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NUMERICAL COMPUTATIONS FOR ESTUARINE FLOOD PLAINS

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ABSTRACT: Construction on estuarine flood plains can contribute significantly to flooding problems during times of large river inflow. A two dimensional depth averaged finite difference model is presented which allows for improved environmental impact assessment of construction on estuarine flood plains. The model is applied to the delta region above Mobile Bay, Alabama where a railroad crosses the flood plains. The railroad is built on a fill with trestles at established channels. The model is used to evaluate the effect which the railroad has on known flooding problems in the delta region. Partial calibration and verification of the numerical model is accomplished with available prototype data from previous flood events. The numerical model demonstrates that while a great amount of water may be stored on flood plains, conditions are not generally conducive for large flow rates. Most of the flood still moves along major established channels. Construction on flood plains may exert a significant influence on flood stage elevations in certain regions with other regions experiencing a very minor effect. In particular, construction in the interior of the flood plains may produce large effects in the interior with only minor effects propagating to the boundaries.

Freshwater inflow, an essential component of estuaries, can produce significant problems during periods of large inflow. The highly variable nature of many estuarine river systems, the geometry, topography, and bathymetry of the estuary and the interaction of local winds and astronomical tides produce a hydraulically complex environment. Man's tendency to cluster around estuaries for food, transportation and other needs invariably results in construction on the flood plains. The result has often been periodic flooding problems at times of major flood events. Numerical models offer potential for improved environmental impact assessment of construction on estuarine flood plains.

Over the past ten to fifteen years, numerical modelling of hydrodynamic systems has become an established science. A variety of numerical models are available based on both finite difference and finite element formulations of the basic governing equations. Hydrodynamic systems are basically three-dimensional; however, for many situations conditions are such that the flow can be satisfactorily approximated by a simplified set of governing equations. The two dimensional depth averaged model has been shown by a number of investigators (Butler and Raney, 1976; Butler, 1980, Leendertse, 1970; Raney and Butler, 1976; Reid, 1968) to satisfactorily represent flow in an estuary or bay when the water body is not stratified.

The present contribution presents a specific application of a two-dimensional depth average finite difference numerical model for flood plain investigations. Flooding problems which exist on Bayou Sara, a bayou on the flood plains above Mobile Bay, are considered. A railroad constructed on a fill crosses the flood plains with trestles at major streams. Because of the location of Bayou Sara relative to the railroad, some speculation exists concerning the effect which the railroad has upon flooding problems which are encountered along the bayou. The numerical model is used to investigate the influence which the railroad exerts on flood stages along Bayou Sara. The model is partially calibrated and verified using available prototype data for known flood events. Boundary conditions are used which produce a range of possible flood events. The two year, five year, ten year, twenty-year, fifty year, one hundred year and five hundred year probability flood events are of particular interest. For each flood event the model was applied for existing conditions and also the condition without the railroad on the flood plains. Differences between flow patterns, flow rates and flood stage elevations are documented. From these differences an assessment can be made of the railroad influence on flooding along Bayou Sara.

The numerical model has general applicability to similar flooding problems on estuarine flood plains. Availability of accurate model input data and flood stage water elevations for model calibration and verification is generally the limiting factor on the accuracy of results.

THE NUMERICAL MODEL

A complete mathematical description of the hydrodynamic flow in a harbor, bay or estuary would require that the velocity and density be completely specified for every point in the system at all times:

$$u = u(x,y,z,t)$$

$$\rho = \rho(x,y,z,t)$$

where

x = longitudinal coordinate measured along the estuary axis

y = transverse coordinate

z = vertical coordinate

t = time

Because of the difficulties in formulating, executing and verifying a three-dimensional model, researchers have devised a variety of numerical models of various degrees of simplification.

A two-dimensional depth averaged model (BAY) is used in this investigation. The model equations are derived from the generalized Navier-Stokes equations by making assumptions consistent with the two dimensional incompressible nature of the flow and integrating the equations over the water depth. Boundary conditions are satisfied at the bottom and at the surface of the water column. Thus, the model considers three dimensional geometry but produces a two dimensional depth averaged flow field. The most important approximations in the model are those of constant density and relatively small variations of velocity over the water depth, conditions which should be reasonably valid in the Mobile Bay delta.

