocity of the 1-percent flood was greater than 20 ft/s at the FR106 bridge and at the constriction in the main channel at XS-5, just upstream from the swimming area (figs. 8 and 13). The mean velocity in the camp areas (calculated as the mean of the velocity magnitude at all nodes in each respective area) was 6.56 ft/s in Area D, 6.90 ft/s in Area C, 6.81 ft/s in Areas A, B, and the Day Use Area, and 3.99 ft/s in Lowry's Camp Albert Pike.

Model of the Flood Corresponding to an Annual Exceedence Probability of 2 Percent

The prediction of flooding that would result from a streamflow corresponding to an AEP of 2 percent indicated that all of Areas C and D and parts of Areas A, B, and the Day Use Area at Albert Pike would be inundated (fig. 9). Predicted water-surface elevations ranged from 938.0 ft at the upstream model boundary to 903.3 ft at the downstream model boundary (fig. 14). The predicted water-surface elevations at the cross sections in Areas C and D were generally 1 ft lower than those modeled by the USFS using the standard step method (Marion, 2012) (table 9). The difference in water-surface elevations is likely the result of the water-surface slope used in the model of the 2-percent flood being computed using the water-surface elevation determined by the USFS at cross-section C04 for the June 11, 2010, flood (Marion, 2012) (table 6), where agreement between the two models was best; at cross-section C04, the water-surface elevations corresponding to the 2-percent AEP differ by only 0.5 ft (table 9).

Predicted depth of inundation was as much as 24 ft in the main channel of the Little Missouri River at the swimming area (fig. 15). The mean depth of inundation in the camp areas (calculated as the mean of the depth at all nodes in each respective area) was 5.59 ft in Area D, 5.88 ft in Area C, 3.90 ft in Areas A, B, and the Day Use Area, and 6.21 ft in Lowry's Camp Albert Pike.

