ANALYSIS OF BACKWATER AT THE I-10 CROSSING OF THE PEARL RIVER IN SOUTHEAST LOUISIANA AND SOUTHWEST MISSISSIPPI

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INTRODUCTION

In April of 1979, 1980, and 1983, major flooding on the lower Pearl River in Louisiana and Mississippi caused extensive damage to homes located on the flood plain in the Slidell, La., area. Both the 1980 and 1983 floods overtopped the Interstate Highway 10 (I-10) crossing of the Pearl River flood plain between Slidell and Bay St. Louis, Miss., interrupting traffic for several hours in 1980 and several days in 1983. Many local residents attributed part of the 1979, 1980, and 1983 flooding in the Slidell area to backwater caused by the I-10 embankments and the U.S. Highway 90 embankments about 5 mi downstream from I-10.

The U.S. Geological Survey, in cooperation with the Louisiana Department of Transportation and Development, Office of Highways, and the U.S. Department of Transportation, Federal Highway Administration, undertook to quantify the effect of I-10 and Highway 90 on water-surface elevations and flow distribution during the 1980 flood and quantify the effect of several alternatives for reducing backwater on water-surface elevations and flow distribution (Lee and others, 1982, 1983; Wiche and others, 1982).

The two-dimensional finite-element surface-water flow modeling system FESWMS was used to study the effects of I-10 and Highway 90 during the 1980 flood and to evaluate the hydraulic effect of alternatives for reducing backwater. The model can be used to simulate both lateral and longitudinal velocities and variations in water-surface elevation, highly variable flood-plain topography and vegetative cover, and geometric features such as highway embankments, dikes, and channel bends. Geometric features of widely varying sizes are easily accommodated within a single finite-element network.

This paper describes the part of the study involving the I-10 crossing. The paper begins with a brief description of the modeling system FESWMS and a description of the study area. Data collection, network design, and model calibration for the 1980 flood are described. Results of the simulation of the 1980 flood both with and without I-10 in place are presented, and backwater and drawdown caused by the roadway are discussed. The simulation of flow for a modification of the I-10 crossing is also discussed.

Throughout this paper, the words "backwater" and "drawdown" denote an increase and a decrease, respectively, in water-surface elevation caused by a flood-plain constriction. Backwater may occur both upstream and downstream from the constriction. Elevations refer to the National Geodetic Vertical Datum (NGVD) of 1929, called sea level in this report.

MODEL DESCRIPTION

The core of the modeling system FESWMS, which is under development by the Geological Survey, is a two-dimensional finite-element surface-water flow model. Around this core, the Geological Survey has developed preprocessing and postprocessing programs which make the system accessible to the user.

Two-dimensional surface-water flow in the horizontal plane is described by three nonlinear partial-differential equations, two for conservation of momentum and one for conservation of mass (Pritchard, 1971). These equations are called the shallow-water equations. The three dependent variables are the depth-averaged velocity components, u and v, in the x- and y-directions, respectively, and the depth, h. The momentum equations use a two-dimensional form of the Chezy equation to model bottom friction.

In FESWMS, quadratic basis functions are used to interpolate velocity components, and linear basis functions are used to interpolate depth on triangular, six-node, isoparametric elements (mixed interpolation). Isoparametric elements permit the use of curved element sides. Model topography is defined by assigning a ground-surface elevation to each element vertex and requiring the ground surface to vary linearly within an element. The finite-element model requires the specification of a constant Chezy coefficient, C, over each element. Flow components are specified at inflow boundary nodes, and water-surface elevations are specified at outflow boundary nodes. Zero normal flow (tangential flow) is specified at lateral boundaries.

Galerkin's method of weighted residuals, a Newton-Raphson iteration scheme, numerical integration using seven-point Gaussian quadrature (Zienkiewicz, 1977, p. 200-201), and a frontal solution algorithm using out-of-core storage (Hood, 1976, 1977) are used to solve for the nodal values of the velocity components and depth. The time derivatives are handled by an implicit finite-difference scheme; in the application reported here, however, only the steady-state forms of the equations were solved.