The rectangular coordinate system is located in the plane of the undisturbed water surface as shown in Figure 1. The equations of motion and the equation of continuity are written as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \eta}{\partial x} - fv = R_x + L_x \qquad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \eta}{\partial y} + fu = R_y + L_y \qquad (2)$$

and

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}[(h + \eta)u] + \frac{\partial}{\partial y}[(h + \eta)v] = 0 \qquad (3)$$

where

u = depth-averaged velocity component in the x-direction

v = depth-averaged velocity component in the y-direction

t = time

x, y = rectangular coordinate variables

g = acceleration due to gravity

η = water level displacement with respect to datum elevation

f = Coriolis parameter

R_x, R_y = the effect of bottom roughness in x and y directions

L_x, L_y = the effect of the wind stress acting on the water surface in the x and y directions

h = water depth

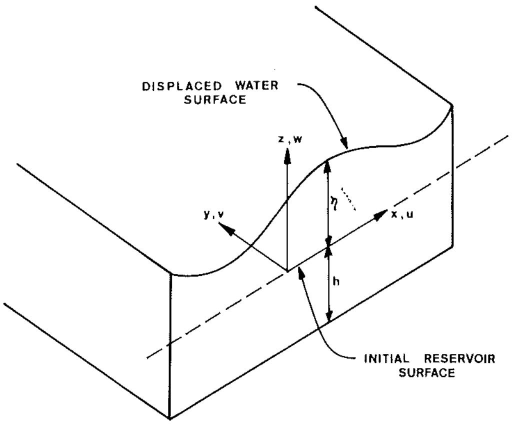

Figure 1. Coordinate System for Problem Formulation.

The continuity equation has been obtained by integrating across the water depth and applying kinematic and dynamic boundary conditions at the surface and bottom of the reservoir. The bottom friction terms are represented by:

$$R_x = \frac{-gu(u^2 + v^2)^{1/2}}{C^2(h + \eta)} \tag{4}$$

$$R_y = \frac{-gv(u^2 + v^2)^{1/2}}{C^2(h + \eta)} \tag{5}$$

where C is the Chezy coefficient. The wind stress terms are of the form:

$$L_x = \frac{T_x}{(h + \eta)} \tag{6}$$

$$L_y = \frac{T_y}{(h + \eta)} \tag{7}$$

where T_x and T_y are the wind stress components acting on the water surface.

A major advantage of BAY is the capability of applying a smoothly varying grid to the given study region. This allows efficient simulation of complex geometries by locally increasing grid resolution in critical areas. For each coordinate direction, a piecewise reversible transformation is independently used to map prototype or real space (x,y space) into a computation space (α_1, α_2 space). The transformation takes the form

$$x = a + b\alpha^c \tag{8}$$

where a, b and c are arbitrary constants. By applying a smoothly varying grid transformation which is continuous and which has continuous first derivatives, many stability problems commonly associated with variable grid schemes are eliminated provided that all derivatives are centered in space (Wanstrath *et al.*, 1976). The transformed equations in space can be written, as

$$\frac{\partial u}{\partial t} + \frac{1}{\mu_1} u \frac{\partial u}{\partial \alpha_1} + \frac{1}{\mu_2} v \frac{\partial u}{\partial \alpha_2} + \frac{g}{\mu_1} \frac{\partial \eta}{\partial \alpha_1} - fv = R_x + L_x \tag{9}$$

$$\frac{\partial v}{\partial t} + \frac{1}{\mu_1} u \frac{\partial v}{\partial \alpha_1} + \frac{1}{\mu_2} v \frac{\partial v}{\partial \alpha_2} + \frac{g}{\mu_2} \frac{\partial \eta}{\partial \alpha_2} + fu = R_y + L_y \tag{10}$$

$$\frac{\partial h}{\partial t} + \frac{1}{\mu_1} \frac{\partial u}{\partial \alpha_1} [(h + \eta)u] + \frac{1}{\mu_2} \frac{\partial u}{\partial \alpha_2} [(h + \eta)v] = 0 \tag{11}$$

To solve the governing equations, a finite difference approximation of the equations and an alternating direction technique are employed. The solution scheme is similar to that proposed by Leendertse (Leendertse, 1967). A space-staggered scheme is used in which velocities, water-level displacement, bottom displacement, and water depth are described at different locations within a grid cell as shown in Figure 2. Central differences are used for evaluating all derivatives in the governing equations. The application of these difference approximations gives rise to corresponding difference equations centered about different points within a grid cell. These expressions require the evaluation of certain quantities at locations different from those defined in the grid system. Such quantities are replaced by values computed from one- and two-dimensional averaging of neighboring values.

