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EFFECTS OF A SIMULATED CHANGE IN LAND COVER ON SURFACE-WATER VELOCITY DISTRIBUTION AT A BRIDGE IN SOUTHEASTERN ARKANSAS

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Abstract:
Changes in land cover immediately upstream or downstream from a bridge can have a substantial effect on surface-water velocity and velocity distribution through a bridge opening. The two-dimensional surface-water model, Finite Element Surface Water Modeling System: Two Dimensional Flow in a Horizontal Plane (FESWMS-2DH), was used to determine the depth-averaged point velocities across the U.S. Highway 79 Roc Roe Bayou bridge opening in the White River floodplain in southeastern Arkansas. The existing highway alignment locates the left bridge abutments in a heavily vegetated area with high Manning's roughness coefficients. The proposed highway alignment moves the left bridge abutment into an agricultural field, which lowers the Manning's roughness coefficient by 67 percent. This change of roughness near the left abutment increases the simulated flow velocity near the abutments by 29 percent. When simulated floodplain vegetation was added to the to the agricultural field in the vicinity of the left abutment, the maximum depth-averaged point velocity decreased by 38 percent from the initial proposed highway alignment. The results of this study illustrate the need for an accurate assessment of land-cover change when new highway alignments are being designed and built.

INTRODUCTION

The hydraulic performance of bridges during floods is a major concern when the opening and grade of drainage structures are designed. In the case of multiple bridge openings, it is important to know the distribution of discharge and velocity through the bridges for an efficient hydraulic design. Changes in land cover and its effects on hydraulics are often overlooked when highway bridges are built or replaced. Initially, this was the case with the U.S. Highway 79 bridges, which spans the White River and its floodplain in southeastern Arkansas.

U.S. Highway 79 is a 2-lane highway constructed during the late 1920's and early 1930's. The town of Clarendon is on the east bank of the White River (fig. 1). Currently, U.S. Highway 79 uses three separate bridges to cross the White River floodplain--one bridge over the White River; one bridge over the First Old River, located west of the White River; and one bridge over Roc Roe Bayou, located west of the First Old Rive (fig 2). Because of a substantial increase in traffic volume and the age and deterioration of the roadway, the Arkansas Highway and Transportation Department (AHTD) made the decision to replace the roadway and bridges crossing the White River and its floodplain.

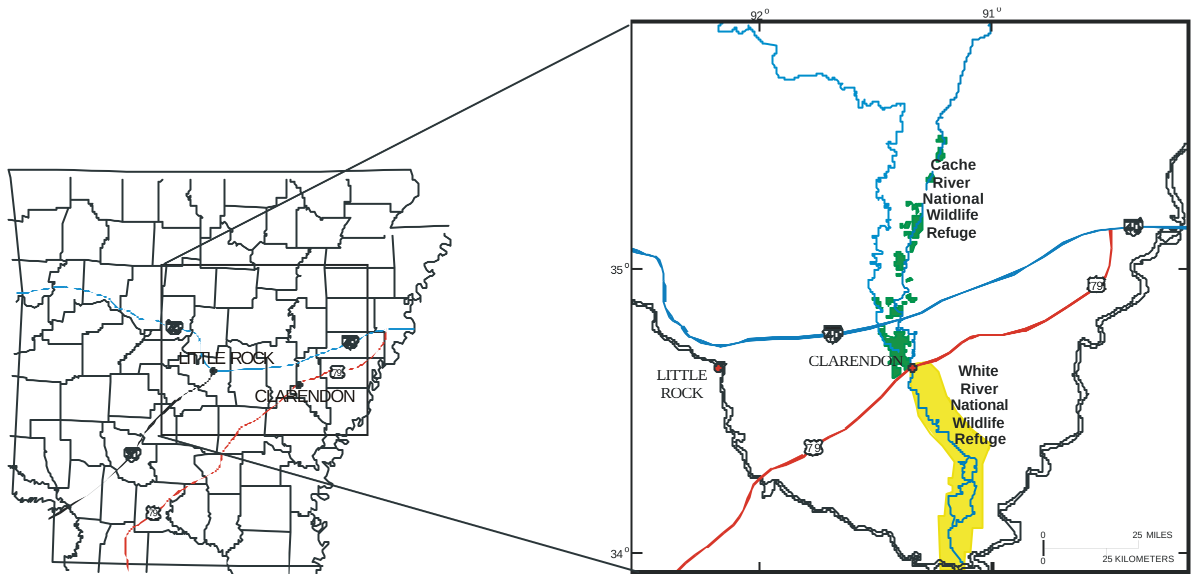

Figure 1. Location of lower White River and National Wildlife Refuges.