DESCRIPTION OF THE STUDY AREA

The reach of the Pearl River flood plain studied in this paper (Fig. 1) is approximately 12 mi long. It is bounded on the north by old U.S. Highway 11 and Interstate Highway 59 (I-59) and on the south by U.S. Highway 90. The eastern and western boundaries are the natural bluffs at the edges of the flood plain. The flood plain varies in width from about 3 to about 7 mi.

The major channels in the study reach are the Pearl (known locally as the East Pearl), East Middle, Middle, West Middle, and West Pearl Rivers, and Wastehouse Bayou. The Pearl flows along the east

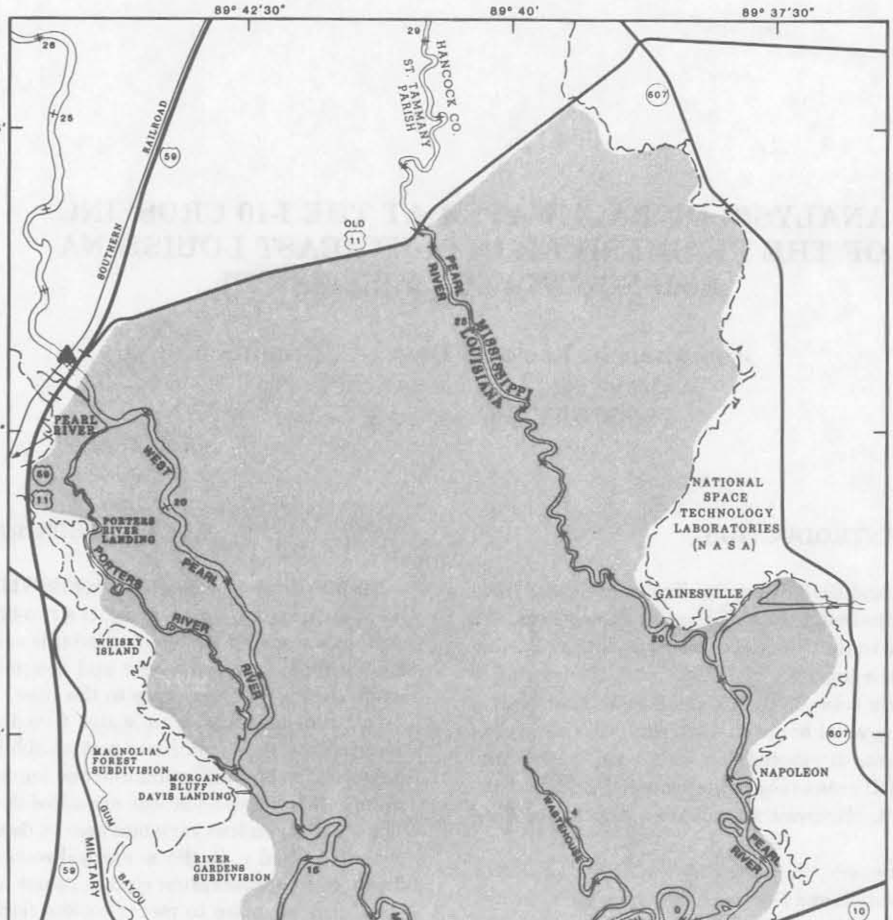

Figure 1. – Study reach of the lower Pearl River basin near Slidell.

side of the flood plain, and the West Pearl along the west side. In the northern part of the study reach, the West Pearl is the largest channel in the flood plain. Near Gainesville, Miss., the channel of the Pearl becomes the largest and remains the largest to the mouths of the river system.

Flood-plain ground-surface elevations range from about 1 ft above sea level in the southern part of the study area to 15 ft above sea level in the northwestern part. Between the upstream boundary and I-10, ground-surface elevations are higher near the West Pearl River than on the east side of the flood plain. Except near Highway 90, the flood plain is covered by dense woods, mixed with underbrush in many places. Near Highway 90, coastal marsh predominates.