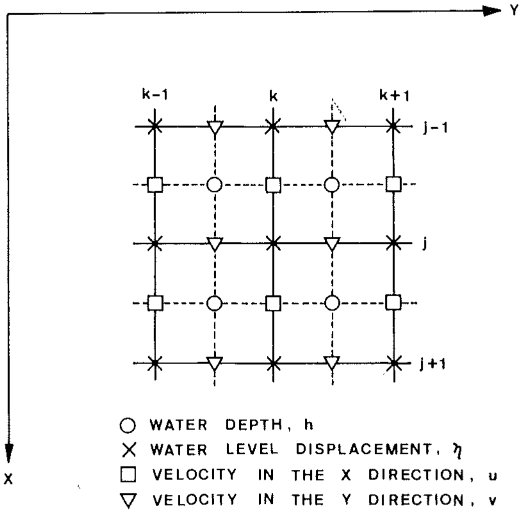

Figure 2. Grid System and Variable Definition Locations.

Three types of boundaries are involved in the calculations: solid boundaries at fixed coastlines, artificial tidal input boundaries arising from the need to truncate the region of computation and river inflows into the bay.

The boundary condition for the solid boundary can be written as

$$\bar{V}_n = 0 \qquad (12)$$

where $\bar{V}_n$ denotes the normal component of velocity. Artificial tidal boundaries were used in the model to describe the tidal action that occurs at the bay computational boundaries. The water surface elevation-time history for the desired tidal cycle is specified at each such boundary and applied during the operation of the model. River inflow boundaries are required to simulate the river hydrograph for significant streams discharging into the study region.

MOBILE BAY DELTA SYSTEM

Mobile Bay is the terminus of the fourth largest river system, in terms of discharge, in the contiguous United States (Morisawa, 1968) and the sixth largest on the North American Continent (Chow, 1968). The river system discharging into Mobile Bay is a complex one as is illustrated in Figure 3. In simplified form, the river system can be considered to start at the confluence of the Alabama and Tombigbee Rivers where the Mobile River is formed. The Mobile River then divides into the Tensaw and lower Mobile Rivers. Both of these rivers branch many times producing a complex network of major channels, creeks, and bayous. The river system flows over a flood plain which extends for over 30 miles south terminating at the northern end of Mobile Bay.

The average discharge of the river system (1929-1978) into the bay is approximately 64,100 cfs (1815m^3/sec) (Bault, 1972). The monthly average discharges have a high flow in February, March and April and a low flow period between June and November.

Significant flooding is considered to occur when flows exceed approximately 247,000 cfs (6994m^3/sec) (Schroeder, 1978). A table of probability floods is shown in Table 1. At the delta-bay inter-

Table 1. Flow rate - expected probability data for Mobile River at Barry Steam Plant.

(BUCKS, ALABAMA)

STATISTICAL RATE OF OCCURRENCE (YRS)	EXPECTED FLOW RATE (CFS)
2	284,000 (8,040 m^3/sec)
5	371,000 (10,500 m^3/sec)
10	425,000 (12,000 m^3/sec)
25	491,000 (13,900 m^3/sec)
50	540,000 (15,300 m^3/sec)
100	588,000 (16,700 m^3/sec)
500	700,000 (19,800 m^3/sec)

face the lower Mobile River and three distributaries, the Tensaw-Spanish River, the Apalachee River and the Blakeley River discharge into Mobile Bay. At the upper end of the study area, I-65 cuts across several water bodies, the Mobile River, Little Lizard Creek, Mifflin Lake, the Middle River, and the Tensaw River. Between the boundaries for the study area lies a great deal of flood plains with an elevation only a few feet above mean sea level. During flood conditions a great deal of water is stored on these flood plains. There have been several general studies (Schroeder, 1977, 1979; Stout, 1979) of the marsh flood plain areas and the effects of river flooding in Mobile Bay. Little attention, however, has been focused on flooding problems in the delta region.

The railroad generally follows a northeast to southwest path across the delta which basically has a north-south alignment. As indicated in Figure 3, Bayou Sara is located in the west-central region of the delta. The geometry of the system suggests that the railroad might have an effect on flood stage elevations along Bayou Sara.