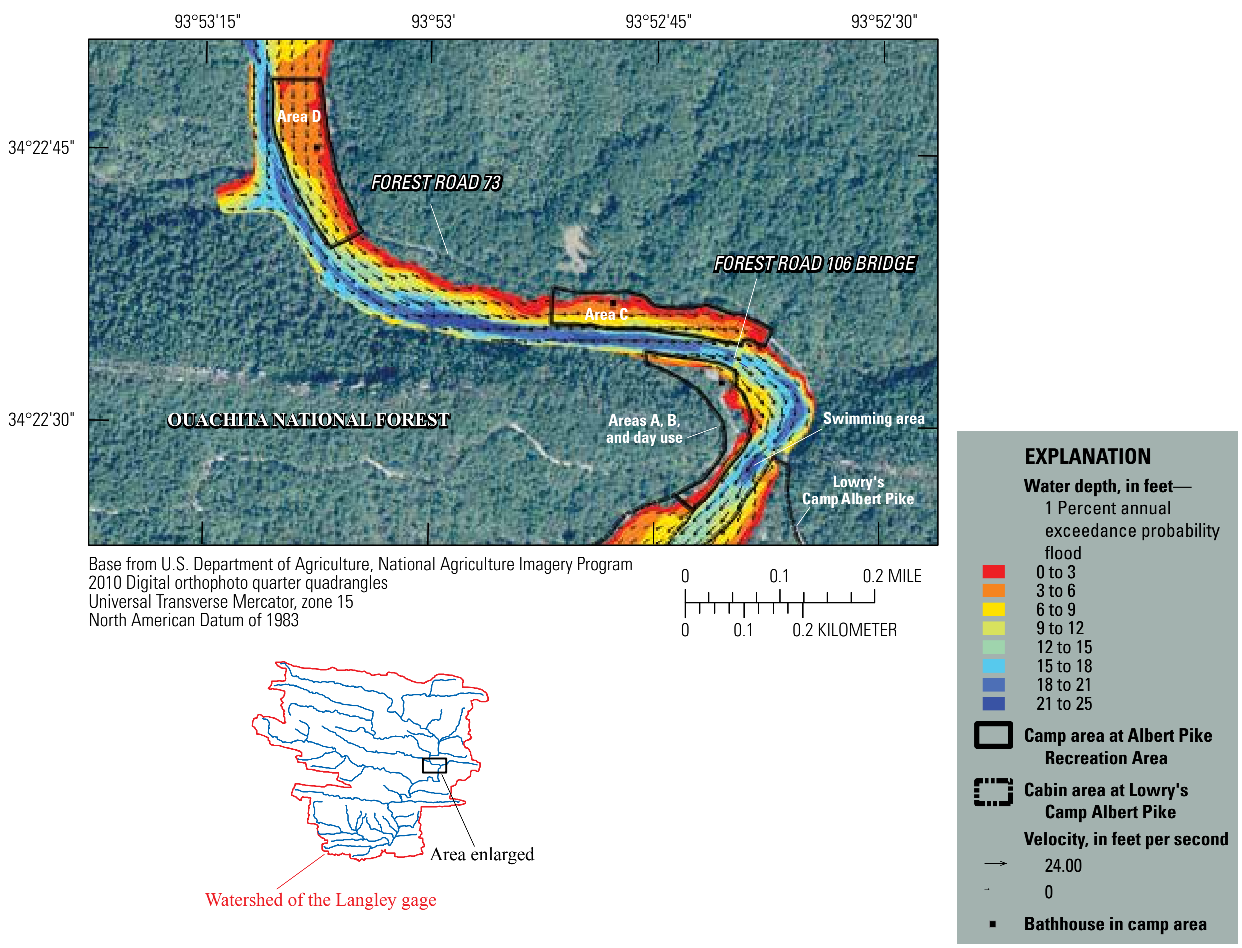


Figure 13. Predicted depth of inundation and velocity magnitude and direction of the streamflow of the Little Missouri River at Albert Pike Recreation Area, Arkansas, corresponding to an annual exceedence probability of 1 percent.

