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Numerical Modeling of the Flow Field at the Confluence of Buffalo and White Oak Bayou in Houston, Texas.

Theodore G. Cleveland, and Keh-Han Wang
Department of Civil and Environmental Engineering
University of Houston
Houston, Texas

Steve Fitzgerald
Harris County Flood Control District
Houston, Texas

Introduction

The Harris County Flood Control District (HCFCD) is altering the stream channel at the confluence of Buffalo and White Oak Bayou to convey flood waters more efficiently and to reduce erosion near Allen's Landing in Houston, Texas. The improvements consider the historical value of the area, aesthetics, and physical location of existing structures to create a setting that will be used as a park during normal flows, yet will safely and efficiently convey water during flood flows. This paper describes a hydraulic modeling effort used to provide information to assist in pre-construction design evaluation of the proposed channel improvements.

The modeling effort used a three-dimensional hydrodynamic model that coupled inflow hydrographs, bayou geometry, and bottom stresses to compute a three-dimensional time varying velocity field and the free surface elevation of water in the confluence. The model was coupled to a digital terrain model that can be modified to reflect different channel geometries, and to a dye simulation model to help visualize the flow fields. Numerical simulations were conducted for both existing and proposed channel geometries using 100-yr design hydrographs as model input to generate comparative data for evaluating the effect of the designs on the bayous' flow field.

The model results indicate that the proposed bayou modifications will more efficiently convey White Oak Bayou flood waters. The model predicts that velocities are reduced in some locations that are sensitive to damage from routine flow conditions.

Digital Terrain Model

A simplified digital terrain model of the study area was constructed using elevation and location data provided by the HCFCD. these data were transfered to a rectangular grid of preselected spatial resolution (100 x 100) using an inverse squared distance algorithm. The algorithm uses the three nearest neighbor points to interpolate the elevation of a grid location. This rule is consistent with rules currently accepted in digital terrain mapping (Jones and Wright, 1991).

In regions of the model where no flow was expected to occur, an arbitrary elevation value of +40 feet is used. This arbitrary upper bound has no effect on the flow region and significantly eases data preparation, but the terrain model is only accurate in the flow model boundary and inaccurate elsewhere. The inaccuracy is most evident at the flow model inflow and outflow boundaries, where the contour lines are closed.

The gridding of the randomly spaced data was performed using SURFER™(Golden Software, 1990). The gridding algorithms explored were kriging (Journal and Huijbregts, 1978), inverse-square interpolation (Shepard, 1968), and minimum curvature (Lancaster and Salkausas, 1986). The inverse squared method produced the best results when field checked. The digital terrain model accuracy was field checked using a pocket transit by recording and comparing angles from a known location to structural features in the model area. Figures 1 and 2 are contour maps generated from the existing and proposed digital terrain models.