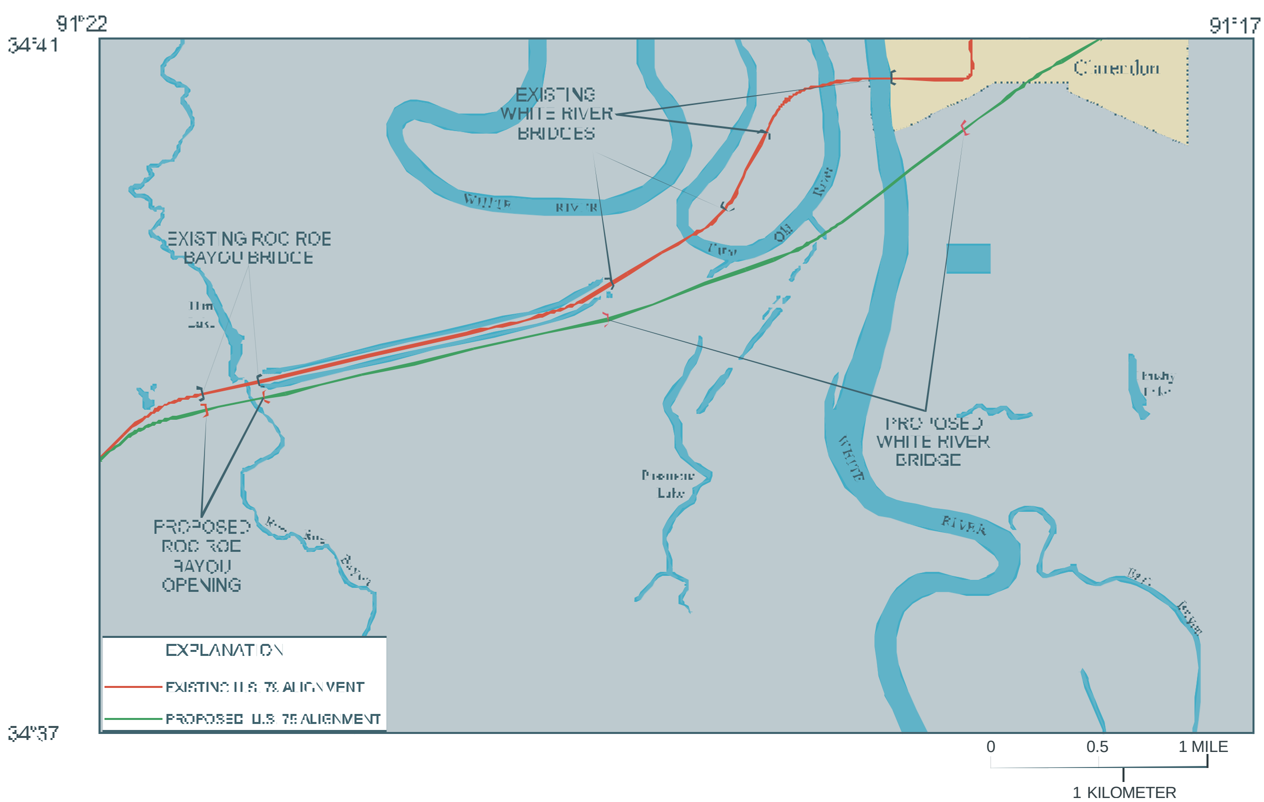

Figure 2. Location of existing and proposed bridges.

Two National Wildlife Refuges meet at the U.S. Highway 79 crossing of the White River. The Cache River National Wildlife Refuge is located to the north and the White River National Wildlife Refuge is located to the south. The U.S. Fish and Wildlife Service (USFWS) and AHTD are concerned about the effects that velocities and velocity distributions generated by the proposed bridges will have on the environment. To deal with these concerns, the AHTD proposed combining the two bridges that cross the White River and the First Old River, and lengthening the bridge that crosses Roc Roe Bayou by 110 feet (fig. 2). The USFWS and AHTD are primarily concerned about potential high point velocities in the Roc Roe Bayou bridge opening and any possibility for scour. The focus of this paper is on flow dynamics and model simulations of point velocity magnitude and velocity distribution through the Roc Roe Bayou bridge opening.