THE FINITE DIFFERENCE GRID

The finite difference grid, Figure 4, used to model the Mobile Bay delta system was developed using a 1:2400 scale nautical chart (U.S. Geological Survey, 1974). A variable grid was developed with the primary objective of good resolution of the main river channels and the area around Bayou Sara. A reasonable representation of other geometric and bathymetric features of the area was established. The dimension of the resulting grid was 78 by 38 cells or 2964 cells. After mapping the grid, it

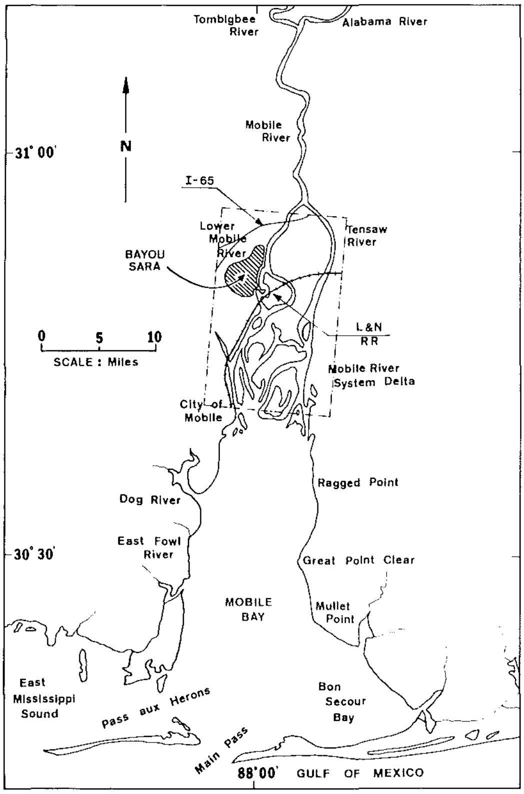

Figure 3. Mobile Bay and River Delta System.

was used as an overlay on the nautical chart to assign boundaries, depth and Manning friction coefficients for each finite difference cell. A set of aerial photographs (Continental Aerial Surveys, 1982) of the delta region taken during February 1982 was also useful in developing the finite difference grid and other input data for the numerical model. Information on construction details of the railroad across the flood plains was also used in establishing the finite difference grid. The manner in which the grid represents the major channels in the study area is illustrated in Figure 5.

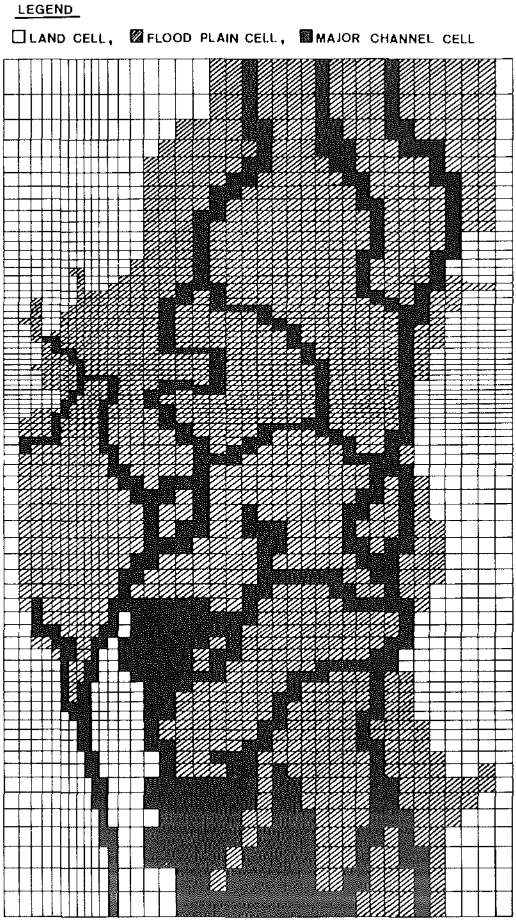

Figure 4. The Variable Size Finite Difference Grid.

