CHAPTER 60

COASTAL FLOOD SIMULATION IN STRETCHED COORDINATES

by

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ABSTRACT

Coastal flooding in developed areas can be catastrophic. As an essential element in coastal water level prediction, a two-dimensional numerical model of long period wave behavior is presented. The time dependency is treated implicitly for cost-effective simulation of coastal flooding from hurricane surges or other hydrodynamic phenomena such as extratropical storm surges, tides, tsunamis, etc.

An important feature of the model is use of a coordinate transformation in the form of a piecewise exponential stretch. Such a technique permits simulation of a complex landscape by locally increasing grid resolution and/or aligning coordinates along physical boundaries.

The model is applied to Galveston Bay, Texas, for storm surge and coastal flooding from Hurricane Carla 1961. Verification for the Galveston area was accomplished by using physical model data from simulations of free gravity waves (tide and design surge). Subsequent hindcasting of Carla produced good agreement between observed and computed surges with a mean absolute error of 0.18 m for peak elevations.

INTRODUCTION

Reliable prediction of coastal inundation from tidal or hurricane surge is extremely complex and is usually complicated by the presence of channels, barriers, bays, and highly variable bathymetry and topography which redistribute water flooding inland from the open sea. The Corps of Engineers, and in particular, the Waterways Experiment Station (WES), have had to address the problem of providing reliable estimates of coastal flooding in order to make sound engineering decisions regarding the design, operation, and maintenance of various coastal projects. Physical models have been used in the past to simulate free gravity surge, however they have the disadvantage of not being able to effectively simulate wind effects. The need of a more generalized numerical model for treating the flooding from storm surges (Wanstrath et al., 1977) in coastal areas has therefore been apparent for some time. Many two-dimensional storm surge models have been presented in the literature during this decade. Each model has exhibited certain advantages but most models have been developed for application to specific locations. The model presented here has been under development at WES (Butler and Raney, 1976; Butler, 1978) for use in storm surge applications as well as other applications where shallow water wave equations can be employed.

The most popular approach to solving the system of differential equations describing storm driven surges has been the application of finite difference techniques (Reid and Bodine, 1968; Leendertse, 1967, 1970, 1971; Pearce, 1972; Reid et al., 1975; Wanstrath, 1976). The model described herein, known as the WES Implicit Flooding Model (WIFM), employs the implicit solution scheme developed by Leendertse (1967). Dependent variables of the centered, alternating-direction procedure used in the model are the vertically integrated fluid transports and surface elevations as a function of position and time. Included in the model are actual bathymetry and topography, time and spatially variable bottom roughness, inertial forces due to advective and coriolis accelerations, rainfall, and spatial and time-dependent wind fields. Horizontal diffusion terms in the momentum equations are optionally present and can be used, if desired, for aiding stability of the numerical solution. Inundation, drying, and/or draining of low-lying terrain during a hurricane surge is simulated by making the location of a land-water boundary a function of local water depth. The model also is capable of treating subgrid barrier effects. Exposed, submerged, and overtopping barriers can be represented within the grid system permitting proper simulation of surge waters breaching narrow barriers such as elevated highways, railroads, control structures, etc. WIFM uses a coordinate transformation in the form of a piecewise exponential stretch to map real space, descretized with a smoothly varying grid, into computational space employing a regular spaced grid. Such a scheme permits a local increase of resolution in strategic areas while minimizing computational cost.

Calculation of coastal water levels from surges requires an estimation of storm windfields. The hurricane windfield model currently used in WIFM follows that used by Jelesnianski (1965) and Wanstrath (1976). An improved windfield model has been suggested by Cardone (1969) and research is ongoing to extend the work of Resio and Vincent (1977) and Cardone to develop a planetary boundary layer windfield model which also accounts for windfield transformation as the storm propagates from the open ocean across coastal flood-prone lands.

Application to Galveston Bay included verification to physical model data and subsequent simulation of storm surge and coastal flooding from hurricane Carla. An open-coast curvilinear coordinate surge model of the continental shelf (Wanstrath, 1977) was used to specify seaward boundary conditions for WIFM. Hindcast results for Carla indicate WIFM's predictive capabilities.

SHALLOW WATER WAVE EQUATIONS

The hydrodynamic equations used in WIFM are derived from the classical Navier-Stokes equations in a Cartesian coordinate system (Fig. 1). By assuming vertical accelerations are small and the fluid is homogeneous, and integrating the flow from sea bottom to water surface, the usual two-dimensional form of the equations of momentum and continuity are obtained:

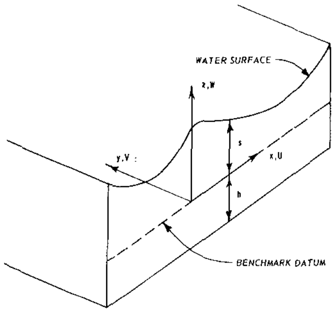


FIGURE 1. CARTESIAN COORDINATE SYSTEM.