During the 100-year flood event, there is flow across the entire White River floodplain. The distance across the floodplain ranges from 3.5 miles at U.S. Highway 79 to 5.5 miles at the upper end of the study reach (2.7 miles upstream of U.S. Highway 79). Average depths across the floodplain for the 100-year flood event range from 19 feet at the upper end of the study reach to 16 feet at the lower end of the study reach (4.6 miles downstream of U.S. Highway 79). For the 100-year flood event, the main channel of the White River ranges in depth from 32 to 65 feet while the main channel depth of Roc Roe Bayou ranges from 20 to 53 feet. Water-surface elevations for the 100-year flood event range from 177.2 feet above sea level at the upper end of the reach to 173.2 feet above sea level at the lower end of the reach.

METHODOLOGY

U.S. 79 crosses the White River floodplain at an average angle (skew) of 30 degrees. Because of the complexity of the site and the two-dimensional nature of the flow, a two-dimensional flood study was used to assess the velocity and velocity distributions through the existing and proposed bridge openings. The two-dimensional flow model, Finite Element Surface-Water Modeling System: Two-Dimensional Flow in a Horizontal Plane (FESWMS-2DH) (Froehlich, 1989) was used to simulate the effects the proposed bridge scenarios and their respective changes in land cover would have on the velocities and velocity distributions through the bridge openings. The model uses the Galerkin finite-element method to solve three partial-differential equations representing conservation of mass and momentum (Lee and Froehlich, 1989). A depth-averaged velocity is computed at each computational point (node) in the model domain. The model area is covered by a grid consisting of triangular and quadrilateral sections (elements) of variable size, which work well for fitting the model to physical features.

Several modeling parameters and options were considered in the modeling process to ensure that the best simulations of floodflows were achieved. Manning's roughness coefficient and base kinematic eddy viscosity were the two model parameters that were varied throughout the modeling. Default values for all other modeling parameters were used for floodflow simulations. These parameters included the following: water density, air density, dimensionless turbulence coefficient, relaxation factor, depth tolerance, and coefficients used to compute the momentum correction coefficient. Additionally, a low-order numerical integration technique was performed for each simulation. Wind effects were ignored and a constant density was assumed (assumed flow was well mixed vertically). Any unsteady effects of the floodflow were ignored.

All hydraulic computations involving flow in open channels require an evaluation of the roughness characteristics of the channel (Barnes, 1967). The Manning's equation (Chow, 1959) plays an important role in the channel's ability to carry flow. The most commonly expressed form of the Manning's equation is:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2}$$

where

V = velocity, in feet per second,
R = hydraulic radius, in feet,
S = slope of energy line, in foot per foot, and
n = coefficient of roughness, specifically known as Manning's n.

Manning's roughness coefficient is a function of friction along the channel bed. For example, water flowing over bed material with small surface areas such as sand, gravel, and grass will have a smaller degree of friction loss resulting in a smaller Manning's roughness coefficient as opposed to channel material composed of large trees and shrubs, which have larger surface areas that create more friction resulting in a larger Manning's coefficient. The higher the friction loss, the slower the water will flow.

The sensitivity of model results to changes in model parameters was investigated. Manning's roughness coefficients and base kinematic eddy viscosity (Froehlich, 1989, eq. 4-19) were adjusted from the original values used in the initial convergence of the model. Changing the Manning's roughness coefficient from 0.14 to 0.125 (an 11 percent change) caused the water surface elevation at the upstream boundary to decrease 0.6 foot. Changing the base kinematic eddy viscosity from 50 to 7 square feet per second (an 86 percent change) raised the water surface elevation at the upstream boundary less than 0.3 feet.

The U.S. Army Corps of Engineers (USACE) has operated a gaging station on the White River at Clarendon since 1927 (fig 3). The installation began as a discharge observation gage and is currently operated as a daily-flow station. This site also is used as a National Weather Service flood forecast point. In 1972, the USACE installed a stage-only gaging station at Aberdeen, which is the lower boundary of the study reach (fig 3).