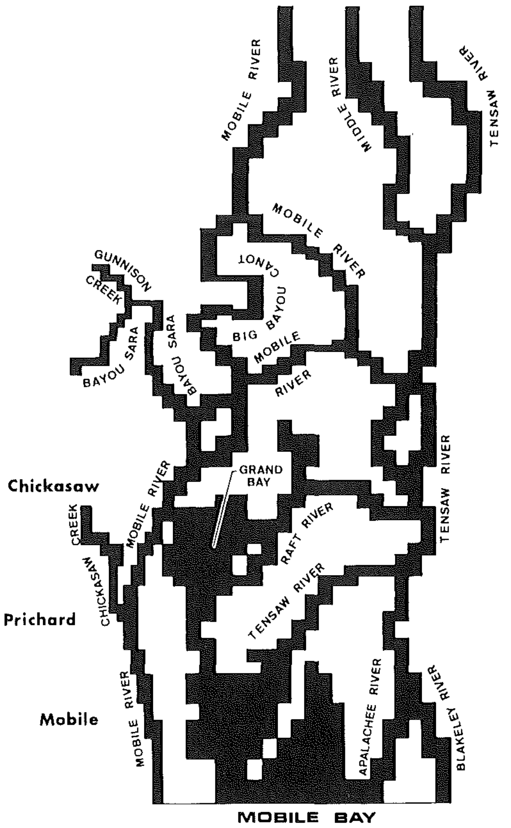

Figure 5. Representation of Major Channels by the Finite Difference Grid.

The smallest cells were used in representing the area around Bayou Sara since this was the region of primary interest. Small cells were also used for the major river channels. Larger cells were used on the flood plain area where the bathymetry was reasonably constant and/or boundary geometry was relatively simple. The smallest cell size was 500 feet and the maximum depth was approximately 45 feet.

Elevation boundary conditions were specified at the Mobile Bay boundary and upstream at the I-65 boundary. The Mobile Bay elevation is primarily dominated by the tide while the elevation boundary condition specified at I-65 is representative of the flood stage. An elevation boundary condition was applied at I-65 rather than a flow boundary condition because of greater accuracy in imposing the boundary condition in the numerical model.

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Depths were assigned to each water cell as delineated by the land boundary. The depth of each cell was determined as a weighted average of the charted depths within the cell. Because of a lack of bathymetric and topographic data of the flood plains, most of these areas were considered to have the same elevation. In areas where the finite difference cell is larger than the actual physical dimension, cell depths were reduced in the model to make the flow cross-sectional areas approximately equal. Manning's n friction values for bottom roughness were assigned on a relative basis according to the bottom type specified by the nautical chart.

The datum of the nautical chart was the National Geodetic Vertical Datum of 1929 (N.G.V.D.). All elevations used in the study were established relative to this datum. Most of the flood plains are only slightly above the N.G.V.D. reference in elevation and are flooded during the flood events to be simulated.

MODEL CALIBRATION AND VERIFICATION

A numerical model must be calibrated and verified before a great deal of confidence is placed in the model results. Calibration consists of demonstrating that the numerical model can be adjusted to produce results which are consistent with a measured prototype data set. Verification consists of applying the calibrated model and reproducing a second set of prototype data to a reasonable degree of accuracy.

For this study one relatively complete set of prototype data (U.S. Army Corps of Engineers, 1979) was available representing high water elevations around the delta region for the flood event of March 1979. This data set was used to calibrate the model. A partial data set (U.S. Army Corps of Engineers, 1979) of high water elevations was available for the Spring 1979 flood event. These data were used to provide a limited verification of the numerical model.

The measured high water elevations at I-65 provided a basis for establishing the northern elevation boundary conditions for model calibration. The tidal elevations measured in Mobile Bay provided the boundary condition for the southern boundary of the model. The model was started with a constant water elevation throughout the delta region including the flood plains. The boundary conditions were then allowed to gradually change until the desired flood condition was reached in about 18 hours. The boundary conditions were then held constant for approximately 6 hours so that a quasi-steady state condition was

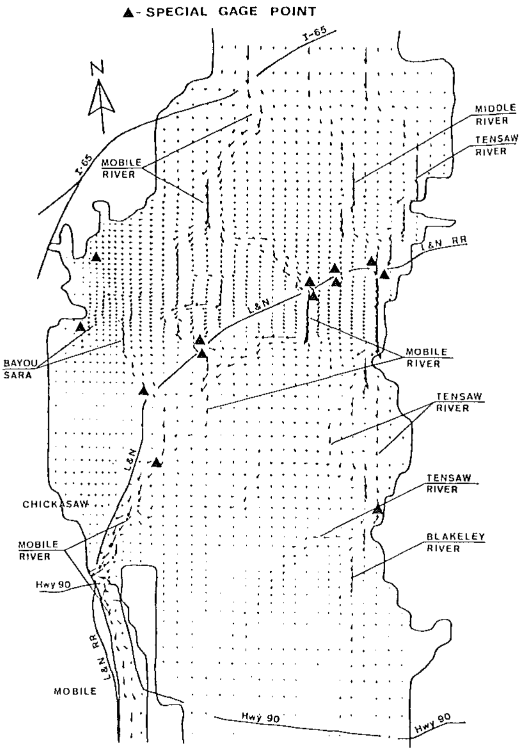

Figure 6. Vector Plot of Velocity Pattern in Delta Region for Calibration Condition.