MOMENTUM

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}\left(\frac{U^2}{d}\right) + \frac{\partial}{\partial y}\left(\frac{UV}{d}\right) - fV + gd\,\frac{\partial}{\partial x}\,(s - s_a)$$
$$+ F_x + \frac{gU}{C^2 d^2}\left(U^2 + V^2\right)^{1/2} - de\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}\right) = 0 \quad (1)$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}\left(\frac{UV}{d}\right) + \frac{\partial}{\partial y}\left(\frac{V^2}{d}\right) + fU + gd\,\frac{\partial}{\partial y}\,(s - s_a)$$
$$+ F_y + \frac{gV}{C^2 d^2}\left(U^2 + V^2\right)^{1/2} - de\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}\right) = 0 \quad (2)$$

CONTINUITY

$$\frac{\partial s}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = R \quad (3)$$

where s is the water surface elevation; s_a is the hydrostatic elevation corresponding to the atmospheric pressure anomaly; U, V are the vertically integrated transports per unit width at time t in the x and y directions, respectively; d = s - h is the total water depth; h is the still water elevation; f is the Coriolis parameter; C is the Chezy frictional coefficient; g is the acceleration of gravity; e is a generalized eddy viscosity coefficient; R represents the rate at which additional water is introduced into or taken from the system (for example, through rainfall and evaporation); and F_x, F_y are terms representing external forcing functions such as wind stress in the x and y directions.

Many numerical modelers have found it difficult to obtain meaningful solutions to the above equations when advective terms (second and third terms of equations 1 and 2) are included. Current research at WES is underway to assess the role of advective terms in the numerical simulation of long period, large amplitude water wave behavior in coastal regions. These terms are not included in the application presented herein, but have been modeled successfully in other simulations (Butler, 1976, 1978). The last terms in the momentum equations are representative of equivalent internal stress resultants due to turbulent and dispersive momentum flux (Vreugdenhil, 1973). They provide a mechanism for dissipating wave energy of wavelength on the order of twice the spatial step by smoothing curvatures developing in the solution. Since energy is transfered to this scale by the non-linear advective terms and these terms have been neglected in the Galveston Bay application, the flux terms have also been omitted. Both terms are presented here for completeness.

STRETCHED COORDINATES

A major advantage of WIFM is the capability of applying a smoothly varying grid to the given study region. For each direction a piecewise reversible transformation (analogous to that used by Wanstrath, 1976) is independently used to map prototype or real space into computational space. The transformation takes the form

$$x = a + b\alpha^{c} \tag{4}$$

where a, b, and c are arbitrary constants. The transformation is such that all derivatives are centered in α-space. By applying a smoothly varying grid whose functional as well as first derivatives are continuous, many stability problems commonly associated with variable grid schemes are eliminated. A time-share code has been designed to calculate the mapping defined by equation (4) allowing complete control of grid resolution at any point along each grid axis.

By using equations similar to (4) the equations of motion in α-space can be written as

MOMENTUM

$$\frac{\partial U}{\partial t} + \frac{1}{\mu_1}\frac{\partial}{\partial\alpha_1}\left(\frac{U^2}{d}\right) + \frac{1}{\mu_2}\frac{\partial}{\partial\alpha_2}\left(\frac{UV}{d}\right) - fV + \frac{gd}{\mu_1}\frac{\partial}{\partial\alpha_1}(s - s_a) + F_{\alpha_1} + \frac{gU}{C^2d^2}\left(U^2 + V^2\right)^{1/2} - T_1 = 0 \tag{5}$$

$$\frac{\partial V}{\partial t} + \frac{1}{\mu_1}\frac{\partial}{\partial \alpha_1}\left(\frac{UV}{d}\right) + \frac{1}{\mu_2}\left(\frac{V^2}{d}\right) + fU + \frac{gd}{\mu_2}\frac{\partial}{\partial \alpha_2}(s - s_a) + F_{\alpha_2} + \frac{gV}{C^2 d^2}\left(U^2 + V^2\right)^{1/2} - T_2 = 0 \qquad (6)$$

CONTINUITY

$$\frac{\partial s}{\partial t} + \frac{1}{\mu_1}\frac{\partial U}{\partial \alpha_1} + \frac{1}{\mu_2}\frac{\partial V}{\partial \alpha_2} = R \qquad (7)$$

where

$$\mu_1 = \frac{\partial x}{\partial \alpha_1} = b_1 c_1 \alpha^{c_1 - 1} \qquad (8)$$

$$\mu_2 = \frac{\partial y}{\partial \alpha_2} = b_2 c_2 \alpha^{c_2 - 1} \qquad (9)$$

Quantities μ_1 and μ_2 define the stretching of the regular spaced computational grid in α-space to approximate a study region in real space. The terms T_1 and T_2 represent the transformed flux terms.

FINITE DIFFERENCE MODEL

Since obtaining a solution to the governing non-linear equations on a region with highly complex geometry and topography is intractable using a pure analytical approach, a numerical technique is employed. A variable rectilinear grid is first developed for the model area. The appropriate variables are defined on the grid in a space-staggered fashion as depicted in Fig. 2 for a typical cell.

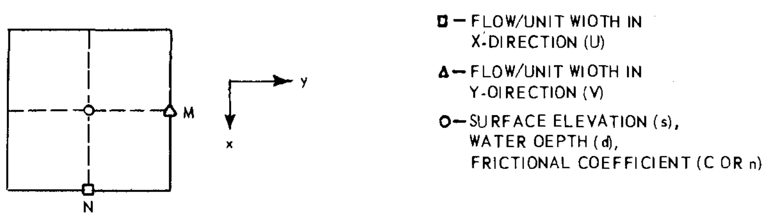


FIGURE 2. COMPUTATIONAL CELL DEFINITION.