Flow enters the study area through the old Highway 11 bridge opening at the Pearl River, through the I-59 opening at the West Pearl River, and through numerous small openings in the old Highway 11 embankments. The I-10 crossing, about 4.4 mi long, spans the flood plain in an east-to-west direction in the middle of the study reach. There are bridges at the Pearl, Middle, and West Pearl River, with lengths of 4,980, 770, and 2,240 ft, respectively. The embankment between the Pearl and Middle Rivers is about 0.8 mi long, and the embankment between the Middle and West Pearl Rivers is about 2.1 mi long. Flow leaves the study reach through five openings in the Highway 90 crossing. The bridge at the Pearl River is 960 ft long; at the East Middle River, 630 ft long; at the Middle River, 580 ft long; at the West Middle River, 580 ft long; and at the West Pearl River, 570 ft long. During the 1980 flood, there was a small amount of flow out of the study area over the top of the U.S. Highway 190 embankment.

SIMULATION OF THE APRIL 1980 FLOOD

Data Collection and Analysis

A large amount of hydrographic and topographic data was collected and analyzed for use in modeling the April 1980 flood. Gage-height records collected by the Geological Survey at Pearl River, La., at the upper end of the study reach, and by the U.S. Army Corps of Engineers at Pearlington, Miss., at the lower end of the study reach, were used to justify a steady-state analysis. (At the time of the downstream peak, the upstream water-surface elevation had fallen less than 0.5 ft from its maximum value.) Discharge measurements made by the Geological Survey and the Corps of Engineers at old Highway 11, I-59, I-10, and Highway 90, during the 1980 and earlier floods were assembled for use in establishing model boundary conditions and calibrating the model. Approximately 200 high-water marks within and near the study area were located and flagged by the Geological Survey as the flood water receded. The high-water marks were examined for validity and grouped for use in establishing model boundary conditions and calibrating the model.

Approximately 50 mi of longitudinal channel profiles were obtained for the significant channels in the study reach, and 73 representative and special purpose cross-section surveys were made to further define channel geometry. Detailed topographic data were obtained at and near the bridge openings. Infrared aerial photographs of the study area were obtained for use in determining vegetation type and density. The collected data were supplemented by historic hydrologic data and Geological Survey topographic maps.

Network Design

The finite-element network, shown in Figure 2, was designed to closely represent the highly nonuniform boundary of the area inundated by the April 1980 flood. The upstream boundary was located just downstream from old Highway 11 and I-59, and the downstream boundary was located at Highway 90. Smooth, curved-sided elements were used along lateral boundaries, at which tangential flow was specified.

After the boundaries were defined, the study area was divided into an equivalent network of triangular elements. Subdivision lines between elements were located where abrupt changes in vegetative cover or topography occurred. Each element was designed to represent an area of nearly homogeneous vegetative cover. In areas where velocity, depth, and water-surface gradients were expected to be large, such as near bridge openings and in areas between overbanks and channel bottoms, network detail was increased to facilitate better simulation of the large gradients by the flow model.

The use of elements with aspect ratios greater than unity made it possible to design the networks with fewer elements than would have been required otherwise. The element aspect ratio is defined as the ratio of the largest element dimension to the smallest. Elements with large aspect ratios were used primarily in defining river channels. The longest element side was aligned with the channel axis, along which velocity and depth changes would typically be small. Element aspect ratios were kept to a maximum of about 10.

Most prototype lengths and widths within the flood plain were realistically represented in the model; however, in order to reduce the number of elements in the network, several approximations were made. Only relatively large channels were included in the network. Prototype channel cross sections were represented in the model by either triangular or trapezoidal cross sections with cross-sectional areas equal to the measured areas. Some meandrous channel reaches with relatively small flows were replaced with artificially straightened, but hydraulically equivalent, reaches. The widths of simulated stream channels less than 200 ft wide were increased to 200 ft.

Boundary Conditions

As stated previously, the model discharge was assumed to be steady. Discharge was distributed at the upstream boundary based on a discharge measurement of 174,000 ft^3/s at I-10 on April 2, 1980, and on previous discharge measurements at the bridge openings in old Highway 11 and I-59. Inflow was concentrated at the old Highway 11 bridge across the Pearl River and the I-59 bridge across the West Pearl River. Flow into the study reach through numerous small openings in old Highway 11 was represented as continuous inflow along the highway embankment. Water-surface elevations at the downstream boundary were based on high-water marks obtained near the five bridge openings in Highway 90.