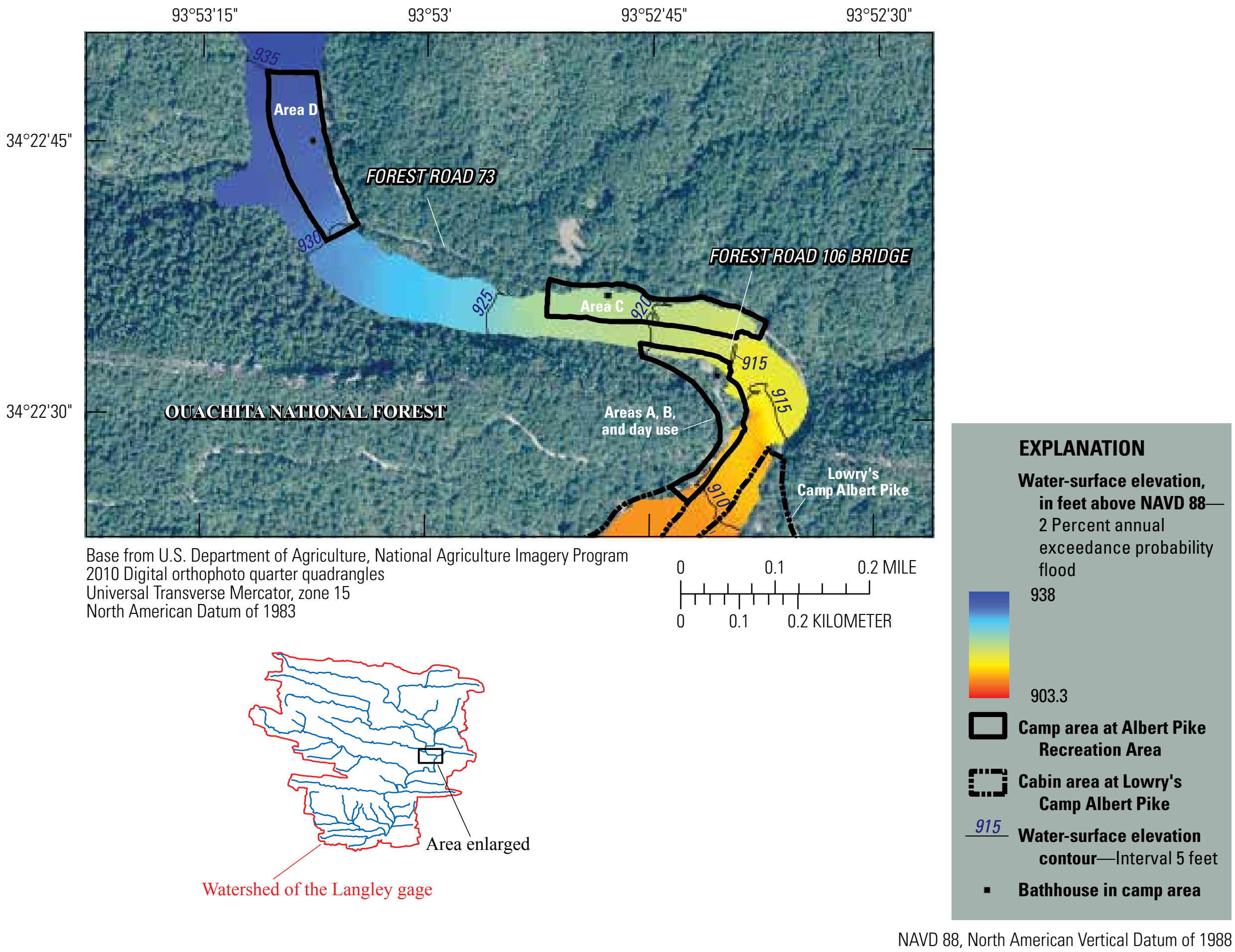


Figure 14. Predicted water-surface elevations of the streamflow of the Little Missouri River at Albert Pike Recreation Area, Arkansas, corresponding to an annual exceedence probability of 2 percent.

Table 9. Predicted water-surface elevation for the streamflow corresponding to an annual exceedence probability of 2 percent at cross sections in Areas C and D, Albert Pike Recreation Area, Arkansas, and water-surface elevations modeled by U.S. Forest Service using the standard step method (Marion, 2012).

[WSE, water-surface elevation; ft, feet; USFS, U.S. Department of Agriculture—Forest Service]

Cross section (fig. 8)	WSE (ft)	WSE (ft)[1] (USFS)	Cross section (fig. 8)	WSE (ft)	WSE (ft)[1] (USFS)
CUS	921.2	922.6	D01	934.5	935.8
C01	921.0	922.1	D1C	934.2	935.8
C1B	920.3	921.7	D02	934.0	935.2
C02	920.3	921.6	D03	932.8	934.5
C03	920.0	920.9	D3B	932.7	934.3
C3B	919.6	920.2	D3C	932.5	934.3
C04	919.2	919.7	D04	932.5	934.2
C05	918.5	919.2	D05	932.1	932.6
DUS	935.3	936.3	DDS	931.4	931.8

[1]From U.S. Forest Service investigation (Marion, 2012).