An alternating-direction technique (Leendertse, 1967) is used to develop a finite difference scheme for solving the transformed equations (5-7). Computations are separated into two cycles corresponding to a sweep of the grid in both directions. The first cycle consists in solving for s and U implicitly; the second cycle computes s and V implicitly. The omitted transport is assumed constant for that cycle. Applying a centered difference operator to the momentum equation (5), and the continuity equation (7), along a grid line parallel to the x-axis, results in a system of linear algebraic equations whose coefficient matrix is tridiagonal. The form of the difference equations for the first cycle is given by

$$U^{k+1/2}_{n,m+1/2} = U^{k-1/2}_{n,m+1/2} + \Delta t \Bigg(f\bar{\bar{V}}^{k}_{n,m+1/2} + F^{k}_{\alpha_1} - \frac{g}{2\Delta\alpha_1}\left(\frac{d^*}{\mu_1}\right)_{n,m+1/2} \Big\{ s^{k+1/2}_{n,m+1} - s^{k+1/2}_{n,m} + s^{k-1/2}_{n,m+1} - s^{k-1/2}_{n,m} - 2\left[\left(s_a\right)^{k}_{n,m+1} - \left(s_a\right)^{k}_{n,m}\right]\Big\}$$

$$- \frac{g\left(U^{k+1/2}_{n,m+1/2} + U^{k-1/2}_{n,m+1/2}\right)}{2\left(d^*\bar{C}^{k}\right)^2}\left[\left(U^{k-1/2}_{n,m+1/2}\right)^2 + \bar{\bar{V}}^{2}_{n,m+1/2}\right]^{1/2}\Bigg) \tag{10}$$

$$s^{k+1/2}_{n,m} = s^{k}_{n,m} - \frac{\Delta t}{2}\left[\frac{1}{\Delta\alpha_1\left(\mu_1\right)_m}\left(U^{k+1/2}_{n,m+1/2} - U^{k+1/2}_{n,m-1/2}\right) + \frac{1}{\Delta\alpha_2\left(\mu_2\right)_n}\left(V^{k}_{n+1/2,m} - V^{k}_{n-1/2,m}\right)\right] + \frac{\Delta t}{2} R^{k}_{n,m} \tag{11}$$

where $d^* = \bar{s}^k - \bar{h}$. In these expressions a single bar represents a two point average and a double bar a four point average. The subscripts m and n correspond to spatial locations and superscript k to time levels. Equations for the second cycle are similar to (10) and (11) and are not presented.

The implicit difference scheme when applied to the linear system of governing equations exhibits unconditional stability as shown by Leendertse (1967). Longer time steps are usually permissible with the implicit scheme in contrast to explicit formulations. In many instances this fact permits a more cost-effective simulation. Inclusion of non-linear terms into the implicit scheme, however, may result in an inherent instability. As mentioned previously, flux terms have been used to overcome this problem but current research is being directed at finding a more satisfactory solution without giving up advantages of the implicit procedure. Weare (1976) has attempted to analyze conditions under which the system is unstable and has obtained a condition which relates velocity, advection, and friction. A fully time-centered scheme is suggested to avoid the problem.

A variety of boundary conditions are employed throughout the computational grid. These include prescribing water levels or flow rates, fixed or movable land-water boundaries, and subgrid barrier conditions.

Open boundaries. Included in this category are seaward boundaries terminating the computational grid or channels exiting the two-dimensional grid at any point in the system. Water levels or flow rates are prescribed as functions of location and time, and are given as tabular input to the code. For economical storm surge application, an open coast surge model may be used to develop the open sea boundary values to drive the inland flooding model.

Water-land boundaries. These conditions relate the normal component of flow at the boundary to the state of the water level at the boundary. Hence, water-land boundaries are prescribed along cell faces. Fixed land boundaries are treated by specifying $U = 0$ or $V = 0$ at the appropriate cell face. Low-lying terrain may alternately dry and flood within a tidal cycle or surge history. Inundation is simulated by making the location of the land-water boundary a function of local water depth. By checking water levels in adjacent cells a determination is made as to the possibility of inundation. Initial movement of water on "dry" cells is controlled by using a broad crested weir formula (Reid and Bodine, 1968). Once the water level on the "dry" cell exceeds some small prescribed value, the boundary face is treated as open and computations for s, U, and V are made for that cell. The drying of cells is the inverse process. Mass conservation is maintained within these procedures.

Subgrid barriers. Such barriers are defined along cell faces and are of three types: exposed, submerged, and overtopping. Exposed barriers are handled by simply specifying no-flow conditions across the appropriate flagged cell faces. Submerged barriers are simulated by controlling flow across cell faces with the use of a time dependent frictional coefficient. Overtopping barrier is a terminology used to distinguish barriers which can be submerged during one segment of the simulation and totally exposed in another. Actual overtopping is treated by using a broad-crested weir formula to specify the proper flow rate across the barrier. Water is transferred from the high to low side according to this rate. Once the barrier is submerged (or conversely exposed), procedures as described for submerged barriers (or exposed) are followed.