reached in the model. For a more detailed study, actual river hydrographs should be used as the river boundary condition. Flood stage elevations at 13 locations in the delta region and the system flow rate were the primary variables used in establishing model calibration and verification. The special gage point locations are shown in Figure 6.

The calibration and verification process was continued until agreement was reached between the numerical model and prototype data sets. A vector plot of the flow pattern for the calibration run is shown in Figure 6. Observe that most of the flow follows the channel with only small velocities on the flood plain areas. Additional results from the calibration and verification process are shown in the next section of the paper along with other model results. An average height of 1.9 feet above N.G.V.D. for the flood plains appeared to produce the most satisfactory results. Manning n values between 0.021 and 0.07 were used.

MODEL APPLICATIONS AND RESULTS

The numerical model was applied for a range of upstream elevation boundary conditions. The lower boundary condition, dominated by the bay tide, was maintained as that used for model calibration. Different upstream boundary elevations were selected to produce flood events with a range of flow rates between approximately 200,000 cfs ($5660 m^3/sec$) and 800,000 cfs ($22,700 m^3/sec$). This range of flow rates contains the 2 year, 5 year, 25 year, 50 year, 100 year and 500 year probability flood events. In each case, the starting condition for the model was an initial constant water elevation and zero velocity in the delta region. The boundary conditions were then allowed to change to produce the desired quasi-steady state flood event in approximately 24 hours. For each set of boundary conditions there were two model applications. The first model application was for existing conditions; i.e., with the railroad crossing the flood plains. The railroad fill was then replaced by flood plains with friction and depth characterisitics similar to surrounding areas.

Figure 7 illustrates the calculated flood stage elevations at one of the special gage points in the delta system as a function of flow rate. Results for existing conditions and for the without railroad case are presented in the figure along with prototype data used for calibration and verification. The numerical model was found to be in general agreement with prototype data for the entire delta region. The railroad does not appear to produce large changes in flood elevations at any of the points in the delta region where prototype data were available. The largest effects at any of the special gage points are in the Bayou Sara area, but even here effects are small compared with the overall flood stage elevation.

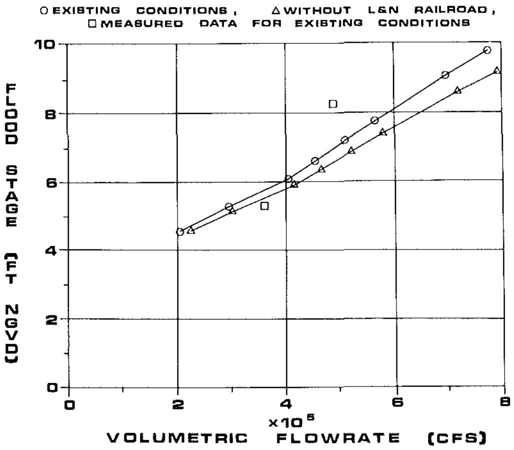

Figure 7. Flood Stage (N.G.V.D.) on Bayou Sara (near Satsuma) as a Function of Flow Rate.

Sample vector plots of overall flow patterns in the delta region are presented

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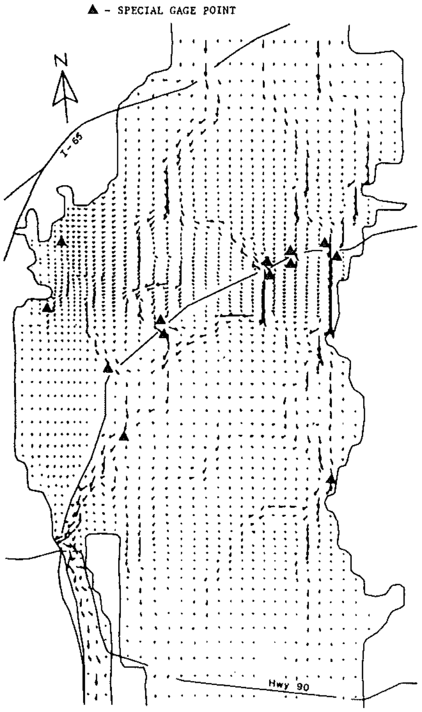

Figure 8. Overall Flow Patterns in the Mobile Bay Delta Region for a Flow Rate of 504,327 cfs.