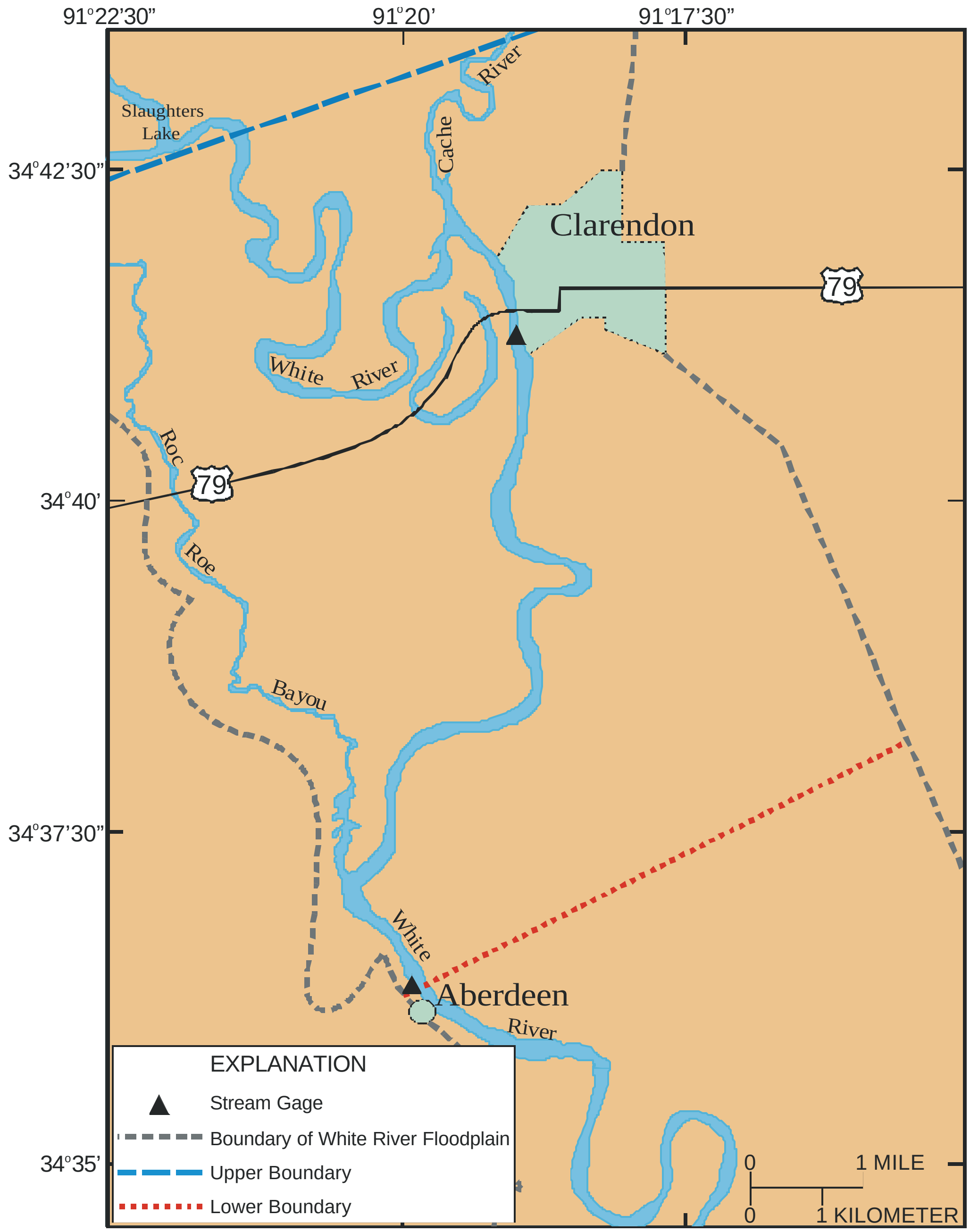

Figure 3. Upper and lower boundaries of the study reach.

The streamflow data gathered at the Clarendon gage and the stage data collected at the Aberdeen gage were used to calculate the necessary boundary conditions for the model. The streamflow data were used with a Log Pearson Type III analysis to compute the discharge for the 100-year flood event of 216,000 cubic feet per second. The 100-year flood water-surface elevations were estimated at both gages using the computed 100-year flood discharge and the rating curve developed for the Clarendon gage by the USACE. The water-surface elevation for the 100-year flood event was determined to be 175.48 and 173.21 feet above sea level at the Clarendon and Aberdeen gages, respectively.

SIMULATED VELOCITIES FOR EXISTING BRIDGE OPENING OVER ROC ROE BAYOU

The model was calibrated using the 100-year flood discharge and water surface elevations for the existing conditions. The existing U.S. Highway 79 bridge over Roc Roe Bayou has spillthrough-type abutments and sloping embankments with wingwalls at an angle of about 30 degrees. The bridge span length is 1,428 feet. The overbank area of the approach section is forested with heavy underbrush north of the Roc Roe Bayou bridge opening. The Manning's roughness coefficient used in the model for this vegetation is 0.12. On the south side of the highway, there is a 265-acre field where crops such as soybeans, cotton, and wheat are commonly grown. In the model, a Manning's roughness coefficient of 0.04 is used for this area. Figure 4 illustrates both the forested and fielded areas near the Roc Roe Bayou bridge and their location with the existing roadway alignment and Roc Roe Bayou bridge opening.

