STORM SURGE EFFECTS OF THE MISSISSIPPI RIVER-GULF OUTLET

Study A

Prepared by

Dr. Charles L. Bretschneider
Dr. J. Ian Collins

Prepared for

U.S. Army Engineer District (New Orleans)
U.S. Army Corps of Engineers
P.O. Box 60267
New Orleans 9, Louisiana

Contract No. DA-16-047-CIVENG-66-316

NESCO Report SN-326-A

September 9, 1966

NATIONAL ENGINEERING SCIENCE COMPANY
711 South Fair Oaks Avenue
Pasadena, California, 91105

CONTENTS

CONTENTS
(Continued)

1. SUMMARY AND CONCLUSIONS

1.1 General Introduction

Hurricane Betsy struck in the vicinity of New Orleans on September 9, 1965, causing widespread damage from flooding as well as hurricane winds.

This report, on the basis of detailed studies of Hurricane Betsy and how it affected the New Orleans area, attempts to evaluate the effects of the Gulf Outlet Channel on hurricane storm tides. The results of this study were then used to predict high surge levels for six chosen synthetic hurricanes.

1.2 Locations of Study Area

The specific study area consists of the area extending generally from the southern end of the Mississippi River-Gulf Outlet to the Inner Harbor Navigation Canal in New Orleans, Louisiana, and the adjacent areas within confining levees. A general location map is shown as Fig. 1.

1.3 Objectives of Study

The primary objective of this study was to determine surge elevations at key locations within the study area utilizing the best available techniques and data. Accurate surge predictions are required to support decisions required in the design of authorized levees and associated works.

A secondary, though equally important, objective was the evaluation of the effects of the Mississippi River-Gulf Outlet Channel, spoil banks and associated works on the hurricane surge environment within the study area.

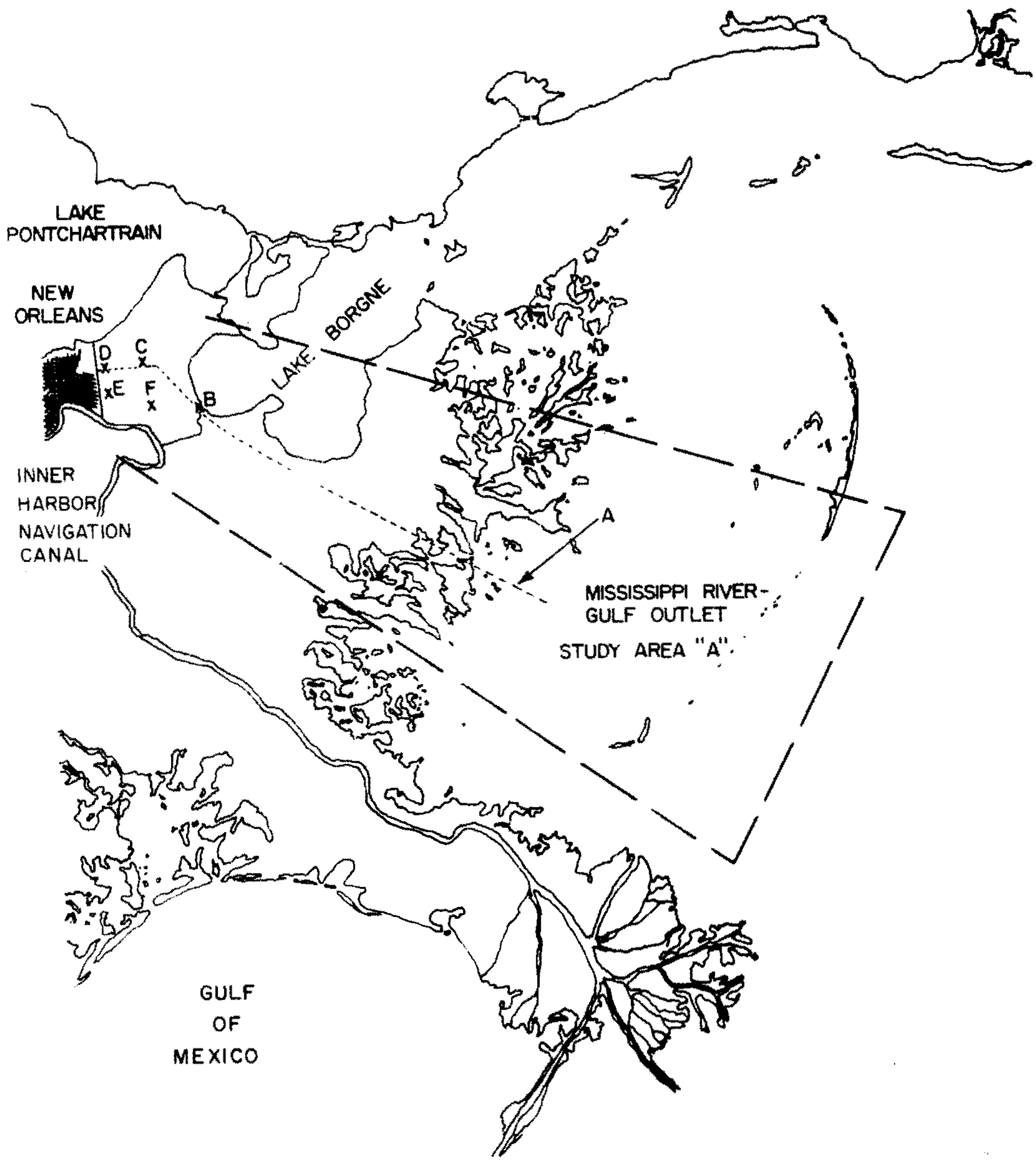


Figure 1

General location map of area under study

PA-3-10289

1.4 Summary of Methods Used

The first step was the evaluation of the hurricane wind fields for Hurricane Betsy and six synthetic hurricanes. The open coast storm surges were computed using the bathystrophic storm tide theory.

Hurricane Betsy and the synthetic hurricanes used in this study can be considered as relatively large storms which produce comparatively slow rising storm surges. The relative effect of the Gulf Outlet Channel on surge elevations can be expected to be extremely dependent upon the rate of rise of the storm surge.

The effects, in the vicinity of the Inner Harbor Navigation Canal, due to rapidly and slowly rising surges were evaluated numerically for four cases:

- I Existing levees with no Gulf Outlet Channel
- II Existing levees with the Gulf Outlet Channel
- III Proposed levees with the Gulf Outlet Channel
- IV Proposed levees with no Gulf Outlet Channel

One further check on the effect of the Gulf Outlet Channel was made by estimating the increased rate at which water could enter the area near the Inner Harbor Navigation Canal due to the Gulf Outlet Channel.

1.5 Summary and Conclusions

Hurricane Betsy was classified as producing a slow rising surge. Based on the numerical computations and estimates of channel conveyance effects, Hurricane Betsy would have produced essentially the same peak surge elevations whatever the conditions prevailing in Area A. The results are summarized in Table I. The degree of confidence

TABLE I

Peak Surge Predictions for Hurricane Betsy for Four Cases

Hurricane and Case \ Station		A	B	C	D	E	F
Betsy	I	10.2	9.2	9.4	10.5	9.3	9.1
	II	10.2	9.6	10.0	10.9	9.7	9.5
	III	10.2	9.6	9.8	10.9		
	IV	10.2	9.6	9.8	10.9		

inherent in the predictions for Hurricane Betsy is satisfactory from the theoretical point of view because the history of Betsy's movement leads to relatively smooth variations in the wind regime.

The synthetic hurricanes were judged to behave more in the manner of Hurricane Betsy producing a slow rising surge. The predicted surge peaks are summarized in Table II.

It is seen that the effect of the Mississippi River-Gulf Outlet is almost negligible for all large hurricanes accompanied by slow rising storm surges. It may be expected that once in a while a storm may occur which has a somewhat freakish, more rapidly rising surge in which case the Gulf Outlet Channel may have a very marked effect. However, such a storm will not produce tides which are as high as the more critical hurricane tracks such as Betsy or the synthetic hurricanes.

TABLE II

Summary of Synthetic Hurricane Surge Peaks for Stations A, B, C, D, E and F for Four Different Cases

Hurricane Track	Hurricane	Station / Case	A	B	C	D	E	F
Sigma	SPH	I	9.1	9.7	9.9	10.4	9.5	9.5
		II	9.1	10.1	10.3	10.8	9.9	9.9
		III	9.1	10.1	10.3	10.8		
		IV	9.1	10.1	10.3	10.8		
	PMH	I	10.4	11.3	11.6	12.2	11.1	11.1
		II	10.8	11.7	12.0	12.6	11.5	11.5
		III	10.8	11.7	12.0	12.6		
		IV	10.8	11.7	12.0	12.6		
Chi	SPH	I	9.5	10.0	10.3	10.8	9.8	9.9
		II	9.9	10.4	10.7	11.2	10.2	10.3
		III	9.9	10.4	10.7	11.2		
		IV	9.9	10.4	10.7	11.2		
	PMH	I	11.3	11.7	11.9	12.7	11.5	11.5
		II	11.7	12.1	12.3	13.1	11.9	11.9
		III	11.7	12.1	12.3	13.1		
		IV	11.7	12.1	12.3	13.1		
Epsilon	SPH	I	10.5	9.9	10.1	10.6	9.7	9.8
		II	10.9	10.3	10.5	11.0	10.1	10.2
		III	10.9	10.3	10.5	11.0		
		IV	10.9	10.3	10.5	11.0		
		I	12.5	11.3	12.0	12.4	11.3	11.4
		II	12.9	11.7	12.4	12.8	11.7	11.8
		III	12.9	11.7	12.4	12.8		
		IV	12.9	11.7	12.4	12.8		

2. THEORY

2.1 Theory for Storm Tide

The basic hydrodynamic equations expressing the conservation of momentum for the motion of water under the action of driving forces can be written as,

Acceleration = total applied force per unit mass

That is,

$$\frac{dQ_y}{dt} = -fQ_x - gD\frac{\partial S}{\partial y} + \frac{\tau_{sy}}{\rho} - \frac{\tau_{by}}{\rho} - W_yP + gD\frac{\partial \eta_o}{\partial y} \qquad (1)$$

Coriolis	Surface Slope	Wind Stress	Bottom Stress	Rainfall Rate	Inverse Barometer

$$\frac{dQ_x}{dt} = fQ_y - gD\frac{\partial S}{\partial y} + \frac{\tau_{sx}}{\rho} - \frac{\tau_{bx}}{\rho} - W_xP + gD\frac{\partial \eta_o}{\partial x} \qquad (2)$$

The above two equations together with the continuity equation

$$\frac{\partial S}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = P \qquad (3)$$

yield a system in which the two discharge components Q_x, Q_y, and the surge elevation S can be solved.

The symbols and units used in Eqs. 1, 2, and 3 and the following equations are defined on the following page.

S	=	the surge height, feet
Qx	=	discharge in the direction of the x-axis, ft^3/sec per foot of width
Qy	=	discharge in the direction of the y-axis, ft^3/sec per foot of width
x	=	distance measured along a line perpendicular to the mean offshore bottom topography, feet
y	=	distance measured parallel to the shoreline, feet
t	=	time, seconds
f	=	$2\omega \sin \varphi$, Coriolis parameter $\omega = 7.28 \times 10^{-5}$ rad/sec, angular velocity of earth
φ	=	latitude in degrees
g	=	acceleration of gravity, 32.2 ft/sec^2
D	=	water depth, feet
τ_{sy}/ρ	=	wind stress parallel to coast per unit volume, $(ft/sec)^2$
τ_{by}/ρ	=	bottom stress parallel to coast per unit volume, $(ft/sec)^2$
τ_{sx}/ρ	=	wind stress perpendicular to coast, per unit volume, $(ft/sec)^2$
τ_{bx}/ρ	=	bottom stress perpendicular to coast, per unit volume, $(ft/sec)^2$
ρ	=	density of water, $slugs/ft^3$
W_x	=	wind speed component perpendicular to coast, ft/sec
W_y	=	wind speed component parallel to coast, ft/sec

η_o = inverted barometer effect, feet of water

P = precipitation rate, ft/sec

For a slow moving storm, the equilibrium wind equation can be deduced from Eq. 1. The assumption of slow motion (no time-dependent variables) and one-dimensional motion (no y-dependent variables) reduces Eqs. 1, 2, and 3 to,

Surface slope = wind stress + inverse barometric effect.

$$gD \frac{\partial S}{\partial x} = \frac{\tau_{sx}}{\rho} + gD \frac{\partial \eta_o}{\partial x} \qquad (4)$$

with

$$\frac{\tau_{sx}}{\rho} = kW^2 \cos\theta$$

this equation reduces to the classical Corps of Engineers formula,

$$\eta = \sum \frac{1}{gD} kW^2 \cos\theta \, \Delta x + \eta_o \qquad (5)$$

Where η_o is the normal astronomical tide plus the inverse barometric effect.