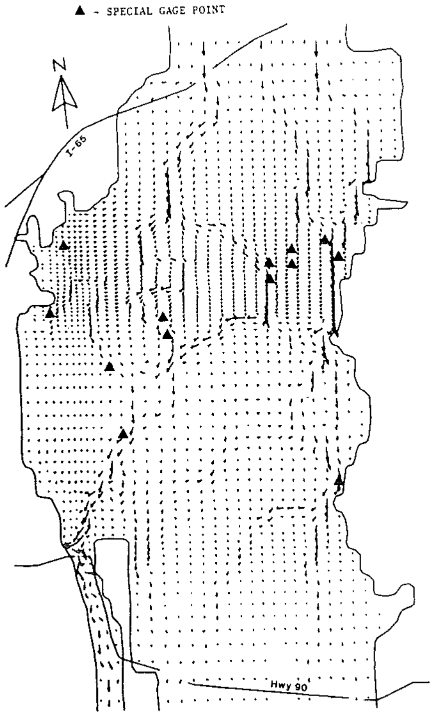

Figure 9. Overall Flow Patterns in the Mobile Bay Delta Region (without the L & N Railroad) for a Flow Rate of 518,636 cfs.

in Figures 8 and 9. Figure 8 is for existing conditions while Figure 9 represents the flow pattern if the railroad did not cross the flood plains. These plots clearly indicate that most of the flow passes along the existing channels regardless of whether the railroad exists or does not exist on the flood plains. There is a great deal of water stored on the flood plains, but there is not a large quantity of flow along (north to south) or across (east to west) the flood plains. The large friction and small depth conditions on the flood plains are not conducive to large flows.

Representative contour plots of flood stage elevation in the delta region are presented in Figures 10 and 11. Figure 10 is for the existing condition and Figure 11 is for the case without the railroad on the flood plains. These con-

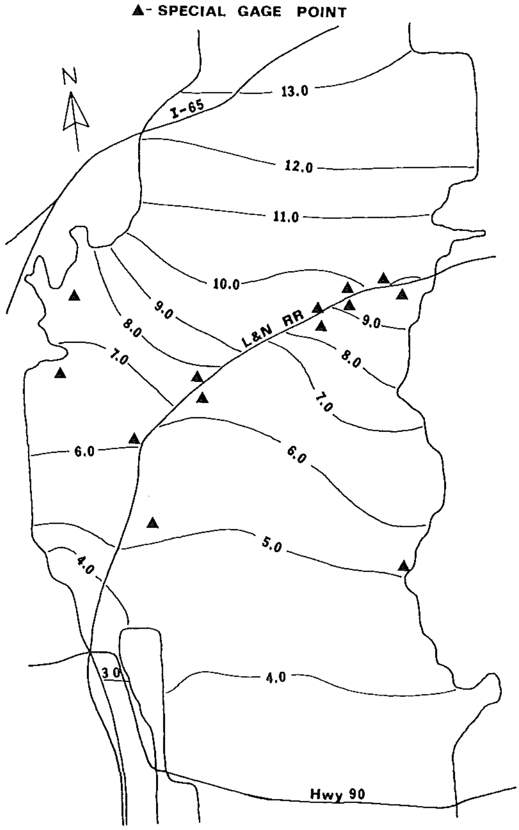

Figure 10. Flood Stage Contours (feet) in the Mobile Bay Delta Region for a Flow Rate of 504,327 cfs (1 ft = 0.305 m, 1 cfs = 0.028 m³/sec).