Model Calibration

Nominal values of Chezy coefficients were selected for initial use with the model on the basis of the infrared aerial photographs of the flood plain and field inspection. In making both the initial estimates of the Chezy values and subsequent modifications to them, care was taken to insure that the assigned values were reasonable and mutually consistent. The Chezy value assigned to a channel element in an artificially straightened reach was derived from the value for the corresponding natural or unstraightened reach on the basis of the equation $C_s = C_n(L_s/L_n)^{1/2}$, where C is the value of the Chezy coefficient (feet to the one-half power per second), L is the length of the reach (feet), and the subscripts s and n denote straightened- and natural-channel-reach values, respectively.

A series of simulations was conducted to determine the relative effect on water-surface elevations of changes in the values of the Chezy coefficients of both overbank and channel elements. Computed water-surface elevations were most sensitive to changes in the value of the Chezy coefficient of the wooded flood plain. Changes in the Chezy values of channel elements had little or no effect on computed water-surface elevations except for channel reaches carrying a significant percentage of the total flow. Such reaches included the Pearl River between I-10 and Highway 90 and reaches located a few thousand feet upstream and downstream from bridge openings. Computed water-surface elevations were moderately sensitive to the values of

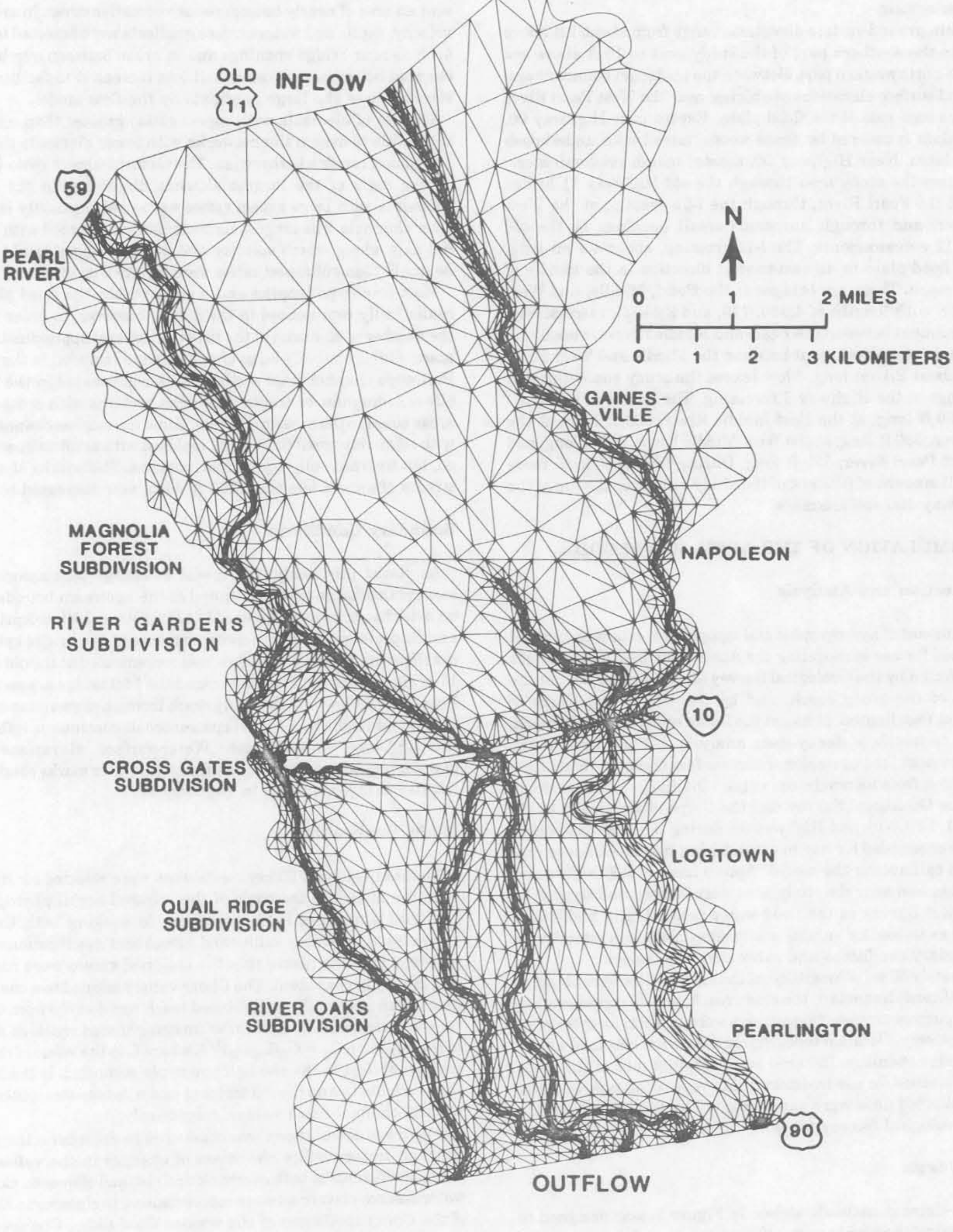

Figure 2. — Finite-element network with I-10 in place for the April 2, 1980, flood.

the Chezy coefficients of the overbank areas under the three I-10 bridges.

Model calibration consisted of matching as closely as possible all observed high-water marks and measured discharges at the three bridge openings in I-10. The final Chezy values were 22 $ft^{1/2}/s$ for the wooded flood plain, 28 to 35 $ft^{1/2}/s$ for the marsh-grass areas, 21 to 40 $ft^{1/2}/s$ for the overbank areas under the three I-10 bridges, and 85 to 115 $ft^{1/2}/s$ for the unstraightened channels. Computed element-averaged flow depths range from 2 to 23 ft for the wooded flood plain, from 4 to 10 ft for the marsh-grass areas, from 4 to 9 ft for the overbank areas under the I-10 bridges, and from 5 to 47 ft for the unstraightened channels. On