A significant improvement on this method was originally proposed by Freeman, Baer and Jung (1957) and called the bathstrophic storm tide. The assumption of a slow moving storm is required and the theory is a quasistatic one. The effects of longshore currents are considered and these produce corrections to the more simple storm tide computation of Eq. 5 because of the Coriolis effect.

The x-component in Eq. 1 is assumed to be a steady state condition such that,

$$\frac{dQ_x}{dt} = 0 \quad \text{and} \quad Q_x = 0 \tag{6}$$

The precipitation P will be neglected because it is very small for most hurricanes when compared with such terms as τ_{sx}/ρ, etc. Also the variation in storm tide elevation along the coast will be assumed as small compared with the variation perpendicular to the coast. That is,

$$\frac{\partial S}{\partial y} << \frac{\partial S}{\partial x} \tag{7}$$

Making use of Eqs. 6 and 7, Eqs. 1 and 2 become

$$fQ - gD\frac{\partial S}{\partial x} + \frac{\tau_{sx} - \tau_{bx}}{\rho} + gD\frac{\partial y_o}{\partial x} = 0 \tag{8}$$

$$\frac{\tau_{sy} - \tau_{by}}{\rho} = \frac{dQ}{dt} \tag{9}$$

(The subscript y on Q can be dropped since by condition (Eq. 6), $Q_y = Q$ and $Q_x = 0$.)

The values of τ_{sx}, τ_{bx}, τ_{sy}, τ_{by} and η_o have to be determined. For a wind blowing at an angle θ with the x-axis, the surface stress components are given by Eqs. 10 and 11.

$$\frac{\tau_{sx}}{\rho} = kW^2 \cos\theta \tag{10}$$

$$\frac{\tau_{sy}}{\rho} = kW^2 \sin\theta \tag{11}$$

where $k \approx 3 \times 10^{-6}$ following Saville (1952).

The bottom stress components are a little more difficult to determine. On the assumption of a uniform velocity distribution and making use of the Manning formula following Freeman et al (1957), the bottom stress components are given by Eqs. 12 and 13.

$$\frac{\tau_{bx}}{\rho} = \frac{KQQ_x}{D^{7/3}} \tag{12}$$

$$\frac{\tau_{by}}{\rho} = \frac{KQQ_y}{D^{7/3}} \tag{13}$$

Following the assumption of Eq. 6, it is seen that τ_{bx}/ρ is negligible when based on uniform flow conditions. Reid (1964) has demonstrated that K is related to Manning's n by

$$K \approx 15n^2 \tag{14}$$

More strictly, the bottom stress terms arise because of friction of the flow with the bed.

Even though Q_x is zero there may be a stress in the x-direction caused by shear at the bed. This is illustrated in Fig. 2.

This phenomenon is qualitatively known, but its exact effect depends a great deal on local conditions. The effect of a finite τ_{bx}, when there is no net discharge, is in the same direction as the wind when the wind stress is onshore. This is often incorporated in the term τ_{sx}/ρ by increasing k from 3×10^{-6} to 3.3×10^{-6} or even 4.0×10^{-6}.

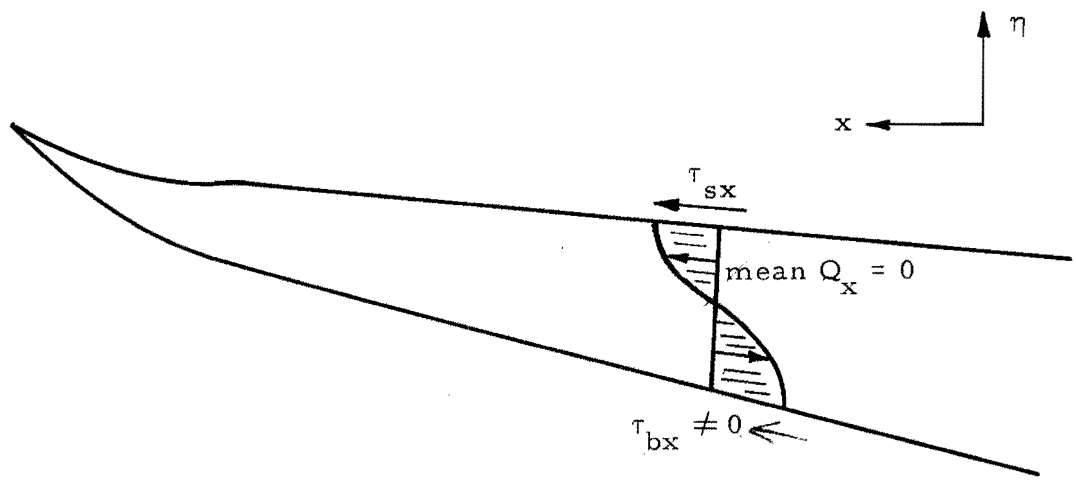


Figure 2
Illustration of bottom stress effect in wind setup

Finally, then, the bathystrophic equations, as used in this study, are written

$$\frac{\partial Q}{\partial t} = kW^2 \sin\theta - \frac{KQQ}{D^{7/3}} \tag{15}$$

$$\frac{\partial S}{\partial x} = \frac{1}{gD}\left[kW^2 \cos\theta + fQ\right] + \frac{\partial \eta_o}{\partial x} \tag{16}$$

For varying wind fields, W and θ are functions of x and t and, Eqs. 15 and 16 have to be solved numerically. In some cases, storm tides can be estimated as a first approximation; in which case, W and θ can be treated as constants and the equations can be integrated analytically.

In most practical cases of hurricanes, the assumption of constant wind speed and direction over the continental shelf is not justified. Equations 15 and 16 have to be evaluated numerically. Before numerical methods are attempted, some modifications in the equations are necessary.

In finite difference form, if $Q_{m,n}$ is a function of x and t at the point $t = n\Delta t$, x , $m\Delta x$, then Eq. 15 reduces to

$$\frac{Q_{m,n} - Q_{m,n-1}}{\Delta t} = \overline{kW^2 \sin\theta}^{\,t} - \frac{kQ_{m,n}\left|Q_{m,n-1}\right|}{D^{7/3}} \tag{17}$$

where $\overline{kW^2 \sin\theta}^{\,t}$ denotes average value of $kW^2 \sin\theta$ over the interval $(n-1)\Delta t$ to $n\Delta t$. The solution of Eq. 17 for $Q_{m,n}$, in terms of the previous value $Q_{m,n-1}$, is given by

$$Q_{m,n} = \frac{\left[\dfrac{\left(kW^2 \sin\theta\right)_{m,n-1} + \left(kW^2 \sin\theta\right)_{m,n}}{2}\right]\Delta t + Q_{m,n-1}}{1 + \dfrac{K}{D^{7/3}} \Delta t \cdot Q_{m,n-1}} \tag{18}$$

Equation 16 will be used in the form

$$\frac{S_{m,n} - S_{m-1,n}}{\Delta x} = \frac{1}{gD}\left[\overline{kW^2 \cos\theta}^{\,x} + fQ_{m,n}\right] + \frac{\Delta \eta_o}{\Delta x} \tag{19}$$

where $\overline{kW^2 \cos\theta}^x$ denotes average value of $kW^2 \cos\theta$ over the interval $(m-1)\,\Delta x$ to $m\Delta x$. Equation 19, solved for $S_{m,n}$ in terms of $S_{m-1,n}$, becomes

$$S_{m,n} = S_{m-1,n} + \frac{k}{2gD}\left[\left(W^2 \cos\theta\right)_{m-1,n} + \left(W^2 \cos\theta\right)_{m,n}\right] + \frac{fQ}{gD}\,\Delta x + \eta_o \tag{20}$$

Now, η_o is the normal increase in water level due to effects other than the wind stress. These include inverse barometric effect and normal astronomical tide. Hence,

$$\eta_o = A_{m,n} + 1.14\,\Delta P_{m,n} \tag{21}$$

where

$A_{m,n}$ = the astronomical tide

$\Delta P_{m,n}$ = the barometric pressure below normal, in inches of mercury

A computer program, written to compute η_o, $S_{m,n}$ and $Q_{m,n}$ according to Eqs. 18, 20, and 21, is given in Appendix A together with a summary for its use and a list of required input data.

Several critical points in the use of Eqs. 18, 20, and 21 arise

a) the best choice of D, the total depth

b) the determination of $\Delta P_{m,n}$

c) the determination of $A_{m,n}$, $(W^2 \cos\theta)_{m,n}$ $(W^2 \sin\theta)_m$

d) initial values of $S_{o,o}$ and $Q_{o,o}$

These points are discussed below.

a) The total water depth used in Eqs. 18 and 20 was chosen as the normal water depth, plus the normal astronomical (paragraph c, following) tide, plus the inverse barometric effect (paragraph b, following), plus the storm tide at the previous station offshore for that time step. In algebraic form, the total depth D used to compute $S_{m,n}$ and $Q_{m,n}$ is given by,

$$D = D_x + A_{m,n} + 1.14\,\Delta P_{m,n} + S_{m-1,n} \tag{22}$$

This formula for D is justified if the step size in x is small such that $S_{m,n} - S_{m-1,n}$ is small.

b) The value of $\Delta P_{m,n}$ is determined from the equation,

$$\Delta P_{m,n} = \left[P_N - P_o(n)\right]\left[1 - \exp\left(-\frac{R}{r}\right)\right] \tag{23}$$

where,

P_N = the normal pressure, inches of mercury

$P_o(n)$ = the CPI of the hurricane, a function of time time $\eta\,\Delta t$, in inches of mercury

R = the radius to maximum winds

r = the distance from the point on the traverse to the center of the hurricane

exp = exponential function of quantity in parentheses, using base $e \cong 2.7183$

c) The values of $A_{m,n}$ are actually treated as values of A_m (or function of time only). The tides are tabulated for the computer input data from the U. S. Coast and Geodetic Survey tables for Hurricane Betsy. For the standard project and probably maximum hurricanes the value of A_n is taken as a constant of 2.0 feet, the high tide computed for the Louisiana coast based on Pensacola, Florida.

The values of $W^2 \cos \theta$ and $W^2 \sin \theta$ for Hurricane Betsy are determined from the weather maps prepared by the U. S. Weather Bureau, Hydrometeorological Section. The wind stress values for the standard project and probable maximum hurricanes are determined from empirical equations chosen to fit the U.S. Weather Bureau, Hydrometeorological Section, Standard Project Hurricanes. Details of this procedure are given in Appendix B. Appendix C gives the computer program which was used to prepare input data cards for the wind fields for subsequent storm surge computations.

d) Initial values of $S_{o,o}$ and $Q_{o,o}$ were not used in this study. All storm surge computations were commenced when the hurricane was far enough offshore that the initial setup $S_{o,o}$ and longshore discharge $Q_{o,o}$ could be assumed to be zero. Provision was made for their inclusion, however, for further applications. Details for inclusion of initial values for S and Q are given in Appendix A in the computer program for the storm surge computation.

2.2 Theory for Regression Correlation

It is assumed that storm tide computations have been performed for three or four points A, B, C, D at several times $t = t_1, t_2, t_3$ ---t_7--- during a hurricane. At another nearby station X, there exists an observed hydrograph which has water levels $X_1, X_2, \text{---} X_7$, as recorded. As long as the stations A, B, C, D --- are close to X, it is a reasonable assumption that the water levels at A, B, C, D --- should be correlated with the observed values at X.