Graphics play an important role in presenting model results. Typical model output and data displays for WIFM include water level hydrographs, contours of water levels over the computational region, time history plots of velocity and volumetric discharge, and vector plots of either velocities or transports over the computational region. Normally, output from this model is used to produce color slides and color movies facilitating portrayal of the coastal flooding.

APPLICATION TO GALVESTON BAY

Galveston Bay, located in southeast Texas, is a large shallow bay covering more than 1000 square kilometers. There are three Gulf of Mexico entrance channels to the bay system, Galveston Entrance Channel, San Luis Pass Channel, and Rollover Pass Channel. Since Rollover Pass is so narrow and carries no more than one percent of the total discharge, it was not included in the simulation. The major channels in the bay are the Houston Ship Channel, Trinity River Channel, Galveston Channel, Texas City Channel, and the Intracoastal Waterway. The average depth of the bay is 2.75 meters while major channels average over 9 meters depth.

The objective of this application was to evaluate and/or illustrate WIFM's use as a predictive tool in simulating coastal flooding. By hindcasting the storm surge and flooding from hurricane Carla (1961) in the Galveston Bay area, such an assessment could be made. The first step was to verify the model for the study area. A variable grid consisting of 3572 grid cells was developed for the Galveston Bay region. The minimum cell width used was 604 meters and the maximum was 2583 meters. Various subgrid barriers were used throughout the grid system to represent features such as jetties, spoil banks, reefs, and major elevated highways. A one-dimensional channel computation extended 30 kilometers beyond the two-dimensional grid for simulating the Houston Ship Channel. A time step of 180 sec per cycle (permissible in the implicit scheme) was selected for both the verification and hindcast phases of application. Fig. 3 depicts the Galveston Bay grid and gage locations used in establishing high water marks and hydrographs for comparison with observed data.

VERIFICATION

The objective of the verification phase of any model study is to demonstrate the model's ability to produce results that agree with data for known conditions. Such a test gives a reasonable degree of confidence for applying the model as a predictive tool. The difficulty in attempting to verify a model for storm surge is usually a lack of prototype data. In the case of Galveston Bay a physical model study was conducted at WES and reported by Brogdon (1969). A wealth of both prototype and physical model data was available for the verification process. Unfortunately the prototype tide data included wind effects, the magnitude of which were unknown. Consequently, it was decided to use physical model results (both for a normal tide and a design surge) in this phase of the study.

Gage locations for verification purposes are shown in Fig. 3. Seven tide gages and four velocity stations were used, and gages T-A, -B,

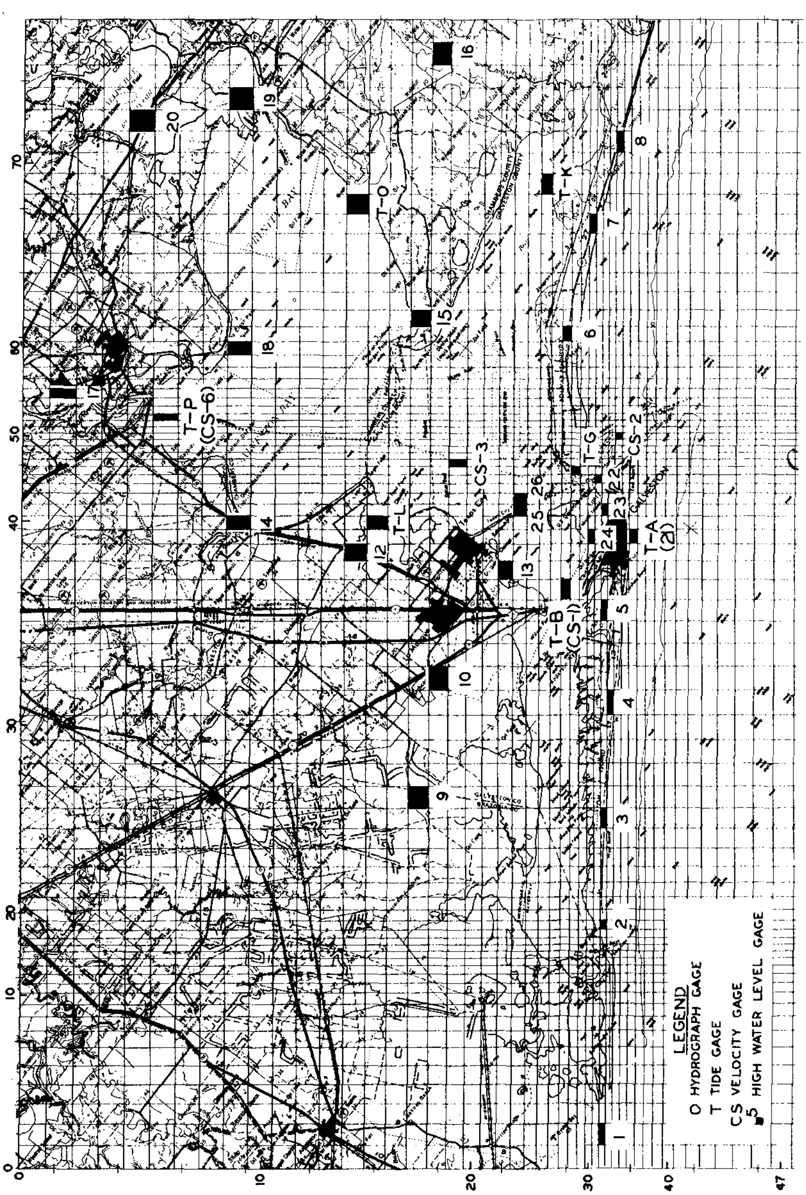


FIGURE 3. COMPUTATIONAL GRID AND GAGE LOCATIONS FOR GALVESTON BAY.