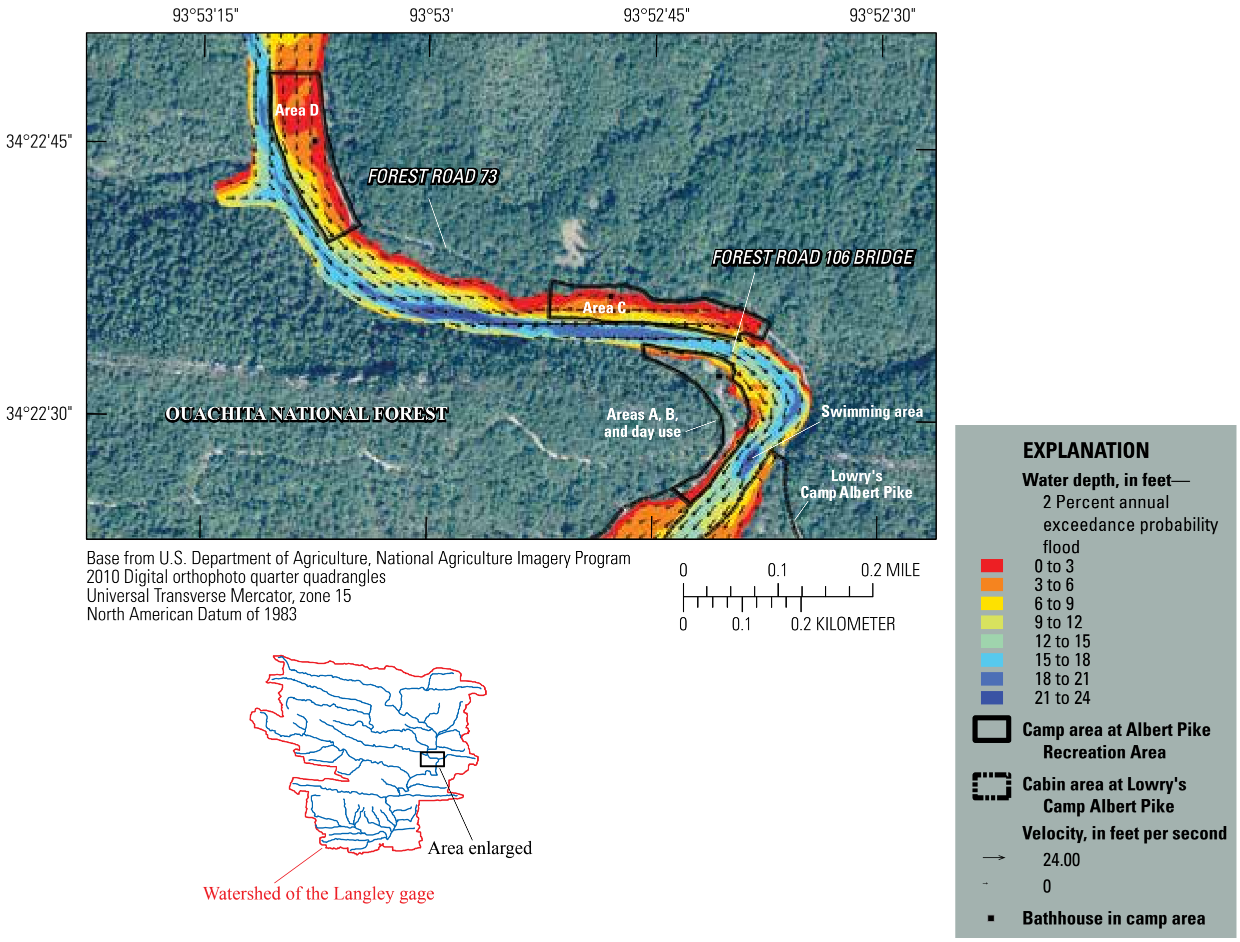


Figure 15. Predicted depth of inundation and velocity magnitude and direction of the streamflow of the Little Missouri River at Albert Pike Recreation Area, Arkansas, corresponding to an annual exceedence probability of 2 percent.

Predicted water velocities were greater than 20 ft/s at the FR106 bridge and at the constriction in the main channel of the Little Missouri River near cross-section XS-5 upstream from the swimming area (figs. 8 and 15). The mean water velocity in the camp areas (calculated as the mean of the velocity magnitude at all nodes in each respective area) was 6.12 ft/s in Area D, 6.81 ft/s in Area C, 6.55 ft/s in Areas A, B, and the Day Use Area, and 3.80 ft/s in Lowry's Camp Albert Pike (fig. 15).

Limitations and Uncertainty

The simulation of the June 11, 2010, flood of the Little Missouri River at Albert Pike could differ slightly from actual flood conditions for several reasons. First, the simulations did not account for inflow to the study area from sources other than the Little Missouri River and Brier Creek, such as flow from two small unnamed tributaries (fig. 2). The sensitivity analysis indicated that varying the flow of tributary Brier Creek ±25 percent, whose drainage area (3.32 mi^2) is nearly twice the size of the combined drainage areas of the two small unnamed tributaries (1.90 mi^2), resulted in an increase of only 0.05 to 0.07 ft in the root mean error of the model (table 7). Therefore, although adding flows from the two small unnamed tributaries may have had small local effects on simulated water-surface elevation, depth, or velocity, it is unlikely they would have had a significant effect on the simulation results. Next, although it was deemed to be small in comparison to the flow over the bridge deck, pressure flow through the FR106 bridge was not calculated. Finally, two mesh elements in the main channel of the Little Missouri River along the upstream boundary of the model repeatedly became unstable in the model during the spin-down process. It was eventually necessary to disable the elements (fig. 16) to ensure model stability, creating what the model perceives as an obstruction to flow in the main channel. However, the upstream boundary of the model was placed sufficiently upstream from Albert Pike and the disabled elements do not appear to affect the model solution in Area D (fig. 16).