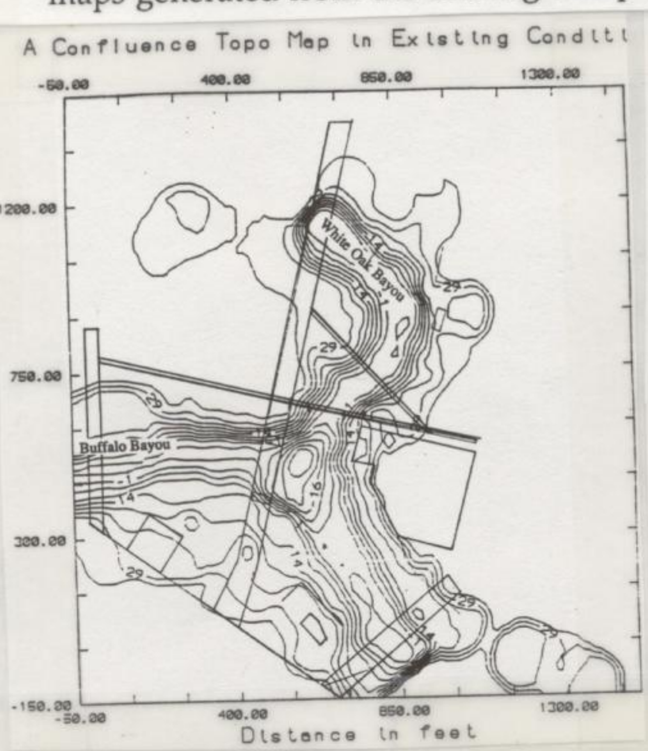

Figure 1. Digital Terrain Map-Existing

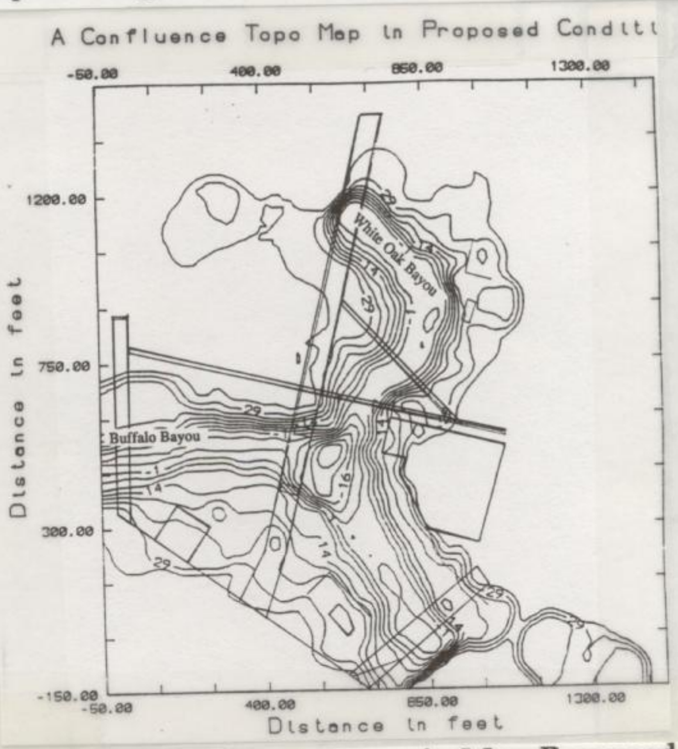

Figure 2. Digital Terrain Map-Proposed

Three-Dimensional Hydrodynamic Flow Model (HFM3D)

The HFM3D hydrodynamic flow model for interconnected riverine systems with a free surface moving boundary condition was developed by modifying a general three-dimensional multi-layered estuary and coastal model, ESCO3D (Wang, 1991).

The model solves the full Navier-Stokes equations and can incorporate as much external and internal boundary detail as desired. The forcing factors used in this study were: confluence geometry, water depth, bottom stress, and volumetric boundary flow rates. A second order turbulence model was used for the turbulent eddy correlations. These complicated features were included so that hydrographic and physiographic changes could be included as needed. HFM3D generates three dimensional velocity fields and water surface elevations as its output.

The feature of a moving flow boundary due to water rising up or dropping down is simulated by the model. The numerical method employed was a three-time-level implicit finite difference scheme that incorporates the complex bayou geometry by a horizontal curvilinear coordinate transformation and vertical dilation (stretching). A staggered grid was used in both the vertical and horizontal dimensions of the computation domain. A mode splitting technique was applied so that the computation of the external free-surface could be decoupled from the full three dimensional equations. This technique produced vertically averaged equations that were solved using the alternating direction implicit (ADI) method (Peaceman and Rachford, 1955). Once the free surface is calculated, the three dimensional velocity field is computed from a momentum balance using a vertically implicit scheme (Wang et al., 1991).