-L, -P and station CS-2 are presented in Figs. 4-8 for displaying sample results. Computation was begun at t = -2 hr, setting the entire water surface down to -0.2 meters msl and assuming a quiescent body of water.

As an additional check and test of the model's predictive capability, an application for a large radius high translation design surge (Brogdon, 1969) was performed. The design surge had a peak elevation of 4.4 meters and a duration of 20 hr. The WIFM simulation was terminated at hour 18. Comparison for gages T-A, -B, -L, and -P between physical and numerical model are displayed in Figs. 9-12. The results were in good agreement at most gages indicating that the model was ready for use in a predictive mode.

Experience in using the model has indicated that once proper resolution of the study area is adopted, application can be carried out with minimal adjusting or tuning of the model. The major adjustment made in the verification phase of the Galveston Bay application was a change in frictional characteristics of the Galveston entrance channel.

CARLA HINDCAST

In order to hindcast surge elevations and coastal flooding from hurricane Carla, two major forcing functions were required: time dependent open sea boundary values and a time and spatially dependent wind field describing winds from Carla. Open sea boundary values were developed by first applying an orthogonal curvilinear open-coast surge model (SSURGE III, Wanstrath, 1977) to the continental shelf region. The curvilinear model avoids necessity of stairstepping the coastline eliminating problems associated with such an approximation. The open-coast model also has a finite-height barrier coast boundary condition and allows for ponding areas. Therefore the boundary conditions computed by SSURGE III for WIFM are not contaminated with excess water caused by an infinite wall boundary condition commonly used in open-coast models. Both WIFM and SSURGE III employ the same wind model using appropriate modifications to account for wind deformation due to land influence (Shore Protection Manual, 1977). This model and the atmospheric pressure model are given by Jelesnianski (1965) but modified by Wanstrath (1976). An additional parameter, maximum wind speed, is required by the wind model. Values for this parameter cannot always be obtained, an important disadvantage for simulating hurricane winds in a predictive mode. The problem can be resolved by incorporating a wind model, based on the physics of the marine boundary layer, that will provide a windfield as a result of dynamic meteorological computations. The composite model would be appropriate for both forecasting and hindcasting. However, the wind model used in this study did produce results in good agreement with observed meteorological data. Comparison of computed and observed wind speed at the Weather Bureau Office, Galveston, Texas, is depicted in Fig. 13. Wind direction comparison for this station is shown in Fig. 14. The astronomical tide was included in the open coast simulation (and consequently in the driving function for the seaward boundary conditions for the inland flooding model) to eliminate uncertainties due to the linear superposition of tide and surge elevations.

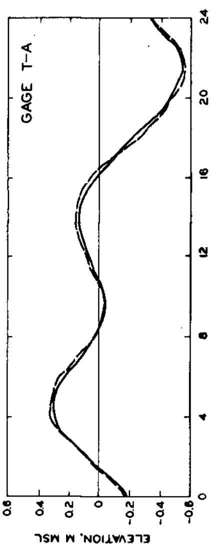
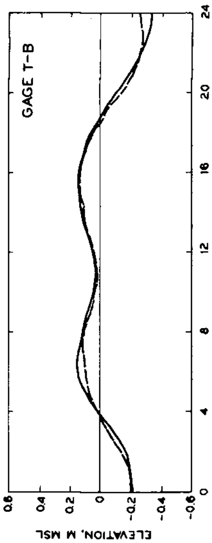


FIGURE 4



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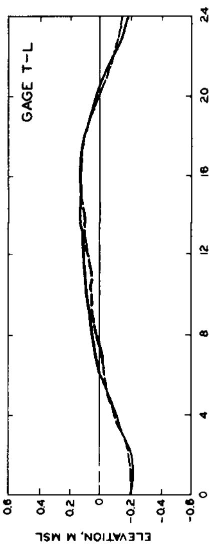

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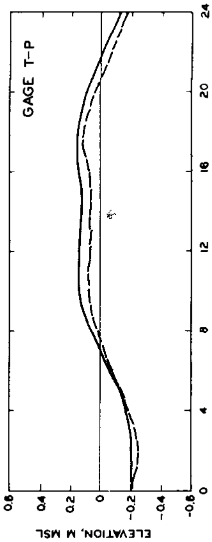

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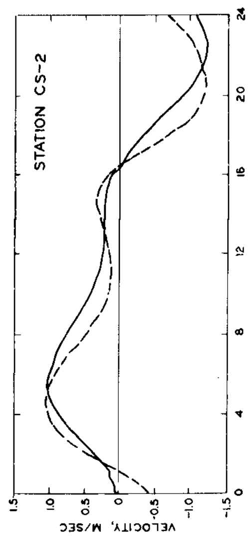