the basis of these depths, values of the Manning n corresponding to the final Chezy values are found to range from 0.077 to 0.114 $ft^{1/6}$ for the wooded flood plain, from 0.055 to 0.074 $ft^{1/6}$ for the marsh-grass areas, from 0.046 to 0.098 $ft^{1/6}$ for the overbank areas under the I-10 bridges, and from 0.021 to 0.033 $ft^{1/6}$ for the unstraightened channels. For a discussion of the relationship of these values of the Manning n to those required to calibrate a one-dimensional model of the same reach, the reader is referred to Lee and others (1983, p. 30-31).

Computed flow depths in the calibrated model average about 21 ft in the channels and about 8 ft on the flood plain. Most cross-sectional average channel velocities are between 1 and 3 ft/s. Somewhat higher velocities occur at several of the bridge openings. The average velocity on the flood plain is about 0.7 ft/s.

Comparison of Computed and Observed Values

The computed water-surface elevation is in close agreement with the elevation of the observed high-water mark or marks at most of the 45 locations where high-water marks were available. The root mean square difference between the computed and observed values is 0.18 ft. The computed water-surface elevations are within +0.3 ft of the elevations of the high-water marks at all but four locations, and at these four locations, the computed elevations are within +0.5 ft of the observed values.

The errors in computed discharge at the bridge openings at the Pearl, Middle, and West Pearl Rivers, as a percent of the measured discharge at each opening, are 7, -10, and -7, respectively.

The model simulates accurately the observed shift of flow from the west side of the flood plain to the east side between the upstream boundary and I-10. At the upstream boundary, 56 percent of the inflow was estimated to pass through the bridge opening at the West Pearl River, but at I-10, 63 percent of the computed discharge passes through the bridge opening at the Pearl River. Fifty-nine percent of the measured discharge passed through the I-10 bridge opening at the Pearl River.

SIMULATION OF THE APRIL 1980 FLOOD WITHOUT THE I-10 EMBANKMENTS IN PLACE

The finite-element network used to simulate the April 2, 1980, flood was modified to represent conditions without I-10 in place, and the hydraulic impact of the I-10 embankments was determined by comparing results with and without I-10.