Moving Boundary Algorithm

A moving boundary algorithm was developed to simulate the moving fluid domain in the confluence of Buffalo and White Oak Bayou. When both bayous convey their base flows or small discharge flows, the flow regions are well defined in the base channel; the banks and flood plain are dry and no flow exists in these areas. Once the storm-water induced flood discharge flows into the bayous, the water surface rises and wets a large area. The model accounts for a flood expanded flow region by using an expanded computational domain. During flood recession, the model assumes that the wetted areas will gradually drain and the computational domain can then be reduced.

To simulate the moving boundary flow region, the maximal region which is expected to be wetted by the design flood is first specified. In this study, flow fields using 100-year flood hydrographs were selected for this purpose. Based on the HEC-2 simulation provided by the HCFCD, the flood stage downstream of Buffalo bayou for a 100-year flood from both Buffalo and White Oak Bayou is 37.8 feet. A physical boundary based on the existing structures and bottom elevation of 36 feet was defined as the maximal extent of flow in this study. The domain inside this area is considered as possible flow area, while the domain outside this boundary is a no-flow zone for the entire simulation. Using this defined boundary, the curvilinear coordinates for the hydrodynamic simulation were generated and are shown on Figure 3.

The bottom elevation at each grid point is calculated from the bayou geometry data provided by the HCFCD. These data are used in the model to determine water depth. If the channel bottom is below the free surface elevation, the water depths in the bayou domain are obtained by subtracting the elevation of the channel bottom from the surface elevation. This depth is used as a reference to determine whether a particular grid location is modeled as dry or wet. When the free surface rises above the bottom elevation of a dry cell (positive reference depth), the dry cell is re-defined as a wet cell. This moving boundary is applied continuously during the model simulation with the entire dynamic effect of variable inflow on the hydrodynamics being reproduced.

Although prediction of the flood area can be conducted with the moving boundary algorithm, the model is designed to model velocity fields through a momentum balance. It is not intended for flood plain delineation. Because an upper bound to the flow region must be specified, the model may underpredict flooded areas and over predict velocities.

Dye Simulation Model (DSM2D)

A two dimensional dye simulation model was developed to help visualize the flow patterns in the confluence of the two bayous. The dye simulation uses the water movement patterns produced by the three-dimensional water flow model to simulate ideal tracer dye transport. The numerical results were converted into animated color images using graphical post-processing software.

The direct simulation approach is used to simulate the behavior of a hypothetical dye injected into the river system. The direct simulation uses analogs originated by Eliason and Foote (1972) for modeling thermal transport in coastal waters.