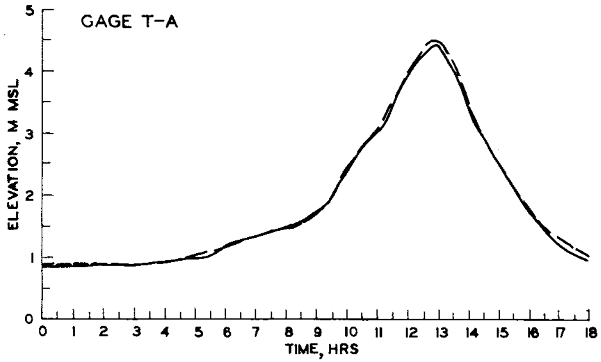
FIGURE 8

LEGEND

---- PHYSICAL MODEL

—— NUMERICAL MODEL (WIFM)

SAMPLE RESULTS FOR TIDAL VERIFICATION.



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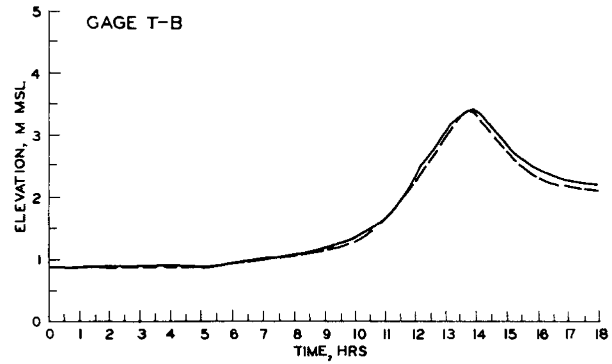

FIGURE 10

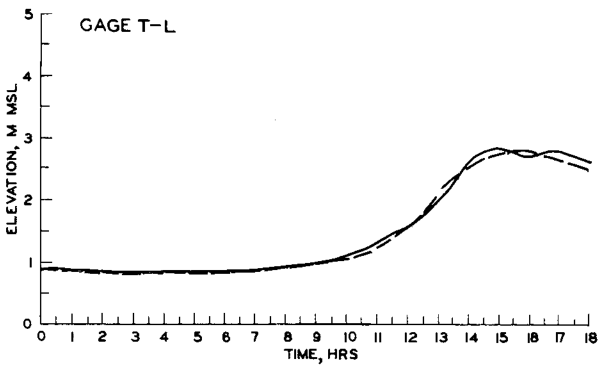

FIGURE 11

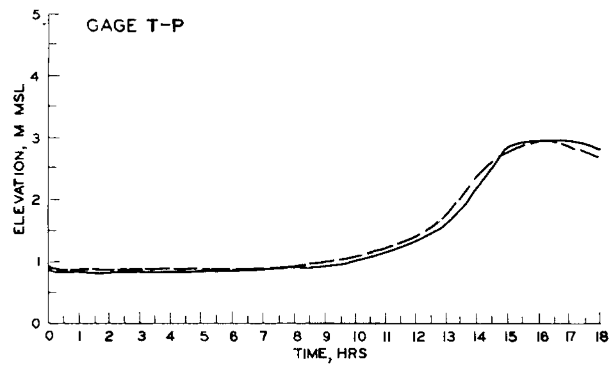

FIGURE 12

SAMPLE RESULTS FOR LARGE RADIUS HIGH TRANSLATION DESIGN SURGE.

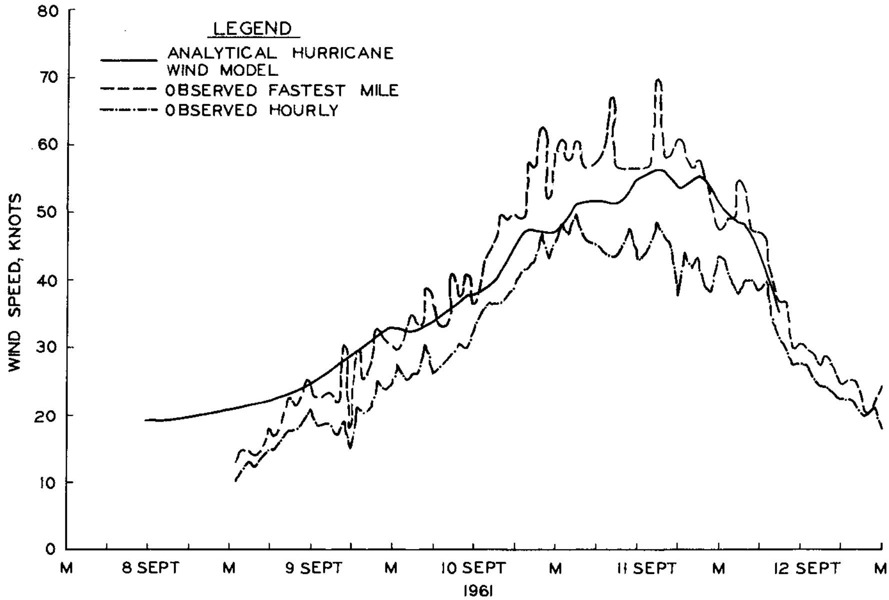

FIGURE 13. COMPARISON OF COMPUTED AND OBSERVED WIND SPEED AT GALVESTON, TEXAS.