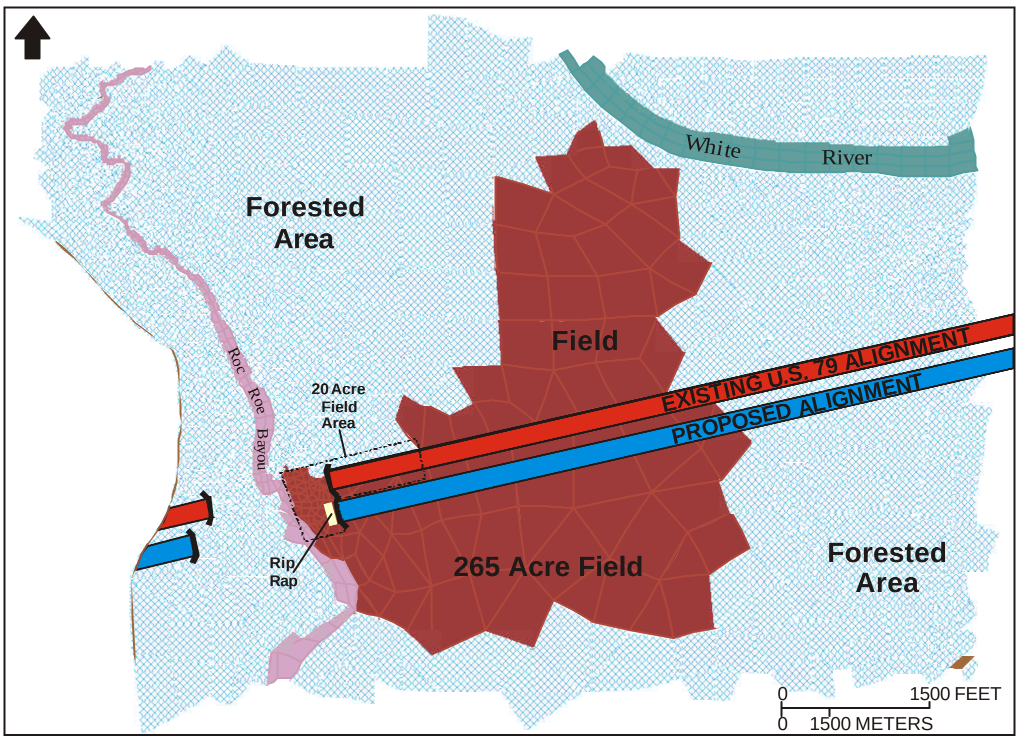

Figure 4. Land use in the vicinity of the existing and proposed Roc Roe Bayou bridge openings.

A model simulation of the 100-year flood event indicates that velocities through the existing Roc Roe Bayou bridge opening are highest near the left (as viewed looking downstream) bridge abutment and decrease considerably across the channel in the direction of the right abutment (fig. 5). The maximum depth-averaged point velocity resulting from flow around the left bridge abutment is approximately 4.1 feet per second.