The prediction equation,

$$X = \alpha_1 A + \alpha_2 B + \alpha_3 C + \alpha_4 D + \ldots \qquad (24)$$

will be used and the problem is posed as how to choose the best values for $\alpha_1, \alpha_2, \alpha_3 \ldots$ to give the best prediction for X.

An example for 7 time steps and 3 stations will be given. The 7 predicted water levels for X are,

$$\left.\begin{array}{lcl} X_1 & = & \alpha_1 A_1 + \alpha_2 B_1 + \alpha_3 C_1 \\ X_2 & = & \alpha_1 A_2 + \alpha_2 B_2 + \alpha_3 C_2 \\ X_3 & = & \alpha_1 A_3 + \alpha_2 B_3 + \alpha_3 C_3 \\ . & = & \\ . & = & \\ . & = & \\ X_7 & = & \alpha_1 A_7 + \alpha_2 B_7 + \alpha_3 C_7 \end{array}\right\} \qquad (25)$$

$$\left(X_1 - \alpha_1 A_1 - \alpha_2 B_1 - \alpha_3 C_1\right)^2 + \left(X_2 - \alpha_1 A_2 - \alpha_2 B_2 - \alpha_3 C_2\right)^2$$

$$+ \quad \cdots\cdots \quad + \quad \cdots\cdots$$

$$+ \left(X_7 - \alpha_1 A_7 - \alpha_2 B_7 - \alpha_3 C_7\right)^2$$

$$= S$$

It is required for the best prediction that,

$$\frac{\partial S}{\partial \alpha_1} = \frac{\partial S}{\partial \alpha_2} = \frac{\partial S}{\partial \alpha_3} = 0$$

These three conditions are met if the following three simultaneous equations are satisfied,

$$\begin{aligned} \alpha_1 \beta_{11} + \alpha_2 \beta_{12} + \alpha_3 \beta_{13} - \gamma_1 &= 0 \\ \alpha_1 \beta_{12} + \alpha_2 \beta_{22} + \alpha_3 \beta_{23} - \gamma_2 &= 0 \\ \alpha_1 \beta_{13} + \alpha_2 \beta_{23} + \alpha_3 \beta_{33} - \gamma_3 &= 0 \end{aligned} \qquad (26)$$

where

$$\beta_{11} = \sum_1^7 A_1^2 + A_2^2 + A_3^2 + \ldots \qquad A_7^2$$

$$\beta_{22} = \sum_1^7 B_1^2 + B_2^2 + B_3^2 + \ldots \qquad B_7^2$$

$$\beta_{33} = \sum_1^7 C_1^2 + C_2^2 + C_3^2 + \ldots \qquad C_7^2$$

$$\beta_{12} = \sum_{1}^{7} A_1 \; B_1 + A_2 \; B_2 + A_3 \; B_3 + \ldots A_7 \; B_7$$

$$\beta_{13} = \sum_{1}^{7} A_1 \; C_1 + A_2 \; C_2 + A_3 \; C_3 + \ldots A_7 \; C_7$$

$$\beta_{23} = \sum_{1}^{7} B_1 \; C_1 + B_2 \; CD + B_3 \; C_3 + \ldots B_7 \; C_7$$

$$\gamma 1 = \sum_{1}^{7} A_1 \; X_1 + A_2 \; X_2 + \ldots \qquad A_7 \; X_7$$

$$\gamma 2 = \sum_{1}^{7} B_1 \; X_1 + B_2 \; X_2 + \ldots \qquad B_7 \; X_7$$

$$\gamma 3 = \sum_{1}^{7} C_1 \; X_1 + C_2 \; X_2 + \ldots \qquad C_7 \; X_7$$

The simultaneous solution of Eq. 25 for α_1, α_2 and α_3 will yield the "best" predictor equation for the point X in terms of the computed tides at A, B and C. It can be noted that A may be the computed tide at X and weighting factors are sought to provide a better prediction than A above in terms of some neighboring points B and C together with A. An example of the use of this regression technique will be given for Hurricane Betsy.

2.3 Theory for Channel Conveyance and Wind Action Effects

It must be expected that a large channel cut through marsh areas will permit more water to arrive at a faster rate in the interior of the marshland, at least in the immediate vicinity of the channel, In addition, the maximum elevation and the steady state peak will be reached at an earlier time. On the other hand, after the storm has passed, the channel should be of considerable benefit in promoting a more rapid fall of water levels, because now the channel acts as a drain. Therefore, the duration of the actual flooding should be short.

Without the channel, the water will rise over the marshlands at a slower rate and it will take a longer duration to reach maximum elevation and steady state conditions. Similarly, after the storm has passed it will take longer for the surge to recede since now there is no channel to act as a drain.

It will be shown that the wind effect over the Gulf Outlet is less than that of the marshland, for two reasons: 1) the combined wind stress $\tau_S + \tau_b$ is less over the channel than over the marsh, and 2) the wind tide effect over deeper water such as the channel is less than that over shallow water even for the same values of $\tau_S + \tau_b$ because the water depth in the channel is greater than over the marshland. The previous two statements can be verified in view of the wind tide equation

$$S_x = \frac{dS}{dX} = \frac{\tau_S + \tau_b}{\rho g \, (D + S)} \, N(X) \qquad (27)$$

In the previous equation, τ_S is the wind stress over the water and will be the same for water over the marsh as that over the channel; τ_b is the bottom stress which can be two to four times more over the marsh marshland than over the channel bottom; D is the water depth which will be greater for the channel than for the marsh; N(X) is the planform factor.

The problem now is to investigate the forced conveyance of water. The velocity of flow through the channel will be two to four times as great as that over the marshland, but the volume of water (velocity times cross-sectional area) determines the total amount of water which will enter Study Area A. It is this latter factor which tends to cause an increase in surge because of the Mississippi River-Gulf Outlet. However, it is the combined effect of the conveyance and the wind stress which produces the final effects. This leads to the definition of forced conveyance, force being associated with the wind stress formula (Eq. 27) and the conveyance being associated with the hydraulic flow.

The conveyance can be investigated by use of Manning's equation. The conveyance factor K can be defined as the flow of water divided by the square root of the water surface slope,

$$K = \frac{Q}{S^{1/2}} = \frac{1.486}{n} A R^{2/3} \tag{28}$$

where

n = Manning's friction factor

A = the cross-sectional area

R = the hydraulic radius

The hydraulic radius is defined as the cross-sectional area divided by the wetter perimeter

$$R = A/P \tag{29}$$

It then follows from Eq. 28 that

$$K = \frac{1.486}{n} \frac{A^{5/3}}{P^{2/3}} \tag{30}$$

The forced conveyance can be defined as the product of Eqs. 27 and 30 whence

$$F = S_x K = \frac{\tau_S + \tau_b}{\rho g (D + S)} \frac{1.486}{n} \frac{A^{5/3}}{P^{2/3}} \tag{31}$$

The forced conveyance factor representing the ratio between that of the Mississippi River-Gulf Outlet and the marsh is defined as

$$\gamma = \frac{F_c}{F_m} \tag{32}$$

where F_c is F for the channel and F_m is F for the marsh.

From Eqs. 27, 30 and 32

$$\gamma = \left(\frac{A_c}{A_m}\right)^{5/3} \left(\frac{P_m}{P_c}\right)^{2/3} \frac{(D + S)_m}{(D + S)_c} \frac{n_m}{n_c} \frac{(\tau_S + \tau_b)_c}{(\tau_S + \tau_b)_m} \frac{N_c(X)}{N_m(X)} \tag{33}$$

2.4 Theory for Numerical Surge Routing in the Vicinity of the Inner Harbor Navigation Canal

2.4.1 Basic Equations

The basic equations for long waves within a confined channel consist of the momentum and continuity equations. The notation is defined in Fig. 3 and the equations are written below.

Momentum:

$$\frac{dV}{dt} = -g \frac{\partial H}{\partial x} - \frac{g}{C_h^2 R} V |V| \tag{34}$$

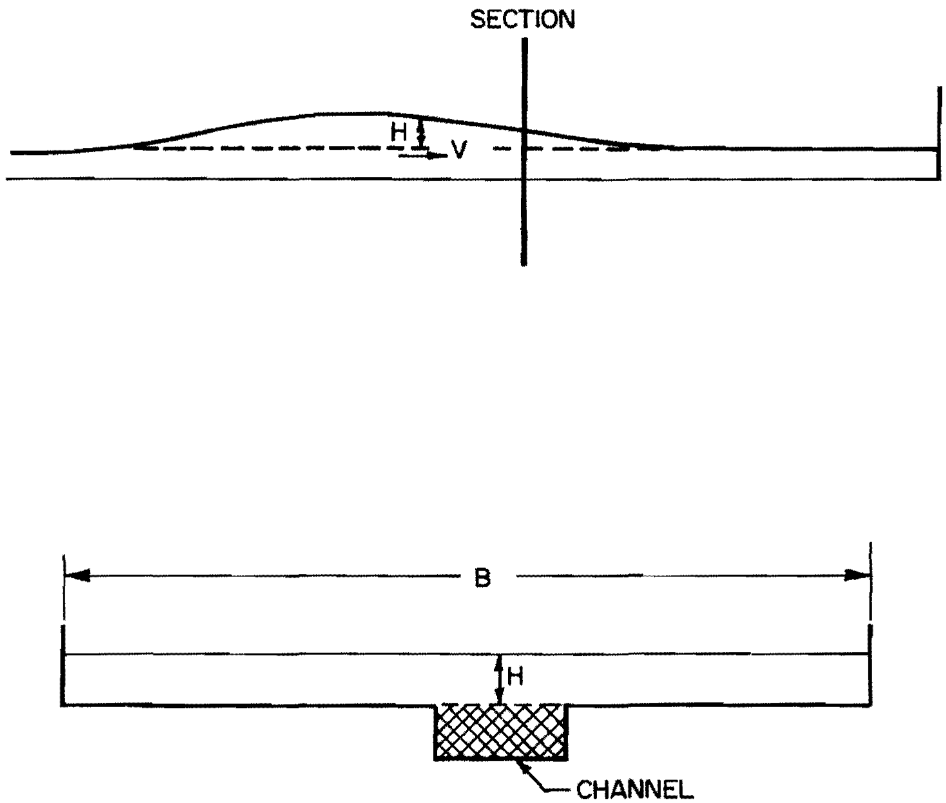


Figure 3
Notation used for basic long wave equations

PA-3-10290

Continuity:

$$B \frac{\partial H}{\partial t} + \frac{\partial (AV)}{\partial x} = 0 \qquad (35)$$

where

V = the mean velocity in a cross section

H = the water level height above the initial level

g = the acceleration due to gravity

C_h = the Chezy coefficient

B = the surface width of the river

A = the cross-sectional area of the river

R = the hydraulic radius of the complex channel

For this study it was decided to transform these equations in terms of the discharge Q (= AV) and wave height H. These become

Momentum:

$$\frac{d(Q/A)}{dt} = -g \frac{\partial H}{\partial x} - \frac{g}{C_h^2 \, A^2 \, R} \, Q|Q| \qquad (36)$$

Continuity:

$$B \frac{\partial H}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad (37)$$

This system was chosen as being most convenient for computation. Some approximations will be necessary in the momentum equation, but the continuity equation is exact. In the V - H notation it is possible to keep the momentum equation exact, but approximations will be required in the continuity equation.