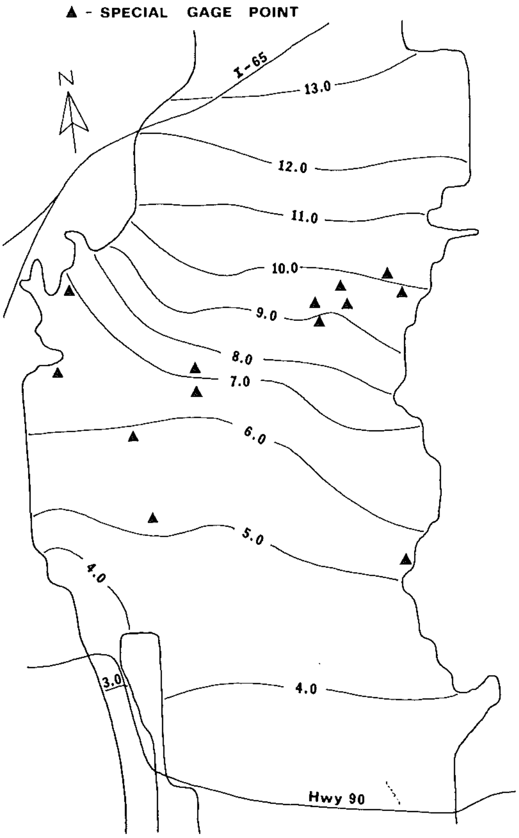

Figure 11. Flood Stage Contours (feet) in the Mobile Bay Delta Region (without the L & N Railroad) for a Flow Rate of 518,636 cfs (1 ft = 0.305 m, 1 cfs = 0.028 m³/sec).

tour plots indicate that the railroad does produce significant differences in flood stage elevations within the interior of the delta region; there is almost 2 ft (0.61 m) differences in elevation across the railroad fill in some locations. Figure 12 represents a contour plot for the difference in flood stage elevation which can be attributed to the railroad crossing the flood plains. Some large differences are observed in the interior of the delta but only relatively small differences extend to the boundary areas.

CONCLUSIONS

The numerical model was calibrated and verified to an extent consistent with the objectives of this investigation. The flows in the delta region are found to be primarily within the existing channels with only a relatively small percentage of the flows along or across the flood plains. Significant differences in flood stage elevations are produced by the railroad within some interior regions of the delta; i.e., across the railroad fill. However, these regions where significant effects are observed are confined to restricted regions within the interior of the delta. The effects are relatively small around the boundaries of the delta.

Based upon the numerical model results, the increase in flood stage elevation along Bayou Sara is small compared with the overall flood stage elevation. Below a system flow rate of 200,000 cfs

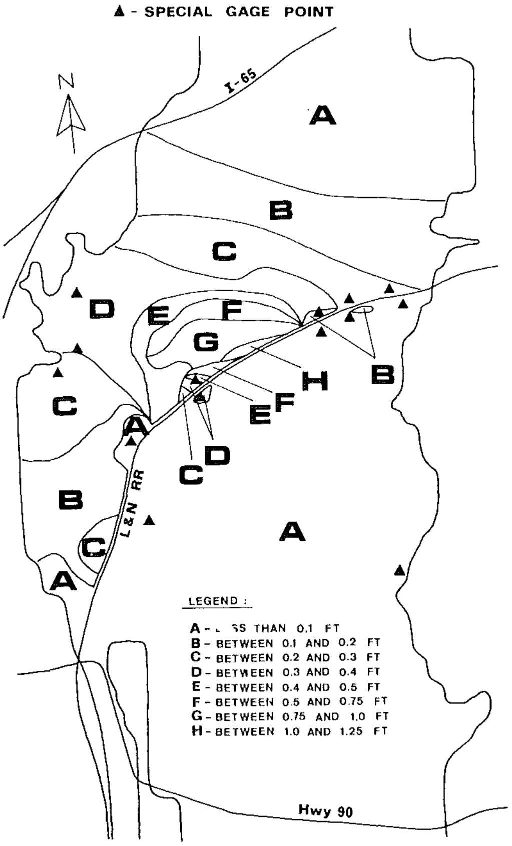

Figure 12. Differences in Flood Stage Elevations in the Mobile Bay Delta Region as a Result of the L & N Railroad for a Flow Rate of Approximately 510,000 cfs (1 ft = 0.305m, 1 cfs = 0.028 m³/sec).

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(5,660 m³/sec) there is a negligible effect caused by the railroad. On a statistical basis, a 200,000 cfs (5,660 m³/sec) flow rate corresponds to a flood event which should occur once each year. The railroad effect at Bayou Sara increases up to approximately six to eight inches (15.2 to 20.3 cm) for a flow rate of 700,000 cfs (19,800 m³/sec). A 700,000 cfs (19,800 m³/sec) flow rate corresponds to a flood event which has a 500 year statistical rate of occurrence. The effects of the railroad on flood stage elevations along Bayou Sara is therefore small compared with overall flood stage elevations.

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