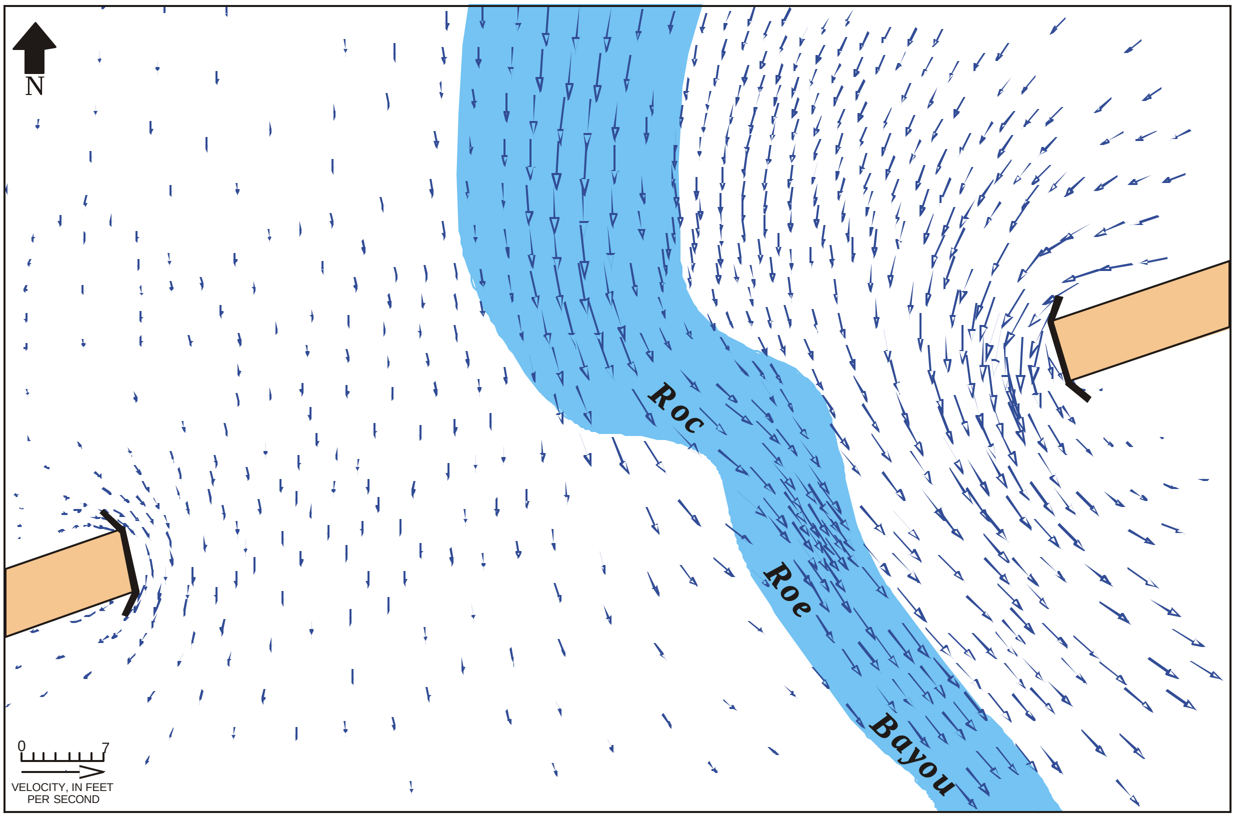

Figure 5. Depth-averaged point velocity distributions for the 100-year flood event through the existing Roc Roe Bayou bridge opening.

SIMULATED VELOCITIES FOR PROPOSED BRIDGE OPENING OVER ROC ROE BAYOU

The proposed U.S. Highway 79 replacement will be a two-lane highway that crosses the White River floodplain at an average angle (skew) of 30 degrees. In this proposed realignment, the simulated highway fill was moved downstream 425 feet and an additional 110 feet of span was added to the Roc Roe Bayou bridge. As a result of this new alignment, 70 additional acres of field are now upstream from the Roc Roe Bayou bridge leaving a 195-acre field downstream from the proposed bridge (fig. 4). The Manning's roughness coefficient used in the model for the area upstream from the bridge in this scenario is 0.04, reflecting less friction loss upstream from the bridge than for existing conditions.

A model simulation of the 100-year flood event indicates that velocities through the proposed Roc Roe Bayou bridge opening are highest near the left bridge abutment and lower across the channel (fig. 6). In this scenario, the simulated 100-year flood event indicates that flow through Roc Roe Bayou bridge would cause a maximum depth-averaged point velocity of approximately 5.3 feet per second near the left abutment, an increase of 1.2 foot per second (29 percent) from existing conditions.