Equation 36, after expansion of $\frac{d(Q/A)}{dt}$ and some approximations (for example, Dronkers, 1964, is reduced to,

$$\frac{\partial Q}{\partial t} + \alpha \frac{Q}{A} \frac{\partial Q}{\partial x} = - \frac{g}{C_h^2 \; A \; R} Q|Q| - g A (I_o - I_B) \tag{38}$$

2.4.2 General Computation Method

The method of solution proceeded by rewriting Eqs. 37 and 38 in a form suitable for application of fourth order Runge-Kutta techniques.

$$\frac{\partial Q}{\partial t} = C_1(H, x) \frac{\partial H}{\partial x} + C_3(H, x) \; Q|Q| \tag{39}$$

$$\frac{\partial H}{\partial t} = C_3(H, x) \frac{\partial Q}{\partial x} \tag{40}$$

In Eqs. 39 and 40 $C_n(H, x)$ denotes coefficients which are functions of H, the wave amplitude at x and the position x. The coefficients C_1 through C_4 are given by

$$\left.\begin{aligned} C_1 &= - g \; A(H, x) \\ C_2 &= - \frac{\alpha}{A(H, x)} \\ C_3 &= - \frac{g}{C_h^2 \; A(H, x) \; R(H, x)} \\ C_4 &= - \frac{1}{B(H, x)} \end{aligned}\right\} \tag{41}$$

where

$A(H, x)$ = the cross-sectional area of the channel

$B(H, x)$ = the surface width

$d_o(x)$ = the starting depth, defined by $A(0, x)/B(0, x)$ (the hydraulic radius)

The space variations in Q and H were evaluated by finite differences and the integrations in time were performed using a fourth order Runge-Kutta method. Consider the point m, n in the x, t plane as in Fig. 4. It is assumed that all values of Q and H have been found up to the time step n. Then $Q_{m,n+1}$ and $H_{m,n+1}$ are given by

$$Q_{m,n+1} = Q_{m,n} + \frac{1}{6}\left(k_m^1 + 2k_m^2 + 2k_m^3 + k_m^4\right) \tag{42}$$

$$H_{m,n+1} = H_{m,n} + \frac{1}{6}\left(\ell_m^1 + 2\ell_m^2 + 2\ell_m^3 + \ell_m^4\right) \tag{43}$$

where the coefficients k_m^1, k_m^2, k_m^3, k_m^4, ℓ_m^1, ℓ_m^2, ℓ_m^3, ℓ_m^3 are successive approximations of the changes in Q and H over the time interval $n\Delta t$ to $(n+1)\Delta t$. For $m = 2$ to $m = M$ these are given by

$$k_m^1 = \Delta t \left[C_1\left(H_{m,n}, X_m\right) \frac{H_{m+1,n} - H_{m-1,n}}{2\Delta x} + C_3\left(H_{m,n}, X_m\right)\left|Q_{m,n}\right| Q_{m,n} \right] \tag{44}$$

$$\ell_m^1 = \Delta t \left[C_4\left(H_{m,n}, H_m\right) \frac{Q_{m+1,n} - Q_{m-1,n}}{2\Delta x} \right] \tag{45}$$

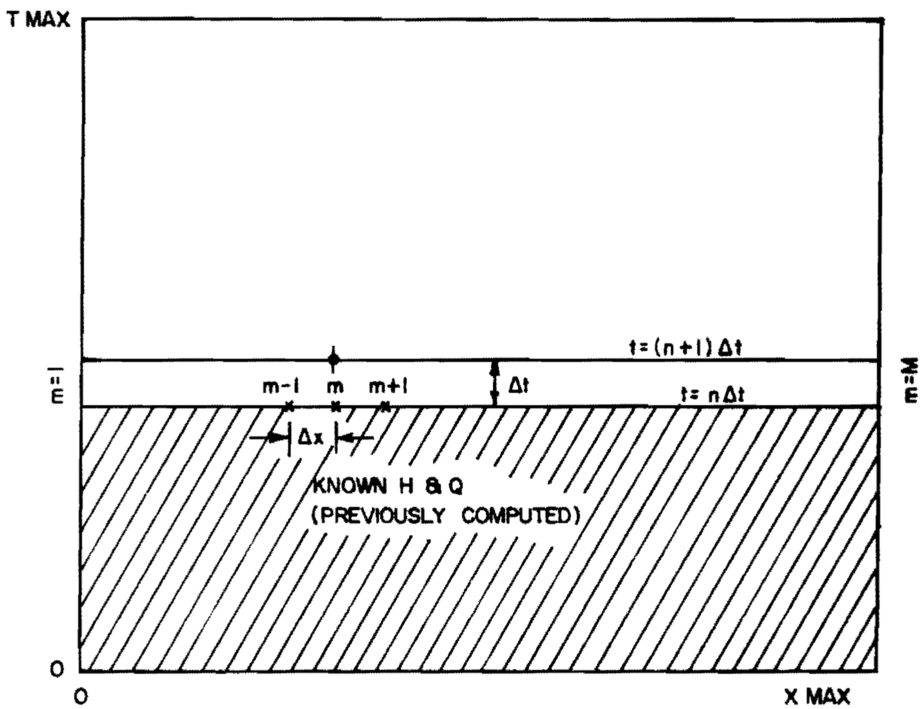


Figure 4
Illustration of numerical integration scheme

PA-3-10291

$$k_m^2 = \Delta t \left[C_1\left(H_{m,n} + \frac{\ell_m^1}{2},\ X_m\right) \frac{H_{m+1,n} - H_{m-1,n} + \frac{1}{2}\left(\ell_{m+1}^1 - \ell_{m-1}^1\right)}{2\Delta x} \right.$$

$$+ C_2\left(H_{m,n} + \frac{\ell_m^1}{2},\ X_m\right)\left(Q_{m,n} + \frac{k_m^1}{2}\right) \frac{Q_{m+1,n} - Q_{m-1,n}}{2\Delta x}$$

$$\left. + \frac{\frac{1}{2}\left(k_{m+1}^1 - k_{m-1}^1\right)}{2\Delta x} + C_3\left(H_{m,n} + \frac{\ell_m^1}{2},\ X_m\right)\left|Q_{m,n} + \frac{k_m^1}{2}\right|\left(Q_{m,n} + \frac{k_m^1}{2}\right)\right] \tag{46}$$

$$\ell_m^2 = \Delta t \left[C_4\left(H_{m,n} + \frac{\ell_m^1}{2},\ X_m\right) \frac{Q_{m+1,n} - Q_{m-1,n} + \frac{1}{2}\left(k_{m+1}^1 - k_{m-1}^1\right)}{2\Delta x} \right] \tag{47}$$

$$k_m^3 = \Delta t \left[C_1\left(H_{m,n} + \frac{\ell_m^2}{2},\ X_m\right) \frac{H_{m+1,n} - H_{m-1,n} + \frac{1}{2}\left(\ell_{m+1,n}^2 - \ell_{m-1}^2\right)}{2\Delta x} \right.$$

$$+ C_2\left(H_{m,n} + \frac{\ell_m^2}{2},\ X_m\right)\left(Q_{m,n} + \frac{k_m^2}{2}\right) \frac{Q_{m+1,n} - Q_{m-1,n}}{2\Delta x}$$

$$\left. + \frac{\frac{1}{2}\left(k_{m+1}^2 - k_{m-1}^2\right)}{2\Delta x} + C_3\left(H_{m,n} + \frac{\ell_m^2}{2},\ X_m\right)\left|Q_{m,n} + \frac{k_m^2}{2}\right|\left(Q_{m,n} + \frac{k_m^2}{2}\right)\right] \tag{48}$$

$$\ell_m^3 = \Delta t \left[C_4\left(H_{m,n} + \frac{\ell_m^2}{2},\ X_m\right) \frac{Q_{m+1,n} - Q_{m-1,n} + \frac{1}{2}\left(k_{m+1}^2 - k_{m-1}^2\right)}{2\Delta x} \right] \tag{49}$$

$$k_m^4 = \Delta t \left[C_1 \left(H_{m,n}^3 + \ell_m^3, X_m \right) \frac{H_{m+1,n} - H_{m-1,n} + \ell_{m+1}^3 - \ell_{m-1}^3}{2\Delta x} \right.$$

$$+ C_2 \left(H_{m,n} + \ell_m^3, X_m \right) \left(Q_{m,n} + k_m^3 \right) \frac{Q_{m+1,n} - Q_{m-1,n}}{2\Delta x}$$

$$\left. + \frac{k_{m+1}^3 - k_{m-1}^3}{2\Delta x} + C_3 \left(H_{m,n} + \ell_m^3, X_m \right) \left| Q_{m,n} + k_m^3 \right| \left(Q_{m,n} + k_m^3 \right) \right] \tag{50}$$

$$\ell_m^4 = \Delta t \left[C_4 \left(H_{m,n} + \ell_m^3, X_m \right) \frac{Q_{M+1,n} - Q_{m-1,n} + k_{m+1}^3 - k_{m-1}^3}{2\Delta x} \right] \tag{51}$$

2.4.3 Boundary Conditions

Boundary conditions are required to solve the problem. Two conditions were prescribed.

a) The initial surge height in the channel was zero at $t = 0$ for all x.

b) The input surge at $x = 0$ was taken as a prescribed hydrograph $H_o(t)$.

One more boundary condition is required along the line $x = 0$ $(m = 1)$ and further conditions are required at the upstream boundary.

The downstream boundary condition along the time axis $x = 0$ would require the specification of Q as a function of time or alternatively a relationship between H and Q along this line. Neither of these was available. It was decided to let the relationship between Q and H at this boundary be computed in the following manner.

$$Q(1,n) = Q(2,n) + \frac{Q(2,n) - Q(4,n)}{2} \tag{52}$$

where $Q(2,n)$ and $Q(4,n)$ were computed as in Section 2.4.2. In order to compute $Q(2,n)$, values of k_1^1, k_1^2, k_1^3, k_1^4 were approximated as

$$k_1^1 = k_1^2 = k_1^3 = k_1^4 = Q(1, n-1) - Q(1, n-2) \tag{53}$$

The upstream boundary was treated as a closed end. That is, the discharge at the boundary is zero and the surge is reflected. The resulting boundary conditions are written as

$$H(M) = 2H(M-1) - H(M-2) \tag{54}$$

$$Q(M) = 0 \tag{55}$$

It is recalled that the values of Q_{M+1} and H_{M+1} are required in the fourth order Runge-Kutta scheme for the ℓs and ks at Q_M, H_M on the next time step as are also the values of the ℓs and ks at $x = (M+1)\Delta x$. The equations used are summarized:

$$H(M+1) = H(M-1) \tag{56}$$

$$\left.\begin{aligned} Q(M+1) &= -Q(M-1) \\ \ell^1(M+1) &= \ell^1(M-1) \end{aligned}\right\} \tag{57}$$

$$\ell^2(M+1) = \ell^2(M-1)$$

$$k^1(M+1) = -k^1(M-1) \tag{58}$$

$$k^2(M+1) = -k^2(M-1) \text{ etc.} \tag{59}$$

2.5 Choice of Coefficients for the Open Coast

Two empirical coefficients have to be used with the bathystrophic storm tide theory. There is a wind stress coefficient for the friction of wind on the water surface and a bottom friction stress coefficient for the drag of water on the bed.

Theoretical developments of wind effect equations have been made by Hellstrom (1941), Keulegan (1951), Thijsse (1952) and others.

2.5.1 Wind Stress Coefficient

Following the assumption that the wind stress is proportional to the square of the wind velocity the wind stress is written

$$\tau_s = k\rho_a W^2 \tag{60}$$

where $k\rho_a$ has been found to be approximately 3×10^{-6}. This was the value that was used. Dronkers (1964) reports observations of $k\rho_a$ as high as 4.5×10^{-6} in the shallow areas of the Zuider Zee, but this large value for shallow water arises because of an underestimation of bottom friction as well as second order effects.

2.5.2 Bottom Stress Coefficient

The other empirical factor is the bottom stress coefficient used for the longshore flow. Following Reid (1964) the bottom stress will be given by

$$\tau_b = \rho \gamma^2 V^2 \tag{61}$$

where V is the current velocity.

We can now make use of Manning's equation, given as follows:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2} = \frac{1.486}{n} R^{1/6} (RS)^{1/2} \tag{62}$$

where

V = mean current speed in feet/second

R = hydraulic radius in feet

S = hydraulic slope in terms of feet/feet

Where Manning's n has the dimension of $(\text{ft})^{1/6}$, the corresponding Chezy-Kutter formula is

$$V = C\,(RS)^{1/2} \tag{63}$$

where the above notation has been defined and C is the Chezy-Kutter coefficient. It can be seen that C is related to Manning's n as follows:

$$C = \frac{1.486}{n} R^{1/6} \tag{64}$$

Returning now to Eq. 61 and from the theory for turbulent flow of Karman-Prandtl it can be demonstrated that τ_b is related to Manning's n by the formula:

$$\tau_b = \frac{3.86n}{D^{1/6}} \approx 0.214\left(\frac{z_o}{D}\right)^{1/6} \tag{65}$$

or

$$n = 0.0555 \left(z_o\right)^{1/6} \tag{66}$$

where z_o is the characteristic roughness height.