Network Modifications

Elements were added in the areas occupied in the original network by the I-10 embankments. Elsewhere, the two networks were identical. Model ground-surface elevations at and near the highway embankments were changed to the elevation of the surrounding natural flood plain. The Chezy coefficients corresponding to the new elements and the elements formerly located in overbank areas under the I-10 bridges were assigned the value 22 $ft^{1/2}/s$, the value used in both simulations for the wooded flood plain. Upstream and downstream boundary conditions were the same as those used in the simulation with the highway embankments in place.

Backwater and Drawdown Caused by the I-10 Embankments

Without I-10 in place, the flow shift from the west side of the flood plain to the east side does not occur as far upstream as with I-10 in place. As expected, water-surface elevations upstream from the I-10 site are lower without the highway embankments in place. A map of backwater and drawdown was obtained by subtracting nodal water-surface elevations computed without the roadway in place from the corresponding nodal water-surface elevations computed with the roadway in place. Lines of equal backwater and drawdown are shown in Figure 3. The 1.2-foot to 2.0-foot lines form a "mound" north of I-10 between the Pearl River and the west edge of the flood plain. Upstream from the roadway, maximum backwater at the west edge of the flood plain (1.5 ft) is greater than maximum backwater at the east edge (1.1 ft), but backwater decreases more rapidly in the upstream direction along the west edge than along the east edge.

Backwater ranging from 0.6 to 0.2 ft extends more than a mile downstream from the Pearl River opening in I-10 at the east edge of the flood plain. A large area of drawdown extends from the downstream side of the highway embankment between the Middle and West Pearl Rivers to the west edge of the flood plain. Drawdown of 0.2 ft or more occurs along approximately 2 mi of the west edge of the flood plain downstream from I-10.

The lateral variations in backwater and drawdown are due in part to the relatively greater constriction of the flow in the western part of the flood plain and in part to the topography of the flood plain.

ANALYSIS OF A NEW BRIDGE AT I-10

FESWMS was used to study the effect on backwater of four alternative modifications of the I-10 crossing. These alternatives were selected for study by the Louisiana Office of Highways in consultation with the Geological Survey. One of the alternatives involved clearing brush and trees and removing spoil at and near the three bridge openings, two involved placing a new 2,000-foot opening in the I-10 embankment between the Middle and West Pearl Rivers, and one involved placing a new 1,000-foot opening in the embankment. To reduce the cost of evaluating the alternatives, the model was run for only the middle part of the full-reach network. The middle part is bounded by the east-west lines crossing the full-reach network (Fig. 2) approximately 2 mi upstream and 1 mi downstream from I-10. Boundary conditions for the alternative simulations were obtained from the results of the calibration simulation. These boundary values were not allowed to vary in the alternative simulations. Thus, results of the alternative simulations differ slightly from results that would have been obtained with the full-reach model had it been used.

The only one of the four alternatives discussed in this paper involved placing a new 2,000-foot opening in the I-10 embankment between the Middle and West Pearl Rivers. The finite-element network was modified to include the new bridge opening. Ground-surface elevations at nodes in the new bridge right-of-way were set at sea level. Clearing of brush and trees in a rectangular area 1,000 ft wide and 3,000 ft long, centered about the new opening with the long side parallel to the roadway, was simulated by assigning a value of 40 $ft^{1/2}/s$ to the Chezy coefficients of the elements in the area. Conditions at the other three bridges were the same as in the calibration simulation.

Lines of equal backwater and drawdown for this simulation are shown in Figure 4. Maximum backwater of 0.7 ft occurs on the upstream side of the I-10 embankment between the Pearl and Middle Rivers. Backwater along the east edge of the flood plain is 0.3 ft between the upstream boundary and I-10. Maximum backwater at the west edge of the flood plain is 0.3 ft near Crawford Landing. The new bridge virtually eliminates backwater upstream from Davis