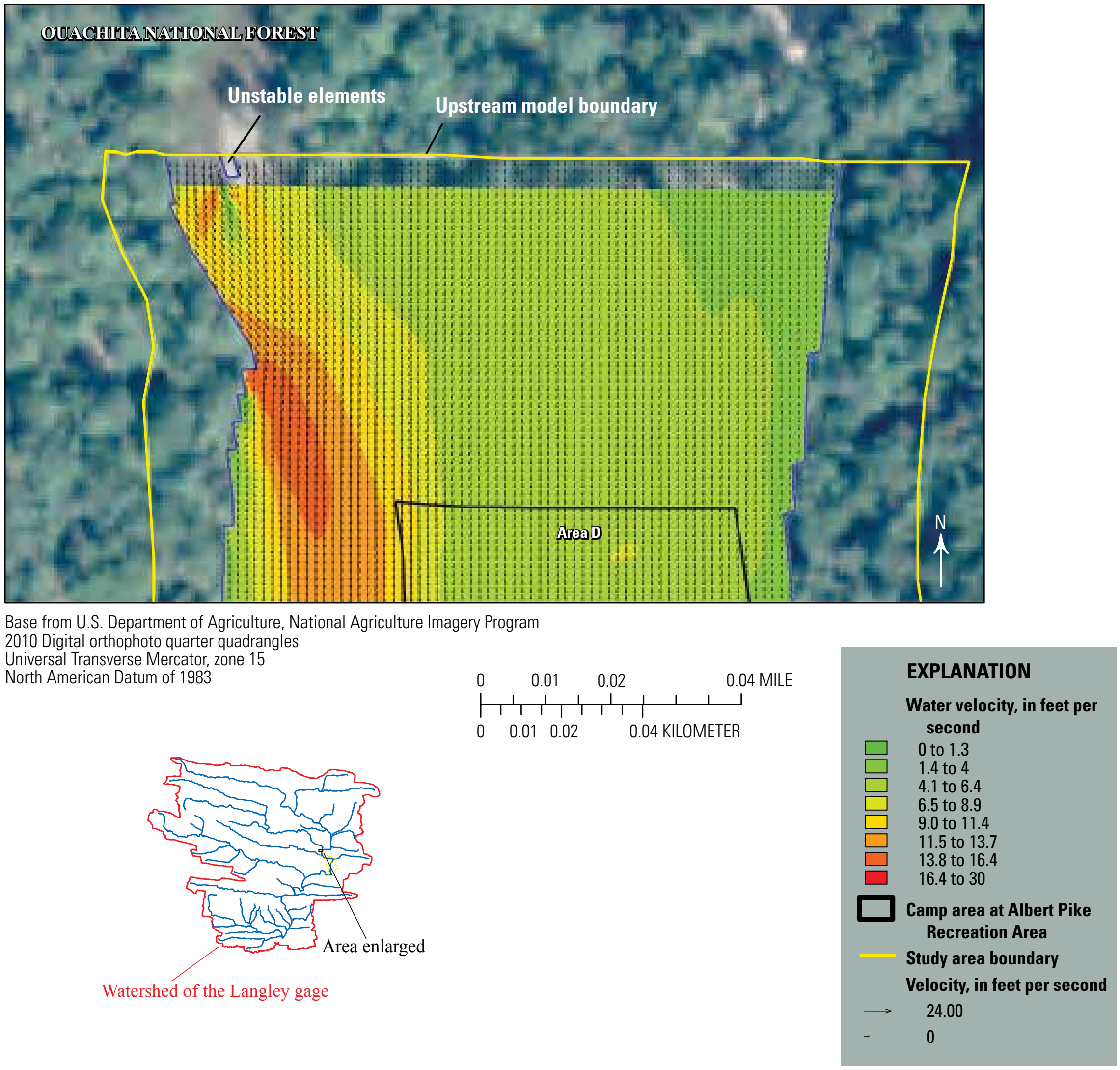


Figure 16. Unstable elements, water depth, and flow paths at the upstream boundary of the model.