In the form used in this study,

$$\frac{\tau_b}{\rho} = \frac{K}{D^{1/3}} V^2 = \frac{K}{D^{1/3}} \frac{Q^2}{D^2} \tag{67}$$

so that it is seen that

$$K = \frac{n^2 g}{(1.486)^2} = 14.6\, n^2 \tag{68}$$

where K has the dimension of $(\text{feet})^{1/3}$.

For a characteristic roughness height on the bed of $z_o = 0.01$ feet, $n = 0.026\,(\text{feet})^{1/6}$, and $K = 1 \times 10^{-2}\,(\text{feet})^{1/3}$, it was found during this study that along the Louisiana coast the best choice of K was about $5 \times 10^{-3}\,(\text{feet})^{1/3}$ corresponding to a Manning's n offshore of about $0.015\,(\text{feet})^{1/6}$.

2.5.3 Choice of Coefficient for Marshland Areas

A detailed investigation of the effective roughness of marsh area has been made. Table III, prepared by Dr. Per Bruun, presents the summary of available data on bottom roughness and bottom friction factors in terms of Manning's n. The recommended Manning's n of 0.08 (feet)$^{1/6}$ leads to a choice for $K_{marsh} = 9.3 \times 10^{-2}$ (feet)$^{1/3}$.

2.5.4 Channel Surge Routing, Chezy Coefficient

The Chezy coefficient was used in the form of the Manning equation

$$C_h = \frac{1.486}{n} R^{1/6} \tag{69}$$

The value of an equivalent Manning's n for a channel with composite roughness to include dredged channels and marsh areas is defined by

$$n_e = \left[\frac{\sum_{1}^{N} P_N \, n_N^{3/2}}{P_N} \right]^{2/3} \tag{70}$$

where P_N are the individual perimeters of the component channels and marsh areas. In application to the sum of a marsh area and the Gulf Outlet Channel Eq. 82 has reduced to

$$n_e = \left[\frac{(B - 500)(0.08)^{3/2} + 500\,(0.025)^{3/2}}{B} \right]^{2/3} \tag{71}$$

Based on the information in Table III, the n factors listed in Table IV are suggested. These values should, however, be adjusted to any particular situation in which the water depth, the nature of the soil, and its surfaced cover and the wind stresses exerted upon the water causing the flow are the determining factors.

TABLE III

Summary of Information on Friction Coefficients for Flow Over Rough Bottom

	Author or Source	Source	Figure or Other Information
1	Task Force on Friction ASCE	ASCE Hyd. Div., Vol. 89, No. 2, March 1963, pp. 97-143	Numerous formulas for open channel flow friction, relation to soil, geometry, depth and sediment transport
2	--	--	Highest resistance recorded by flume experiments (Simons & Richardson) with 0.28 mm sand was n = 0.027 (lower regimen)
3	L. Prandtl } Bruno Eck } (Germany)	Stromungslehre, 1949 Technische Stromungslehre, 1960	No information of particular interest.
4	Bazin (France)	ASCE Hyd. Div., Vol. 89, No. 2	$n = 0.05\ ft^{1/6}$ (h = 9 ft). Exceptionally rough channels.
5	Bretting (Denmark)	Hydraulik, 1960	n may be as high as $0.04\text{-}0.07\ ft^{1/6}$ for section with heavy growth.
6	--	ASCE Hyd. Div., Vol. 91, No. 2	Information of importance for prediction of roughness and slope for known material and discharge.
7	--	Correspondence	$n = 0.04 - 0.05\ ft^{1/6}$ ($k > 3$ ft)
8	Rouse	Fluid Mechanics for Hydraulic Engineers, 1908	$n = 0.025 - 0.040\ ft^{1/6}$ for "earth with weeds."
9	Simons	Colorado State Univ. Col. Cer. No. 57, DBS 17	$n = 0.03\ ft^{1/6}$ for "some weed effect."
10	Ven Te Chow	Open-Channel Hydraulics 1959	$n > 0.1\ ft^{1/6}$ for very heavy growth (p. 102)
11	--		$n \sim 0.08\ ft^{1/6}$ for depth > 4 ft with brush and waste. (p. 104)
12	--		Combined evaluation including soil, irregularity, cross-section, obstruction and vegetation $n = 0.06\ ft^{1/5}$ and $0.07\ ft^{1/6}$ for meandering (p. 109).
13	--		n = 0.05 for pasture and high grass and mature field crop
14	Parsons	"Vegetative Control of Stream-bank Erosion." Misc. Pub. 970, U.S. Agric. Dept. Paper No. 20, 1965	$C = 23 \log R_e \text{ Alog } \frac{hC}{6500} - 98$ (Fig. 21) with the kind of conditions described in photos of n = 0.05 - 0.07
15	Ree	Agriculture Engineering for April 1949, pp. 184-187	$n \sim 0.03 - 0.3\ ft^{1/6}$
16	Tickner	Tech Memo # 95 (USCE), 1957	Flume tests, U_{max} 35 ft/sec $n \sim 0.05\ ft^{1/6}$
17	Dutch Government	Special Report	$n \sim 0.05$ to $0.07\ ft^{1/6}$

(by courtesy of Per Bruun)

TABLE IV

n Factors Suggested

Condition	Slow Inflow	Rapid Inflow	Steady State Two-dimensional Return Flow	Steady State Three-dimensional Return Flow	Return Flow in General
Depth range approximate	< 3 ft	> 5 ft	6-10 ft	6-10 ft	10 ft dropping down
Mean velocity range	1-2 ft/sec	> 4-5 ft/sec	Small. Bottom velocity < 3 ft/sec	Bottom velocity 3 ft/sec	Varies greatly, e.g. from 1 ft/sec - 6 ft/se
Length of grass	1-3 ft	Any length	About 3 ft	About 3 ft	Any length
Other	Irregular growth	Irregular growth	Irregular growth	Irregular growth	
n = (order of magnitude)	0.1 - 0.2 $ft^{1/6}$	0.05 $ft^{1/6}$	0.08 $ft^{1/6}$	0.06 $ft^{1/6}$	n = 0.04 - 0.05 $ft^{1/6}$ for rapid flow, maximum depth n = 0.06 - 0.07 $ft^{1/6}$ for medium depth, rapid flow n = 0.1 - 0.2 $ft^{1/6}$ for shallow depth, slow flow

(by courtesy of Per Bruun)

An initial table of B as a function of distance from the open end of the channel was already stored in the computer. For the cases where the Gulf Outlet Channel was assumed not to exist n_e was simply taken as 0.08.

The hydraulic radius of a composite channel was taken as the area divided by the surface width.

3. THE EFFECT OF THE MISSISSIPPI RIVER-GULF OUTLET ON SURGE ELEVATIONS IN STUDY AREA A

Hurricane Betsy and the Synthetic Hurricanes used in this study can be considered as relatively large storms which produce comparatively slow rising storm surges. The relative effect on surge elevations of the Gulf Outlet Channel can be expected to be extremely dependent upon the rate of rise of the storm surge.

The problem at hand is one of time dependency. In order to evaluate the time dependency two approaches were used.

a) The area near the Inner Harbor Navigation Canal was treated as a channel and the effect of fast and slow rising storm surges at the entrance near Lake Borgne on surge levels within the channel was investigated numerically.

b) The Gulf Outlet Channel will act as a channel to increase the conveyance of water into the area of interest. On the other hand, the surface wind stresses will be reduced because of the inverse depth effect of the wind setup equation. An attempt was made to evaluate this effect.

3.1 Results of Numerical Surge Routing

Figure 5 shows a schematic of the numerical models employed. The theory was presented in Section 2 and the computer program used is given in Appendix D.

Figures 6, 7, and 8 are the results of these calculations from a very rapidly rising hydrograph, a moderately fast rising hydrograph, and a slow rising hydrograph, respectively. The four separate cases used