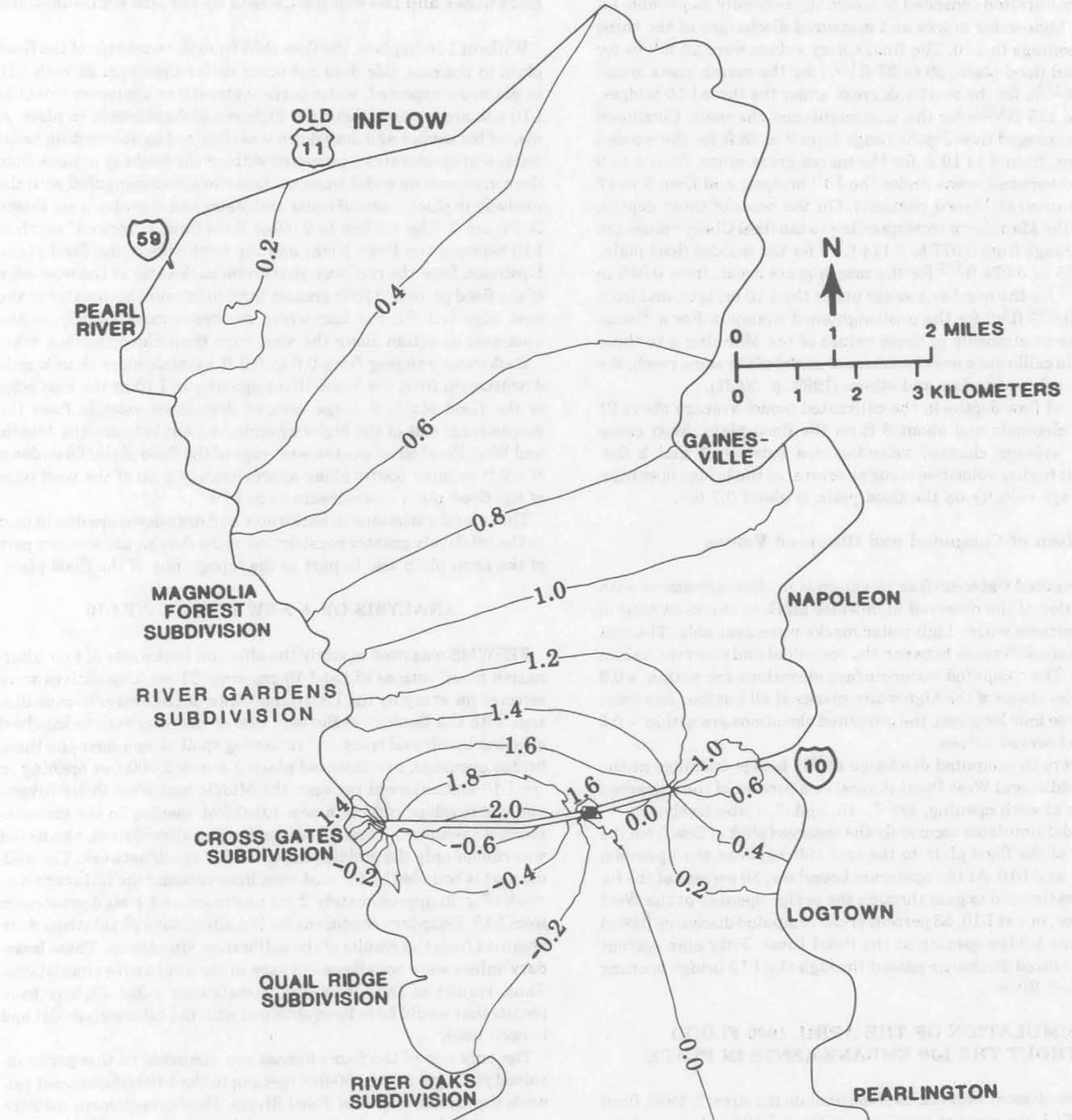

Figure 3. – Backwater and drawdown with I-10 in place for the April 2, 1980, flood, interval 0.2 ft.

Landing at the west edge of the flood plain and greatly reduces the mound of backwater that extended more than a mile downstream from the Pearl River bridge opening on the east side of the flood plain in the calibration simulation. The drawdown that the I-10 embankments caused on the west side of the flood plain is also reduced.