Uncertainty in the predictive models of streamflows corresponding to AEPs of 1 and 2 percent can be attributed to the lack of available water-surface elevation data and limitations of the regional regression method used to determine the streamflows. First, to obtain water-surface elevations used as the downstream model boundary in the predictions, it was necessary to assume that the water-surface slope for the streamflows corresponding to AEPs of 1 and 2 percent would be the same as the water-surface slope calculated from the calibrated model of the June 11, 2010, flood. While this is a standard assumption in hydraulic modeling, it is possible the water-surface slope that was used would not be the same as that experienced during those streamflows. Second, the mean elevations of the Little Missouri River and Brier Creek watersheds (table 1) exceeded the maximum mean watershed elevation (1,250 ft) used in the development of the USGS regional regression model for Arkansas Region B (Hodge and Tasker, 1995); the mean watershed elevation is one of the three watershed characteristics (drainage area, mean watershed elevation, and shape factor) used to estimate flood magnitudes with the regional regression model (Hodge and Tasker, 1995). Also, streamflows estimated using the regional regression model have large 90-percent confidence intervals (table 1). As such, reasonable uncertainty exists in the streamflow inputs that were in the predictions of the floods corresponding to AEPs of 1 and 2 percent; however, better methods for estimating streamflows in ungaged watersheds in the region are not currently available.

Summary

During the evening of June 10 and the early morning hours of June 11, 2010, as much as 7 inches of rain fell on the upper Little Missouri River watershed in the Ouachita National Forest of west-central Arkansas, resulting in substantial flooding at the Albert Pike Recreation Area in the Ouachita National Forest of west-central Arkansas that killed 20 campers. To better understand the flood, the U.S. Forest Service needed information concerning the extent and depth of flood inundation, the water velocity, and flow paths throughout the Albert Pike Recreation Area. This information also was needed for streamflows corresponding to annual exceedence probabilities of 1 and 2 percent.

The study area included an approximately 1.5-mile reach of the Little Missouri River that flows through Albert Pike Recreation Area and part of the privately-owned Lowry's Camp Albert Pike that is located immediately downstream from the Albert Pike Recreation Area. The study area is located approximately 8.5 miles upstream from USGS streamflow gaging station 07360200 (Little Missouri River near Langley, Arkansas).

The two-dimensional flow model Fst2DH (part of the Federal Highway Administrations's Finite Element Surface-Water Modeling System) was used to perform a steady-state flow simulation of the flood. A model of the study area was constructed using the graphical user interface Surface-Water Modeling System (SMS). Land-surface elevations of the study area were obtained from a 10-meter digital elevation model supplemented with land-surface elevations obtained during a ground survey. Peak streamflows of the Little Missouri River at Area D at Albert Pike Recreation Area and for Little Missouri River tributary Brier Creek, determined in previous investigations by the slope-area indirect measurement technique, were used as streamflow inputs to the model. The model was calibrated to the surveyed elevations of high-water marks left by the flood. The calibrated model was then used to predict streamflows of the Little Missouri River and Brier Creek corresponding to annual exceedence probabilities of 1 and 2 percent that were determined using the U.S. Geological Survey regional regression model for Arkansas Region B.