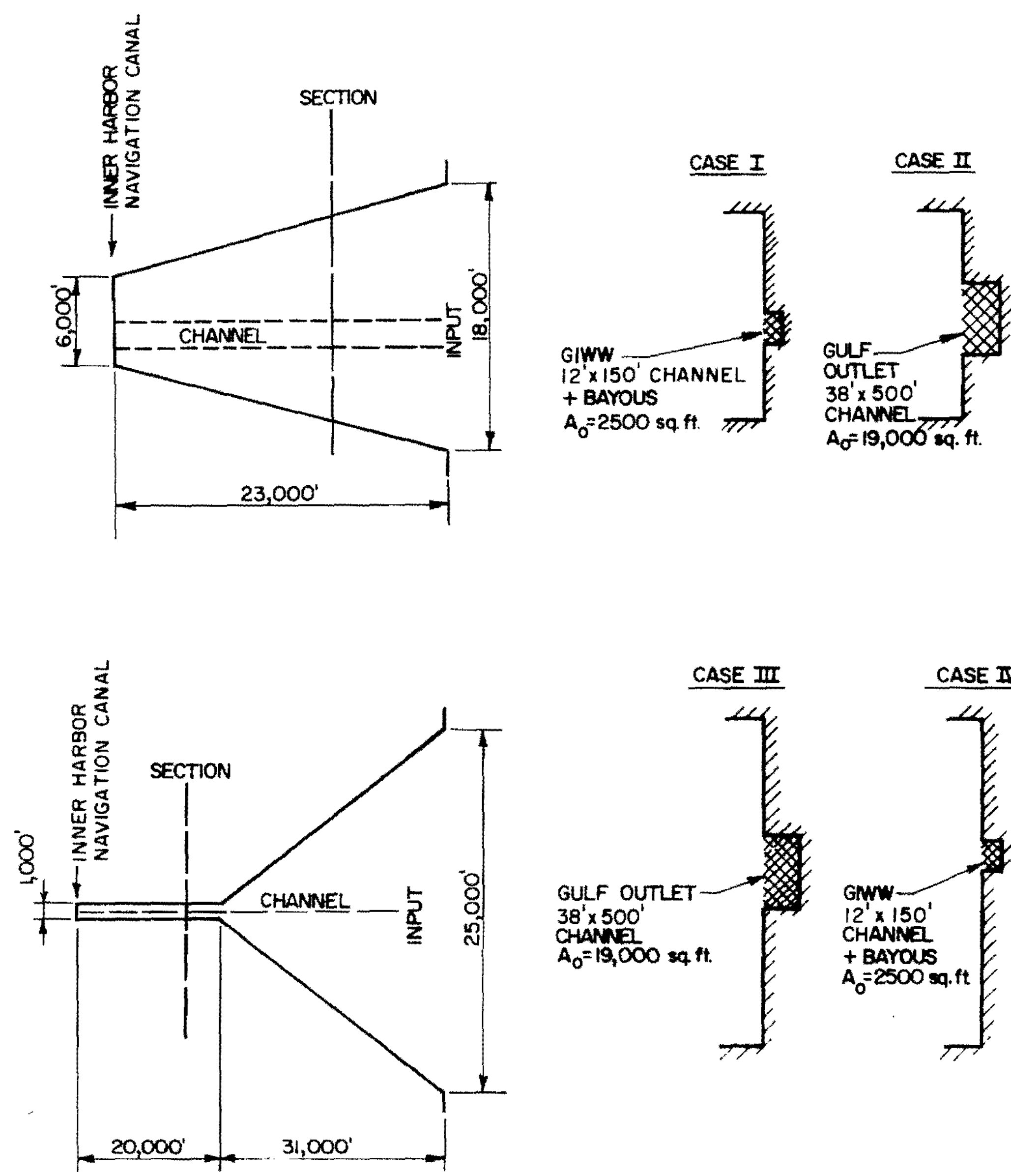


Figure 5

Schematic models used for numerical computations

PA-3-10292

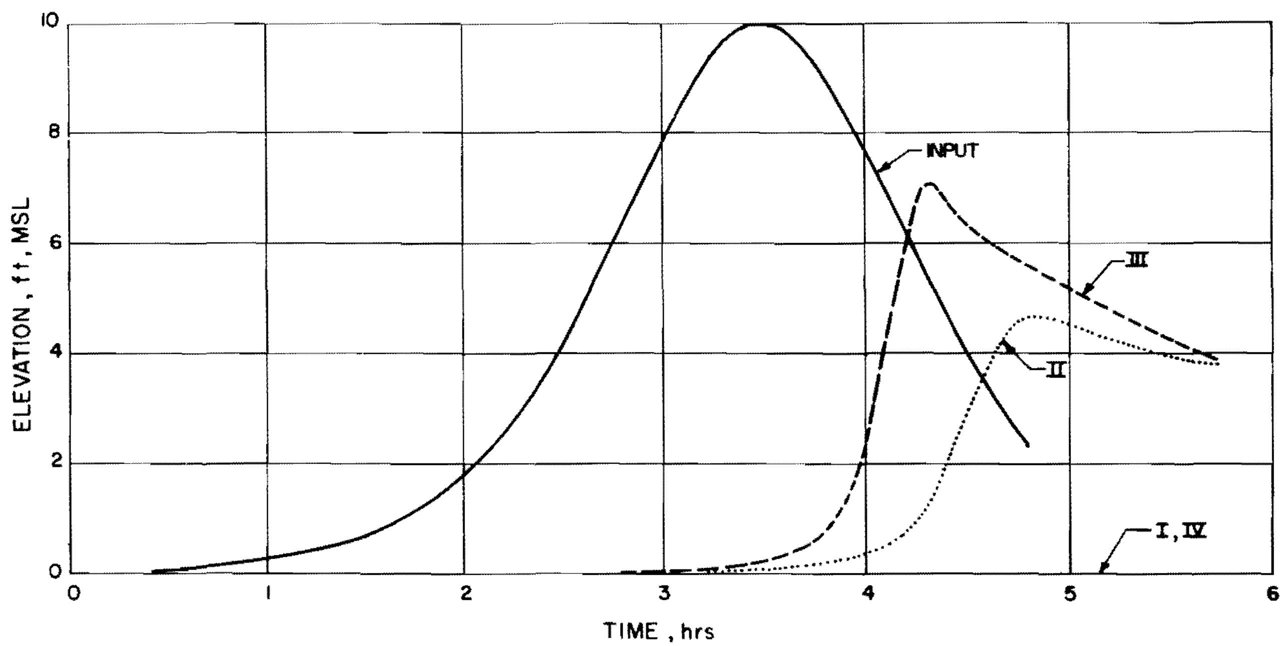


Figure 6
Results of surge routing at the inner harbor navigation canal for a very rapidly rising surge

PA-3-10293

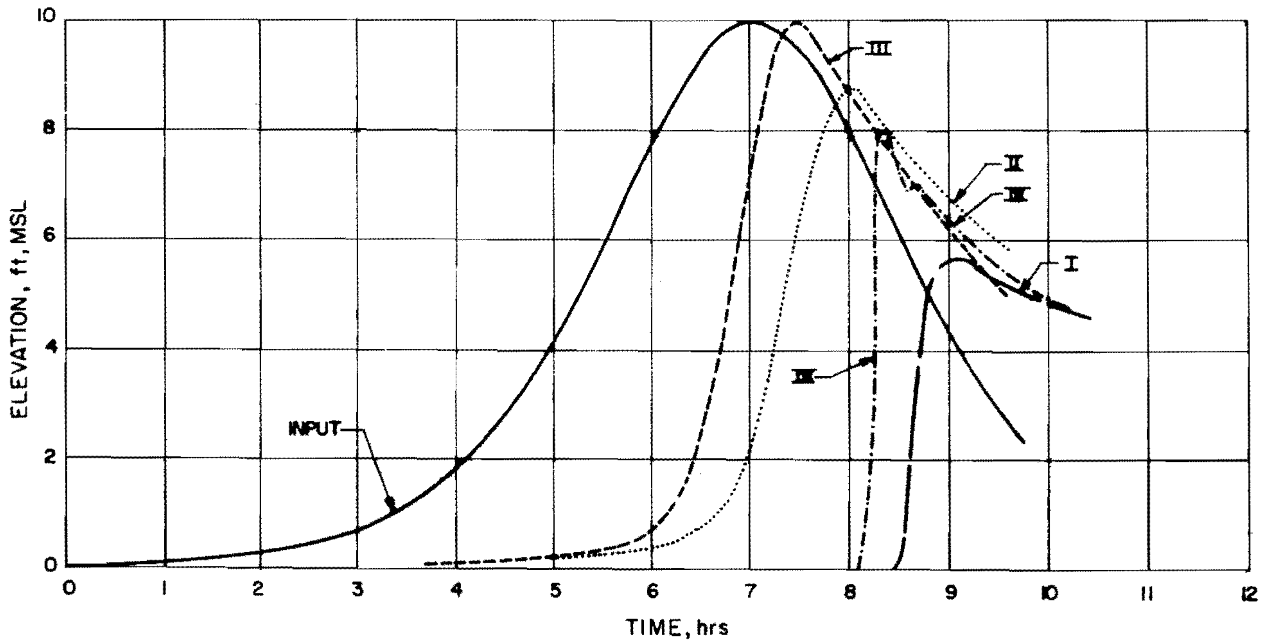


Figure 7
Results of surge routing at the inner harbor navigation canal
for a moderately fast rising surge

PA-3-10294

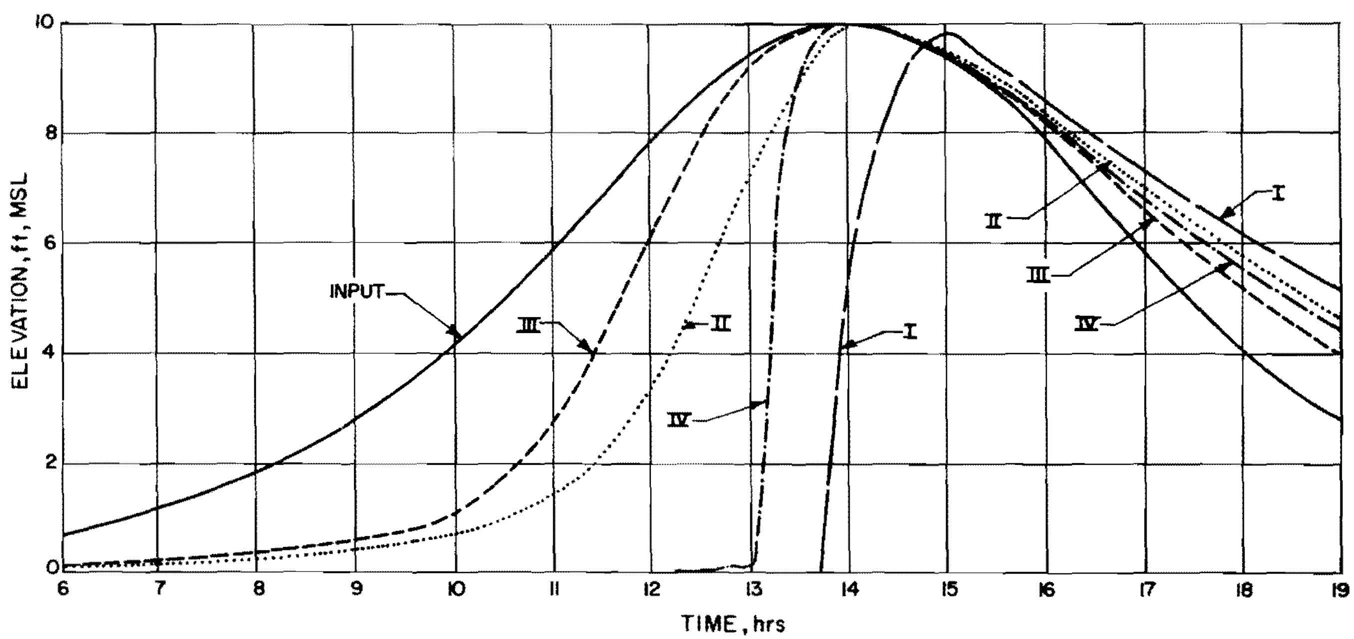


Figure 8
Results of surge routing at the inner harbor navigation canal for a slow rising surge

PA-3-10295

with each hydrograph are:

I	existing levees with no Gulf Outlet Channel
II	existing levees with the Gulf Outlet Channel
III	proposed levees with the Gulf Outlet Channel
IV	proposed levees with no Gulf Outlet Channel

It is seen from the above study that there is a decided difference in effects from fast and slow rising hydrographs. For the slowest rising hydrograph, the maximum surge elevations are essentially the same for all four cases studied. It can be concluded, therefore, that the Mississippi River-Gulf Outlet had very little effect on the maximum storm surge generated over Study Area A by Hurricane Betsy.

3.2 Effects of Channel Conveyance and Surface Wind Stress

An alternative method can be used to establish the effect, if any, that the Mississippi River-Gulf Outlet might have had on the increase in surge elevations. This was discussed in Section 2.3 on conveyance factor.

The equation for the conveyance factor is repeated here from the section on theory:

$$\gamma = \left(\frac{A_c}{A_m}\right)^{5/3} \left(\frac{P_m}{P_c}\right)^{2/3} \frac{(D+S)_m}{(D+S)_c} \frac{n_m}{n_c} \frac{(\tau_S + \tau_b)_c}{(\tau_S + \tau_b)_m} \frac{N_c(X)}{N_m(X)} \qquad (72)$$

where the symbols have been previously defined.

It will be convenient at this time to take into account the actual dimension of A, P and D for both the channel entrance and the marshland entrance. The planform factor N can be taken into account later to determine γ for various reaches up the channel to the final terminal.

For the Mississippi River-Gulf Outlet channel the mean depth will be taken as $D_c + S = 38 + S$, where it can be assumed that such depth corresponds approximately to the conditions when the marshland is just on the verge of flooding, so that the depth of the marsh is equal to the surge elevation, i.e., $D_m + S = S$.

The wetted perimeter of the channel will only be approximated by $P_c = 500 + 2(38 + S) = 576 + 2S$, assuming that the tide above the marshland level will enter this part of the problem. The wetted perimeter of the marshland, taken by the Lake Borgne portion, is approximately 11 miles or $P_m = 58,000$ feet.

The cross-sectional area of the channel, of course, will rise above the marshland elevation and should be based on a mean width channel of 500 feet such that the area is given by $A_c = 500(38 + S)$. The cross-sectional area of the marshland entrance will be given simply by $A_m = 58,000\ S$.

Combining the above three hydraulic geometry factors, one obtains for this Study Area A

$$\left(\frac{A_c}{A_m}\right)^{5/3}\left(\frac{P_m}{P_c}\right)^{2/3}\frac{(D+S)_m}{(D+S)_c} = 0.345\left[\frac{38+S}{S(288+S)}\right]^{2/3} \qquad (73)$$

For the marshland $n_m = 0.08$ and for the Gulf Outlet $n_c = 0.025$ have been estimated whence

$$\frac{n_m}{n_c} = \frac{0.08}{0.025} = 3.2 \qquad (74)$$

The combined wind stress and bottom stress $\tau_S + \tau_b$ for the marshland is known to be greater than that for an ordinary cut channel. An estimate of the relative magnitude can be obtained by considering

$$\frac{\left(\tau_S + \tau_b\right)_c}{\left(\tau_S + \tau_b\right)_m} = \frac{1 + \frac{\tau_{bc}}{\tau_S}}{1 + \frac{\tau_{bm}}{\tau_S}} \tag{75}$$

since τ_S for the water surface will be the same for either the channel or the flooded marshlands. The stress is proportional to the square of the velocity (wind or water), and from Manning's equation, it can be seen that

$$\tau_{bc} \sim n_c^2 \quad \text{and} \quad \tau_{bm} \sim n_m^2$$

Hence, the ratio

$$\frac{\tau_{bm}}{\tau_{bc}} = \left(\frac{n_m}{n_c}\right)^2 = (3.2)^2 = 10.2$$

and for ordinary bottom conditions such as the channel, and based on Lake Okeechobee studies,

$$\frac{\tau_{bc}}{\tau_S} = 0.1$$

It then follows that

$$\frac{\left(\tau_S + \tau_b\right)_c}{\left(\tau_S + \tau_b\right)_m} = \frac{1.1}{1 + 1.02} = 0.55 \tag{76}$$

The next factor to consider is the planform factor N(X). For a channel of constant width and depth $N_c(X) = 1.0$ for all stations up the channel. For the marshland the depth remains essentially constant but the width changes with distance inward from Lake Borgne. It then follows that the ratio is

$$\frac{N_c(X)}{N_m(X)} = \frac{1}{N_m(X)} \tag{77}$$

when $N_m(X)$ is the planform factor for the marshland, and at the entrance $N_m(0) = 1$, but increases to $N_m(L) = 1.36$ at the upper end. The derivation of the planform factor is presented in Appendix E.