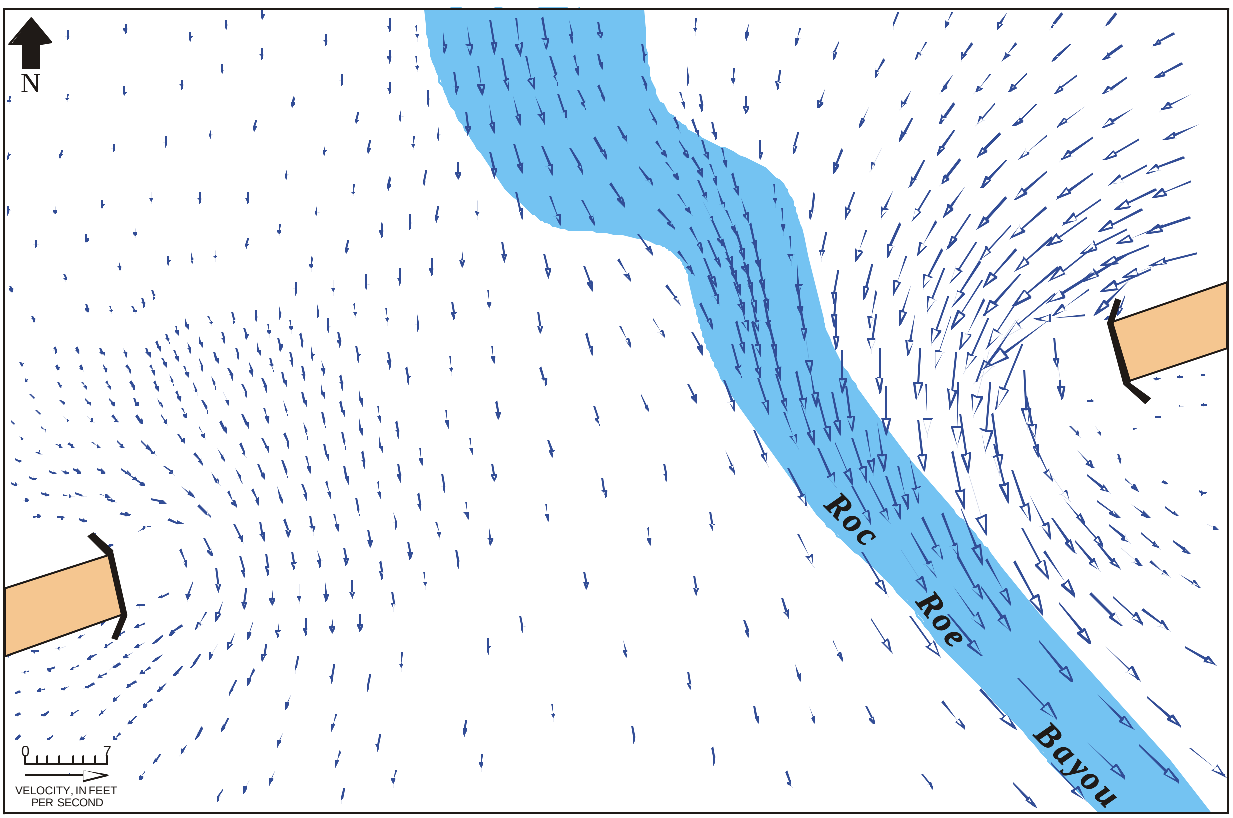

Figure 6. Depth-averaged point velocity distributions for the 100-year flood event through the proposed Roc Roe Bayou bridge opening.

SIMULATED VELOCITIES FOR PROPOSED BRIDGE OPENING OVER ROC ROE BAYOU WITH LAND COVER CHANGE

The model was rerun for the proposed realignment with the Manning's roughness coefficient increased to 0.12 upstream and downstream from the Roc Roe Bayou bridge. This simulated the conversion of 20 acres of field upstream and the 195-acre field downstream from the Roc Roe Bayou bridge opening that was present in the original proposed scenario to forest vegetation (fig. 4). Riprap was also simulated around the left abutment in an effort to lower the velocity.

A model simulation of the 100-year flood event through the proposed Roc Roe Bayou bridge opening with additional forestation upstream and downstream of the bridge results in an improved velocity distribution with highest depth-averaged point velocities occurring in the main channel (fig. 7). By increasing the Manning's roughness coefficient (to simulate a forested area), the model simulation of the 100-year flood event through the Roc Roe Bayou bridge opening results in a maximum depth-averaged point velocity of approximately 3.3 feet per second, a decrease of 0.8 foot per second from existing conditions. The additional forestation and riprap also shifted the location of the highest point velocity away from near the left abutment to the main channel of Roc Roe Bayou.