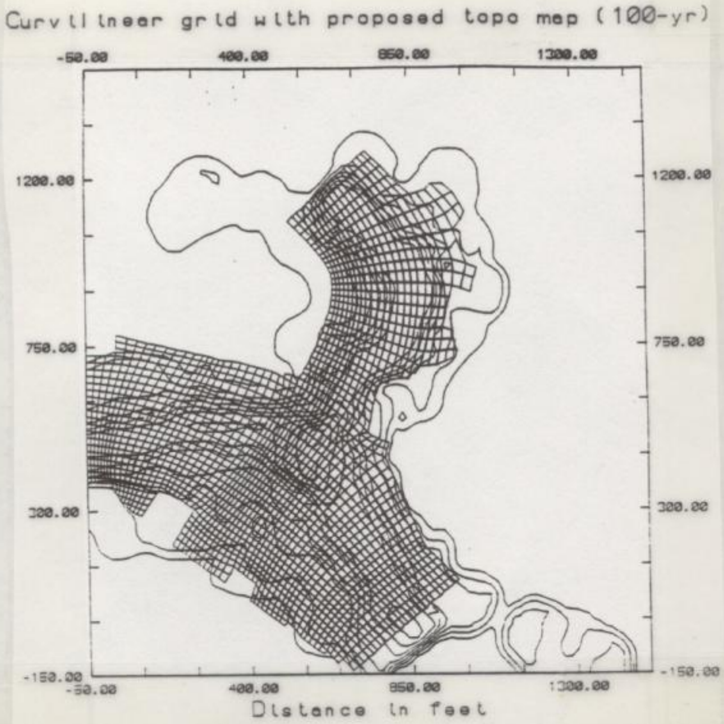

Figure 3. Curvilinear Simulation Domain

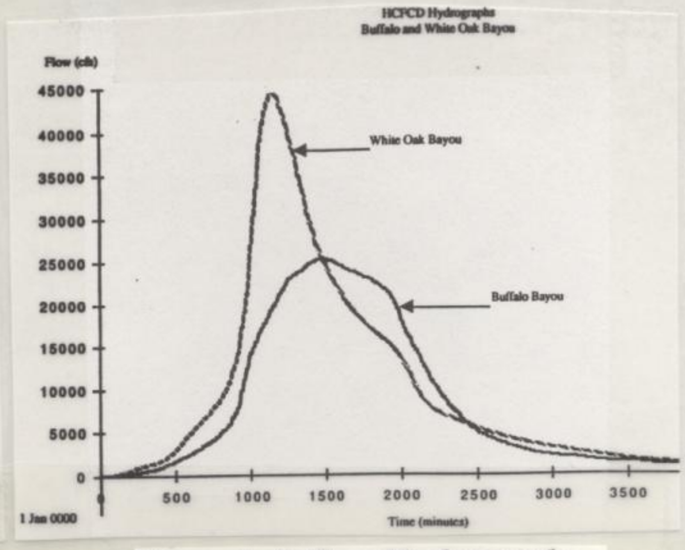

Figure 4. Inflow Hydrographs

Model Performance Evaluation

The hydrodynamic flow model was calibrated using steady base flow and steady 10-year flow conditions. These runs indicated that the model was behaving reasonably well (Wang et al., 1991). The hydrodynamic flow model was additionally evaluated by comparing its predictions with the predictions from the HEC-2 model currently used by HCFCD. During the first eight simulation hours, the water levels obtained from HEC-2 agree closely with HFM3D. During the peak discharge HFM3D underpredicts HEC-2 by 5 ft, yet the HEC-2 model exhibits the static model effect of water level dropping instantly when the inflow discharge is reduced. HFM3D indicates that water level can still rise even when inflow discharge decreases (water is moving into bank storage). Rating curves generated from each model were also different. HFM3D generates a loop rating curve which we believe to be more representative of the progress of a typical flood flow than the nearly linear relationship generated by HEC-2.

Simulation Application and Results

The discharge inflows from Buffalo and White Oak Bayou's are the design 100-year flood flows provided by HCFCD. The hydrographs are shown on Figure 4. In order to study the flow field under different conditions, six conditions were selected: (a) 100-year flow both bayous, both geometries; (b) 100-year flow White Oak Bayou, both geometries; (c) 100-year flow Buffalo Bayou, both geometries. Flow fields and water surface levels were simulated for both existing and proposed conditions. Velocity profiles for each geometry for each time were constructed; Figures 5 and 6 are examples. we selected five cross sections (three along White Oak Bayou, and two along Buffalo Bayou), marked A-A,B-B, C-C, D-D, and E-E, and tabulated cross section velocity distributions, stages, stages, and discharges. These data are used to compute the velocity magnitude, forces, and water levels along these critical sections.