Equations 72, 73, 74, 76, and 77 lead to the forced conveyance factor γ whence

$$\gamma = 0.61 \left[\frac{38 + S}{S(288 + S)}\right]^{2/3} \frac{1}{N_m(X)} \tag{78}$$

The average increase in surge of the Study Area A due to the Mississippi River-Gulf Outlet is given by

$$\Delta S = \gamma S \tag{79}$$

whereas the total increase in surge due to both the Mississippi River-Gulf Outlet and the planform factor is given by

$$\Delta S = N_m(X)\, \gamma S \tag{80}$$

It can be seen from Eqs. 77, 78, 79 and 80, that the total increase in storm surge due to both the Mississippi River-Gulf Outlet and the planform factor is exactly the same for the entrance as it is for the upper reaches, since $N_m(X)$ from Eq. 78 cancels that given in Eq. 80. This is as should be expected because the case at hand is one of steady state.

It can also be seen, because of the convergence of the marshland, that the direct effect due to the Mississippi River-Gulf Outlet is more pronounced at the entrance to the marshland than it is for the upper reaches. That is, the effect at the entrance is 1.36 times that at the upper end of Study Area A.

At the entrance to the marshland from Lake Borgne, $N_m(X) = 1.0$ whence

$$\gamma = 0.61 \left[\frac{38 + S}{S(288 + S)} \right]^{2/3} \tag{81}$$

and

$$\Delta S = 0.61 \left[\frac{38 + S}{S(288 + S)} \right]^{2/3} S \tag{82}$$

At the upper end of the marshland near the Inner Harbor Navigation Canel $N_m(L) = 1.36$, whence

$$\gamma = 0.45 \left[\frac{38 + S}{S(288 + S)} \right]^{2/3} \tag{83}$$

and

$$\Delta S = N_m(L)\, \gamma S = 0.61 \left[\frac{38 + S}{S\,(288 + S)} \right]^{2/3} S \tag{84}$$

Figure 9 gives relations for γ and ΔS for the entrance and the upper end of the marshland based upon the previous equations. As suggested previously, Eqs. 82, and 84 give identical ΔS vs S relationships for, respectively, the entrance to, and the upper end of, the marshland because the planform factor appears as a ratio on itself.

The conclusion from this part of the study is that the Mississippi River-Gulf Outlet had an effect of increasing the storm surge throughout the marshland for Hurricane Betsy by about 0.3 to 0.4 feet maximum elevation.

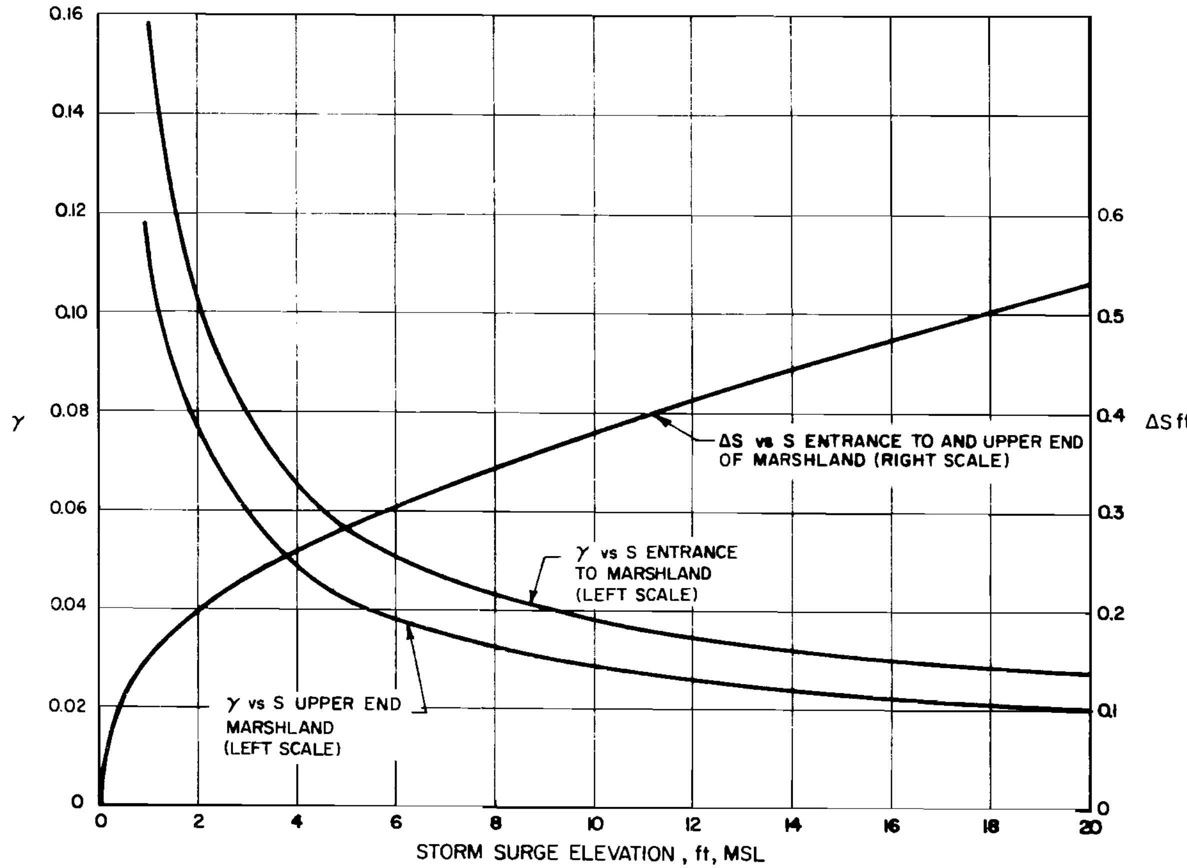


Figure 9

Marsh-channel forced conveyance ratios and computed corrections to storm surges for channel effects

4. HURRICANE WINDS AND SURGE PREDICTIONS

4.1 Hurricane Tracks

The hurricane tracks which were used in this study are shown on Fig. 10. The Hurricane Betsy track was taken from the maps supplied by the New Orleans District, Corps of Engineers from the U.S. Weather Bureau Hydrological Meteorology Section. The SPH and PMH tracks were chosen to yield the maximum surges in the area under study.

4.2 Choice of Traverses to be Used for Predictions

The area for which predictions are required is not accessible by a direct traverse. A traverse drawn from the area (Fig. 10) perpendicular to the offshore bottom profiles will cross the "Surge Reference Line" of the New Orleans District Report. The "Surge Reference Line" appears to be the locus of maximum observed surge elevations. Behind this line it is no longer possible to consider a buildup of water level with distance under the direct action of wind stress.

Two traverses were chosen (although others were tried) and are shown on Fig. 10. They cross the edge of the marsh at the locations:

1) Mississippi River-Gulf Outlet Mouth
   Lat. 29.705° Long. 89.425°

2) Christmas Camp Lake
   Lat. 29.828° Long. 89.309°

The zero points on the traverses were located at the latitudes and longitudes given above. Distances offshore were taken as positive and distances measured over the marsh were taken as negative.

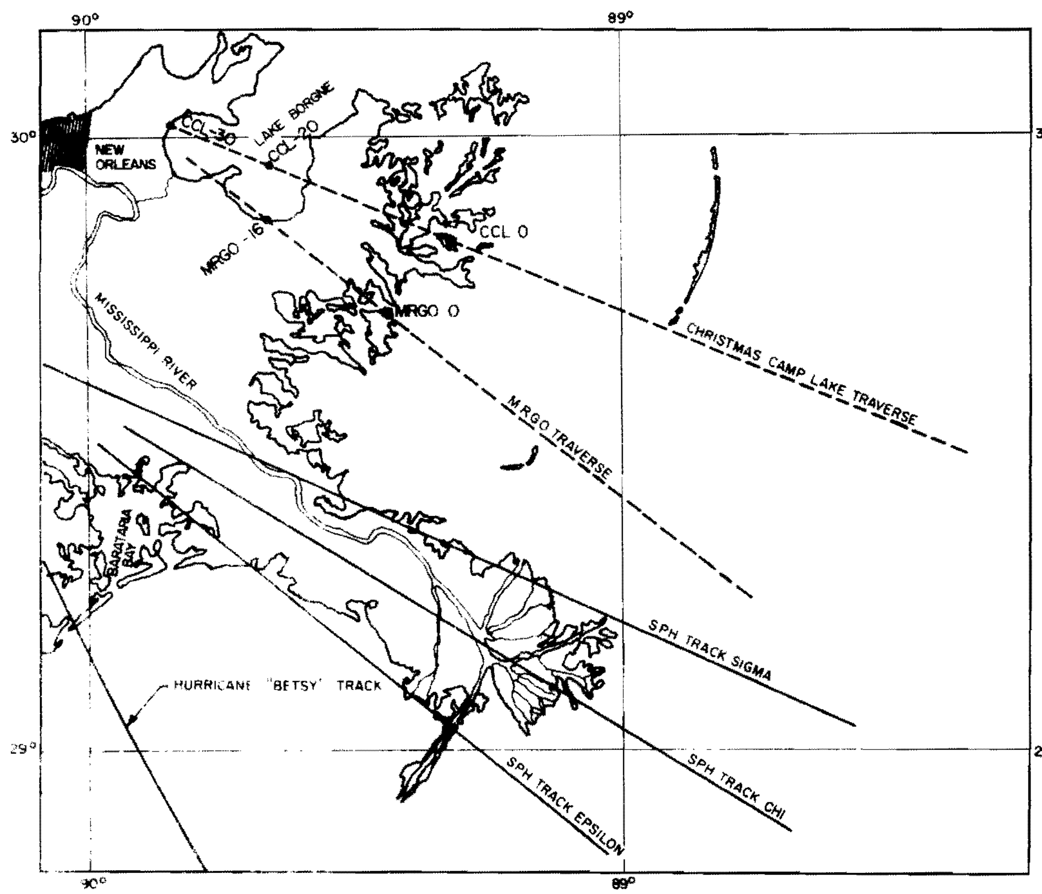


Figure 10

Map showing hurricane track and offshore traverses

PA-3-10297

The marsh was assumed to have a water depth of -2 feet, mean low water. All other water depths were used as read off U. S. Coast and Geodetic Survey Maps 1115, 1116, 1270, 1271 and 1272, relative to mean low water.

4.3 Results for Hurricane Betsy

4.3.1 Windfields, Pressures and Hurricane Track

The x-components (onshore) of the wind stresses as a function of time during Hurricane Betsy for the Mississippi River-Gulf Outlet traverse and the Christmas Camp Lake traverse are given in Figs. 11 and 12. The CPI, radius to maximum winds and hurricane center coordinates are given at various times in Table V. The values plotted in Figs. 11 and 12 and tabulated in Table V were used as input to the computer program for the bathystrophic storm tide.

4.3.2 Storm Tide Predictions for Chosen Traverses

The storm surges as predicted by the computer programs with the coefficients tabulated in Table VI for selected stations are shown plotted in Figs. 13 and 14.

4.3.3 Comparison and Correlation with Observations

The points at which storm surge predictions are required are shown as B, C, D, E, and F on Fig. 15. Figure 16 presents a summary plot of all records in the vicinity of the current study.