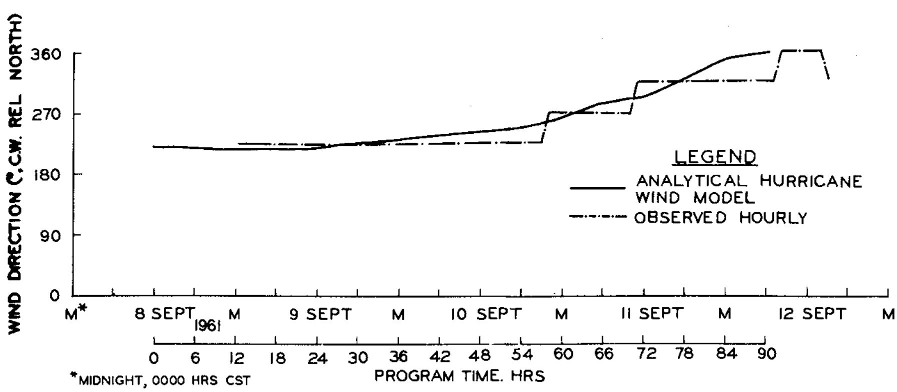

FIGURE 14. COMPARISON OF COMPUTED AND OBSERVED WIND DIRECTION AT GALVESTON, TEXAS.

The variable grid employed by WIFM is of finer resolution and lies askew to the open-coast grid, and thus interpolation of discrete values of water level from the open-coast grid is required. The interpolation scheme is based on a four-point, distance-weighted averaging procedure. The open-coast simulation, began at 12 noon on 8 September 1961, continued for 93 hours to 0900 on 12 September, and was calibrated to give good agreement between observed and model data at Pleasure Pier (gage 21, same as T-A). For economy of application the inland simulation was begun at hour 18 of the open-coast run and continued for 72 hours to hour 90. The water level throughout the model area at hour 18 was approximately 1.1 meters and thus the bay was spun up from a quiescent state with initial elevation of the entire bay at +1.1 meters. No change in model parameters was made after the verification phase was completed. Fig. 15 displays observed and model results at the Pleasure Pier open coast gage 21. Additional hydrograph comparisons are given in Figs. 16 and 17 for gages at Pelican Bridge (24) and Texas City Dyke-North (26). The major difficulty in the application was the calibration of the wind model to simulate Carla's winds. The overshoot in the computed results around program hours 60-66 is possibly due to the inability of the wind model to account for sheltering effects from the city of Galveston (winds were directly on-shore during this period).

Table 1 illustrates a comparison of observed high-water levels at various locations throughout the system with those computed by WIFM. Mean absolute error for 26 gages was 0.18 meters. The largest deviation from observed high water levels at any one gage was 0.64 meters at Sea Isle Beach (gage 3). The observed peak water level at Sea Isle was nearly 0.5 meters higher than that at any neighboring gage, indicating (assuming the data were correct) that some local anomaly existed which was not modeled by WIFM. All observed data were taken from a USAE Galveston District Report (1962). Peak elevation data were obtained from a tide gage reading crest of tide or still high water elevation marks. The reported gages were taken as representative of conditions experienced around the bay.

CONCLUSIONS

The following conclusions can be drawn from the material presented:

1. A two-dimensional implicit finite difference coastal flooding model in stretched coordinates has been developed. It is applicable to predict coastal flooding from storm surges, tides, tsunamis, or any long-period wave phenomena where boundary conditions can be specified.

2. The variable grid characteristic of WIFM (its principle advantage relative to other two-dimensional models) permits the capability to obtain finer resolution in important local areas without sacrificing economical application of the model.

3. A verification of the efficacy of the model was clearly demonstrated through application of the model to hindcast hurricane surge