SUMMARY AND CONCLUSIONS

The two-dimensional finite-element surface-water flow modeling system FESWMS was used to study the effect of I-10 on water-surface elevations and flow distribution during the April 2, 1980, flood on the Pearl River near Slidell, La. A finite-element network was designed to represent the topography and vegetative cover of the study reach. Hydrographic data collected for the April 2, 1980, flood were used to calibrate the flow model. The finite-element network was then modified to represent conditions without I-10 in place, and the hydraulic impact of I-10 was determined by comparing results with and without I-10.

The model was also used to study the effect of alternative modifications on backwater at the I-10 crossing. The simulation of one of these alternatives was discussed in this paper. The analysis used the model's capability to simulate changes in flood-plain topography, flood-plain vegetative cover, and highway-embankment geometry. The alternative reduced backwater to a fraction of its former value.

The capability of the modeling system FESWMS to simulate the significant features of steady-state flow in a complex multichannel river-flood-plain system with variable topography and vegetative cover was successfully demonstrated in this study. These features included lateral variations in discharge distribution and backwater or drawdown.

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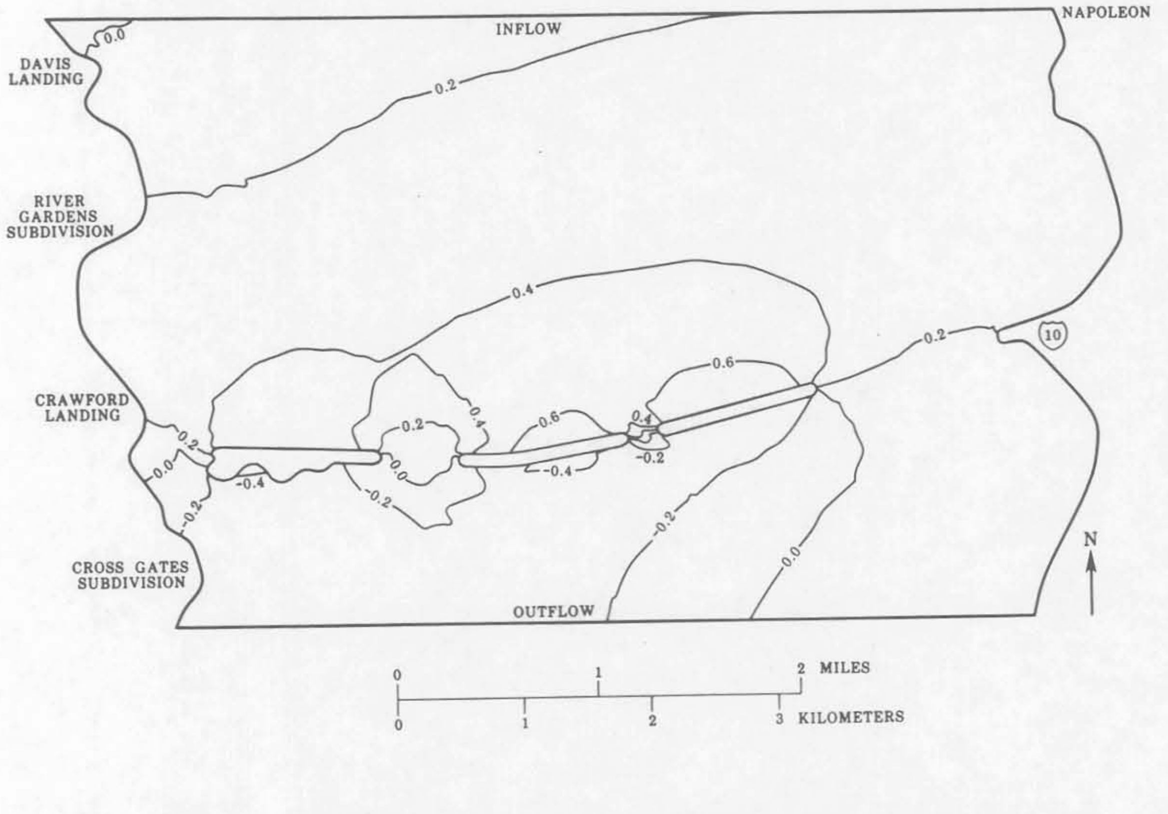

Figure 4. – Backwater and drawdown for a new bridge in I-10, interval 0.2 ft.