The simulated extent of flood inundation replicated the observed extent of flooding at Albert Pike Recreation Area. Simulated water-surface elevation ranged from 940.0 feet (ft) at the upstream boundary of the study area to 905.6 ft at the downstream boundary of the study area. Simulated water-surface elevations at cross sections in Areas C and D were lower than those modeled by the U.S. Forest Service using the standard-step method, but the comparison was favorable with a mean absolute difference of 0.58 ft in Area C and 0.32 ft in Area D. The greatest differences between the models occurred at the four upstream cross sections in Area C and were attributed to variability in high-water mark elevations used in the two models. The mean depth of inundation in the camp areas was 8.5 ft in Area D, 7.4 ft in Area C, 3.8 ft in Areas A, B, and the Day Use Area, and 12.5 ft in Lowry's Camp Albert Pike. Comparison with the results of a HEC-RAS model of the Little Missouri River watershed upstream from the Langley gage for the area in common with the two-dimensional model indicated that the mean water depth simulated by the models differed by only 0.2 ft. The simulated water velocity in the main channel of the Little Missouri River was greater than 20 feet per second (ft/s) at the Forest Road 106 bridge and at the constriction in the channel just upstream from the swimming area. The mean water velocity in the camp areas was 7.2 ft/s in Area D, 7.6 ft/s in Area C, 7.2 ft/s in Areas A, B, and the Day Use Area, and 7.6 ft/s in Lowry's Camp Albert Pike. Generally, simulated water velocities at cross sections in Areas C and D compared favorably with water velocities computed at those cross sections as part of the slope-area indirect measurements of peak streamflow of the Little Missouri River. Comparison with the results of a HEC-RAS model of the Little Missouri River watershed upstream from the Langley gage for the area in common with the two-dimensional model indicated that the mean stream velocity simulated by the models differed by only 0.5 ft/s. A sensitivity analysis of the effects of varying *n*-values, water-surface elevation at the downstream model boundary, and streamflow inputs on simulated water-surface elevation indicated that varying the streamflow of the Little Missouri River had the greatest effect, while varying the water-surface elevation at the downstream model boundary or the streamflow of tributary Brier Creek had the least effect.

The prediction of flooding that would result from a streamflow corresponding to an annual exceedence probability of 1 percent showed all of Areas C, D, and the Day Use Area and parts of Areas A and B at Albert Pike Recreation Area were inundated, and the extent of inundation of the June 11, 2010, flood exceeded the 1-percent flood. Predicted water-surface elevations ranged from 939.0 ft at the upstream model boundary to 904.2 ft at the downstream model boundary and were approximately 1 ft lower than water-surface elevations modeled by the U.S. Forest Service in Areas C and D. The mean depth of inundation in the camp areas was 6.51 ft in Area D, 6.51 ft in Area C, 3.84 ft in Areas A, B, and the Day Use Area, and 6.90 ft in Lowry's Camp Albert Pike. Predicted water velocity was greater than 20 ft/s at the Forest Road 106 bridge and at the constriction in the channel just upstream from the swimming area. The mean velocity in the camp areas was 6.56 ft/s in Area D, 6.90 ft/s in Area C, 6.81 ft/s in Areas A, B, and the Day Use Area, and 3.99 ft/s in Lowry's Camp Albert Pike.

The prediction of flooding that would result from a streamflow corresponding to an annual exceedence probability of 2 percent showed that all of Areas C and D, the Day Use Area, and parts of Areas A and B were inundated. Predicted water-surface elevations ranged from 938.0 ft at the upstream model boundary to 903.3 ft at the downstream model boundary and were approximately 1 ft lower than water-surface elevations modeled by the U.S. Forest Service at cross sections in Areas C and D. The mean depth of inundation in

the camp areas was 5.59 ft in Area D, 5.88 ft in Area C, 3.90 ft in Areas A, B, and the Day Use Area, and 6.21 ft in Lowry's Camp Albert Pike. Predicted water velocities were greater than 20 ft/s at the Forest Road 106 bridge and at the constriction in the channel just upstream from the swimming area. The mean water velocity in the camp areas was 6.12 ft/s in Area D, 6.81 ft/s in Area C, 6.55 ft/s in Areas A, B, and the Day Use Area, and 3.80 ft/s in Lowry's Camp Albert Pike.

Uncertainty in the simulation of the June 11, 2010, flood of the Little Missouri River at Albert Pike Recreation Area was attributed to excluding flow from two small unnamed tributaries and pressure flow through the Forest Road 106 bridge and to an area of instability at the upstream model boundary. The effects of these uncertainties on the overall simulation results were deemed to be negligible. Uncertainties in the predictions of floods corresponding to annual exceedence probabilities of 1 and 2 percent were attributed to assuming that the water-surface slope used in the predictions would be the same as the water-surface slope from the simulation of the June 11, 2010, flood and to limitations of the regional regression model used to derive the streamflows used for model input. Despite these uncertainties, results of the simulation of the June 11, 2010, flood and of the predictions of flooding resulting from streamflows corresponding to annual exceedence probabilities of 1 and 2 percent are considered reasonable, given the streamflow data currently available for the upper Little Missouri River watershed and accepted methods for estimating peak streamflows for ungaged watersheds in the region.

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