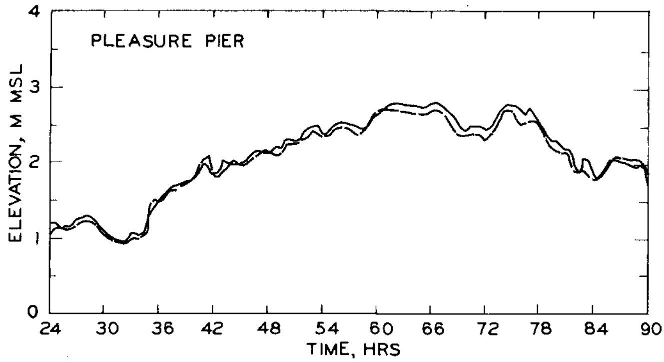

FIGURE 15

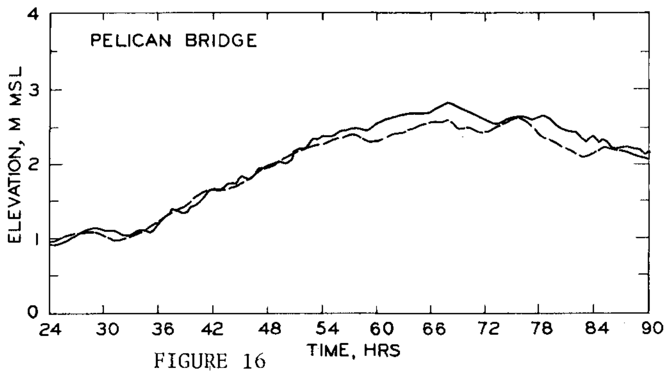

FIGURE 16

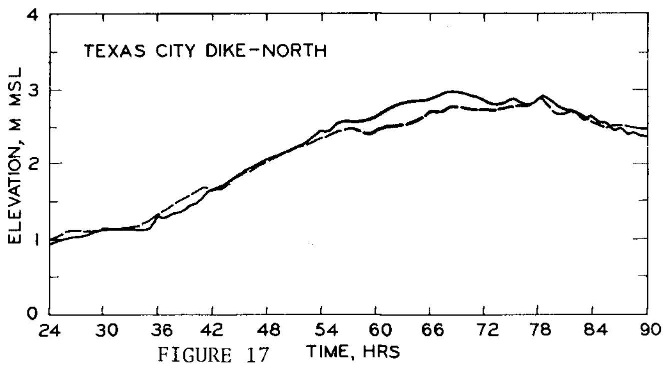

FIGURE 17

LEGEND

- - - - OBSERVED DATA
——— NUMERICAL MODEL (WIFM)

COMPARISON OF COMPUTED AND OBSERVED SURGE ELEVATIONS IN THE GALVESTON BAY AREA.

TABLE 1

COMPARISON OF HIGH WATER LEVELS AT SELECTED GAGE LOCATIONS

GAGE NO.	GAGE LOCATION	OBSERVED m	COMPUTED m	DIFFERENCE m	GAGE NO.	GAGE LOCATION	OBSERVED m	COMPUTED m	DIFFERENCE m
1	OYSTER CREEK	3.11	3.29	+0.18	15	SMITH POINT	2.99	3.17	+0.18
2	SAN LUIS PASS	3.29	3.05	-0.24	16	OYSTER BAYOU	3.20	3.35	+0.15
3	SEA ISLE BEACH	3.69	3.05	-0.64	17	SCOTT BAY	4.33	4.30	-0.03
4	BERMUDA BEACH	3.20	2.99	-0.21	18	HUMBLE DOCKS	4.18	3.84	-0.34
5	SCHOLES FIELD	2.59	2.93	+0.33	19	ANANUAC	3.78	3.87	+0.09
6	BOLIVAR BEACH	2.83	2.83	+0.00	20	WALLISVILLE	4.27	4.26	+0.00
7	CRYSTAL BEACH	2.68	2.87	+0.18	21	PLEASURE PIER	2.83	2.87	+0.03
8	ROLLOVER BEACH	2.93	2.83	-0.09	22	FORT POINT	2.74	2.90	+0.15
9	HALLS BAYOU	4.36	4.30	-0.06	23	PIER 21	2.68	2.90	+0.21
10	HIGHWAY SIX	3.84	3.87	+0.03	24	PELICAN BRIDGE	2.74	2.87	+0.12
11	SIEVERS COVE	3.23	2.83	-0.39	25	TEXAS CITY DYKE (SOUTH)	2.90	3.05	+0.15
12	DICKINSON BAYOU	3.47	3.60	+0.12	26	TEXAS CITY DYKE (NORTH)	2.96	3.05	+0.09
13	CARBIDE DOCKS	3.35	3.17	-0.18					
14	KEMAH	4.33	3.90	-0.43					

MEAN ABSOLUTE ERROR = 0.18 m.

elevations and coastal flooding for Hurricane Carla. The mean absolute difference between observed and computed water levels was 0.18 m and the observed and computed hydrographs (time dependency of surge elevations) were in good agreement.

4. The relative ease of application, variable grid capability, implicit computing scheme, and flexible output characteristics (when considered together) make W1FM a very useful model for performing practical engineering computations to aid in the solution of real-world problems.

RECOMMENDATIONS

A number of recommendations for future efforts are apparent as a result of the work contained herein and are delineated below:

1. Although W1FM has been successfully applied with the nonlinear advective terms incorporated into the solution on several occasions, there are more stability problems associated with their use than desirable. Additional research is needed to develop better methods of treatment of these instabilities. Some work is proceeding along these lines at WES and it is hoped that others also will actively pursue this important problem in order to minimize the time when use of the nonlinear advective terms in practical engineering applications becomes routine.

2. Additional research also is needed to better define the role of the advective terms in problems involving catastrophic flooding (such as storm surges and tsunami inundation). It may turn out that the advective terms have little effect on the extent of catastrophic flooding, in which case, they may be neglected from a practical engineering point of view.

3. Simulation of narrow rivers or channels would be improved in W1FM with even more potential cost savings by incorporation of a scheme similar to that of Reid et al. (1975) which uses the concept of dynamically coupled one-dimensional subgrid channels. It is planned to add this capability to W1FM during the next application of the model.

4. For storm surge predictions, a planetary boundary layer windfield model which also accounts for windfield transformation from ocean to land would represent a substantial improvement to W1FM and other two-dimensional flooding models.

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