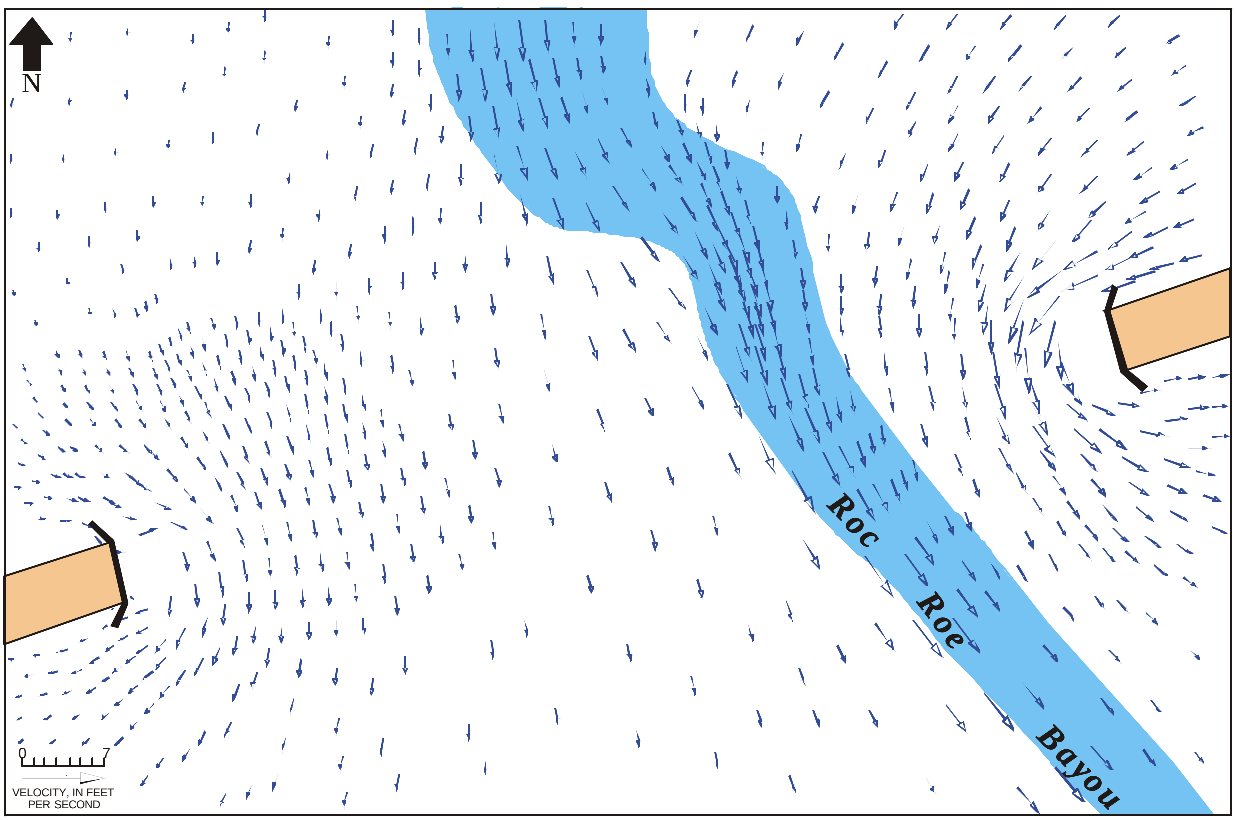

Figure 7. Depth-averaged point velocity distributions for the 100-year flood event through the proposed Roc Roe Bayou bridge opening with additional forestation.

CONCLUSIONS

The AHTD proposes to replace U.S. Highway 79 and its bridges over the White River and its floodplain near Clarendon, Arkansas. For simulation of possible conditions associated with the proposed alignment near Roc Roe Bayou, the existing highway embankment was moved downstream 425 feet. This placed the proposed alignment in a field where soybeans, cotton, and wheat commonly are grown. The Manning's roughness coefficient used for the field is 0.04 compared to 0.12 used for the forested area. Relocating the bridge in an area with a lower Manning's roughness coefficient caused the maximum simulated depth-average point velocity through Roc Roe Bayou bridge to change from 4.1 to 5.3 feet per second, or an increase of 29 percent. To decrease the depth-averaged point velocities, Manning's roughness coefficient was changed from 0.04 to 0.12 to simulate the impact of forestation in the downstream 195-acre field and in 20 acres of the field upstream from the Roc Roe Bayou bridge opening and the addition of rip rap around the left abutment. Increasing the roughness caused the maximum simulated depth-averaged point velocity to change from 5.3 to 3.3 feet per second, or a decrease of 38 percent.

Setting the Manning's roughness coefficient to 0.12 in the 195-acre field downstream and in the 20-acres of the field upstream reflects a proposed change in land use from being soybean, cotton, and wheat fields to forested vegetation with heavy underbrush. This change in vegetation and the added rip rap around the left abutment would increase the friction loss between the flowing water and the floodplain bed material, as reflected by the Manning's roughness coefficient, thus causing the water velocity to decrease considerably. The simulation of added vegetation and rip rap also shifted the maximum simulated depth-averaged point velocity from occurring near the left abutment to occurring in the main channel of Roc Roe Bayou.

The results of this study illustrate the need for an accurate assessment of land cover change when new highway alignments are being designed and built. By adding floodplain vegetation around bridge openings and rip rap material around bridge abutments, the velocity of water can be substantially reduced.

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