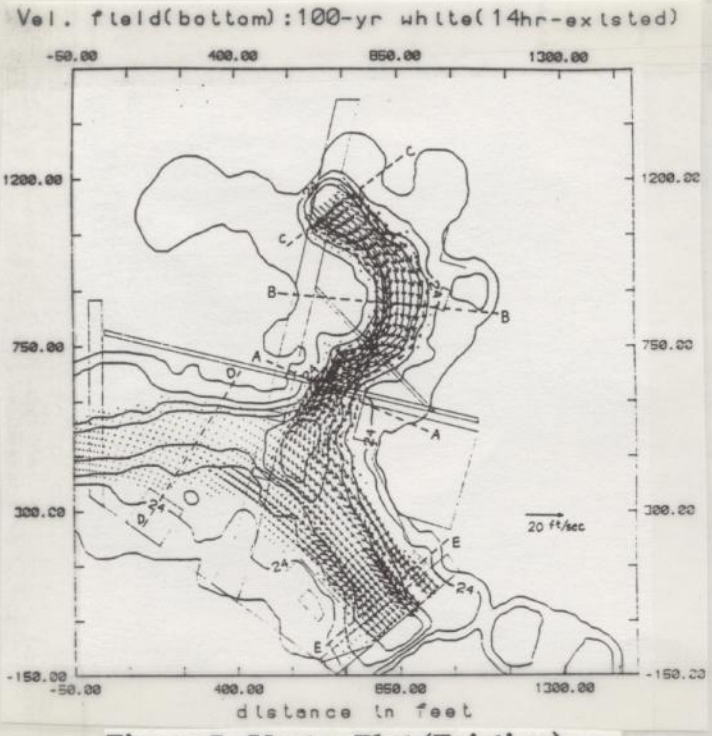

Figure 5. Vector Plot (Existing)

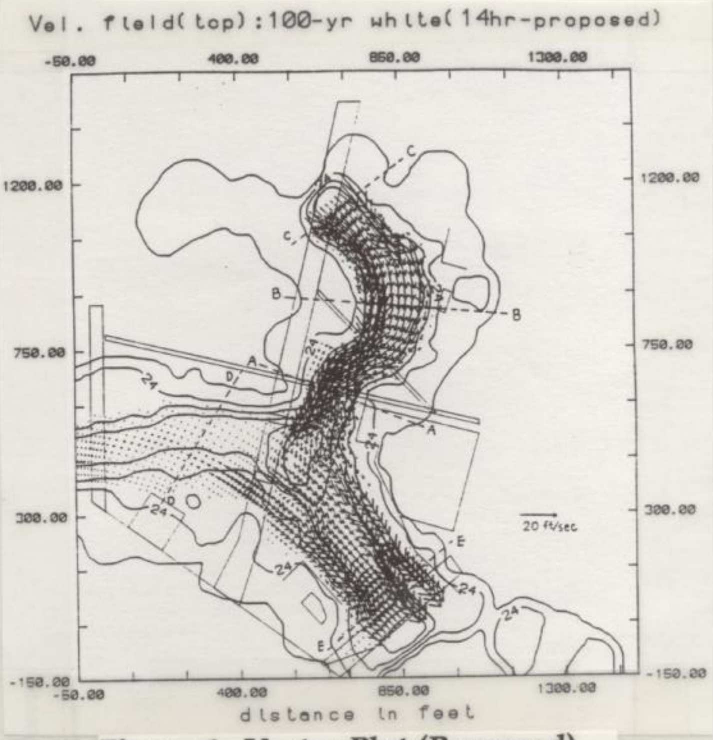

Figure 6. Vector Plot (Proposed)

Comparisons of the velocity fields under existing and proposed conditions indicate that the proposed modifications improve the flow situation. A more uniform velocity distribution occurs under the proposed conditions; the fluid follows a smoother path and turns downstream toward the confluence while still in White Oak Bayou. The velocities in the proposed geometries are larger than in the existing conditions, but the channel is smoother so there is less resistance to flow. Recirculation eddys are formed in both conditions, although the magnitude of recirculation is less in the proposed conditions. The proposed improvements do not appear to significantly reduce the normal component of flows at Allen's Landing, and some channel armor will still be required to reduce or stop the erosion at this historical site.

Summary

A three-dimensional hydrodynamic model that coupled inflow hydrographs, bayou geometry, and bottom stresses to compute a three-dimensional time varying velocity field and the free surface elevation of water in the confluence. The model was coupled to a digital terrain model that can be modified to reflect different channel geometries, and to a dye simulation model to help visualize the flow fields.

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