There is no recording gage near points A or B. The Paris Road gage is very close to point C such that correlations of the predicted hydrographs along the chosen traverses could be made with the Paris Road Bridge gage. Three point predictions were chosen to correlate with the Paris Road Bridge record. They are shown together with the Paris Road

TABLE V

Parameters for Hurricane Betsy

Day	Time, CST	Hurricane Center		Radius to Max Winds, nautical miles	CPI, inches of mercury	Forward Speed, knots	Max Winds, knots
		Latitude, degs	Longitude, degs				
Sept. 9	0000	25.90	85.25	22.0	28.0	15.25	100
	0600	26.35	86.75	24.0	28.0	14.11	100
	1200	27.15	88.05	27.0	28.0	14.22	101.5
	1500	27.75	88.60	30.0	28.0	10.27	105
	1800	28.35	89.15	31.0	28.0	10.86	106
	2100	28.94	89.85	37.0	28.0	11.41	106
Sept. 10	0000	29.60	90.50	37.0	28.0	10.32	91
	0300	30.10	91.05	37.0	28.0	9.04	86
	0600	30.64	91.55	37.0	28.3	8.97	70.5

TABLE VI

Traverse Parameters and Coefficients for Hurricane Betsy Storm Tide Predictions

Traverse	Azimuth, degree	Latitude of shoreline, degree	Longitude of shoreline, degree	Wind Stress coefficient	Offshore bottom friction coefficient	Marsh bottom friction coefficient	Coriolis Parameter
Mississippi River Gulf Outlet	309.2	29.705	89.425	3×10^{-6}	5×10^{-3}	9×10^{-2}	7.28×10^{-5}
Christmas Camp Outlet	294.0	29.828	89.309	3×10^{-6}	6×10^{-3}	9×10^{-2}	7.28×10^{-5}

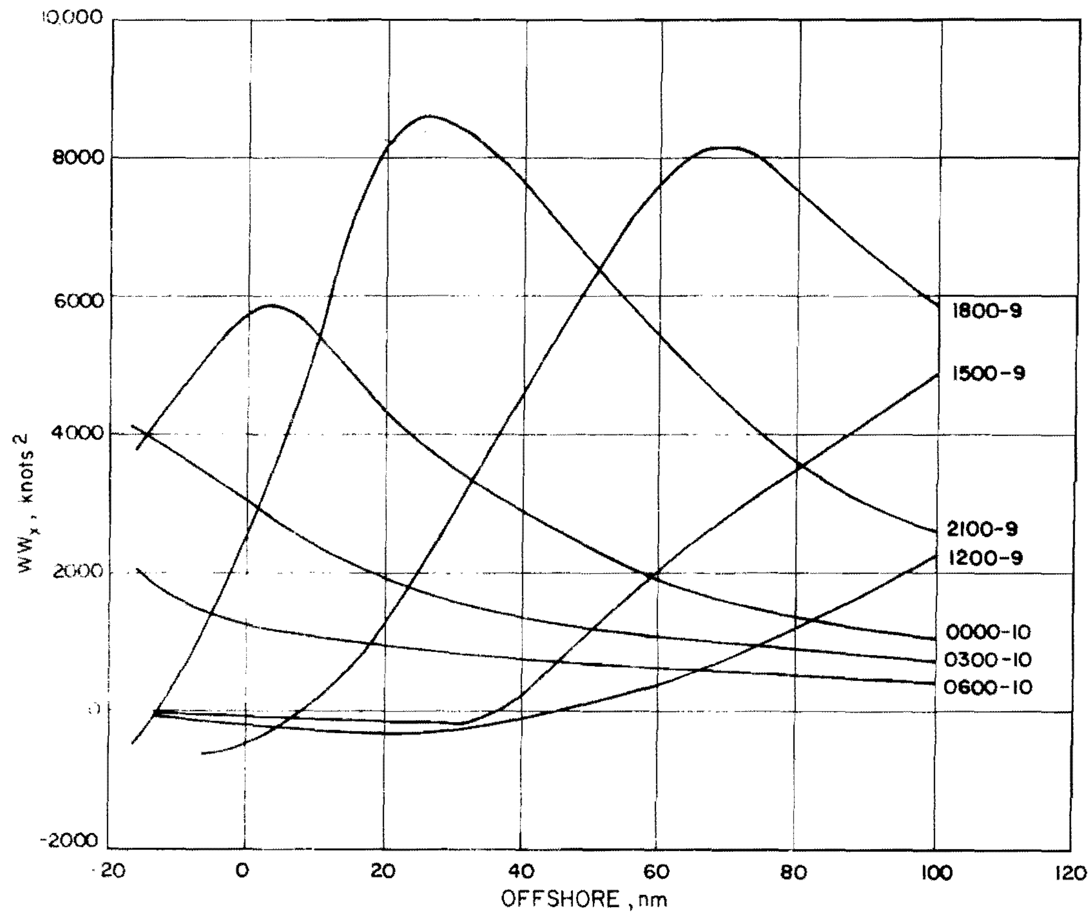


Figure 11

Onshore wind stress along Mississippi River-gulf outlet traverse, Hurrican Betsy

PA-3-10298

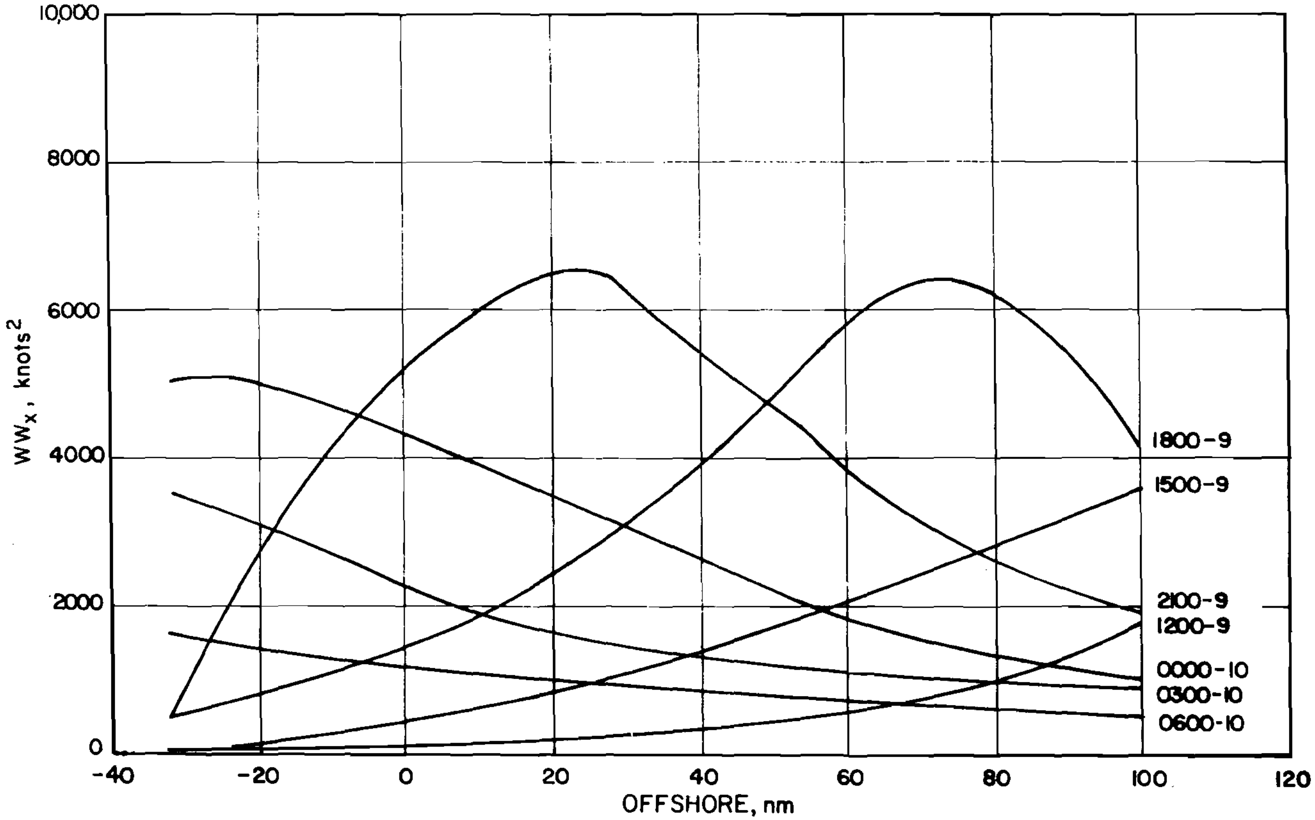


Figure 12

Onshore wind stress along Christmas Camp Lake traverse, Hurricane Betsy

PA-3-10299

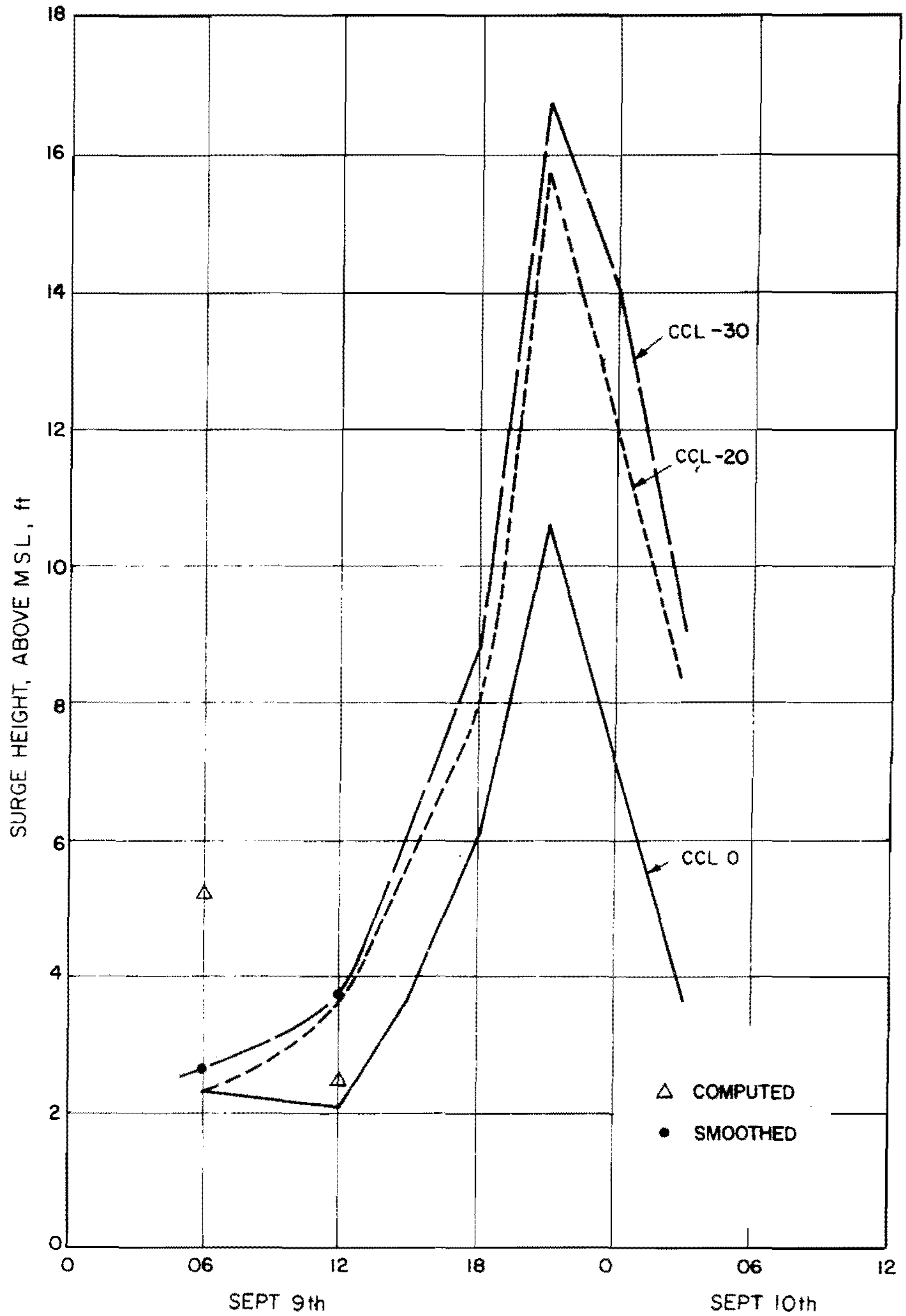


Figure 13
Storm surge computations along Christmas Camp Lake traverse, Hurricane Betsy

PA-3-10300

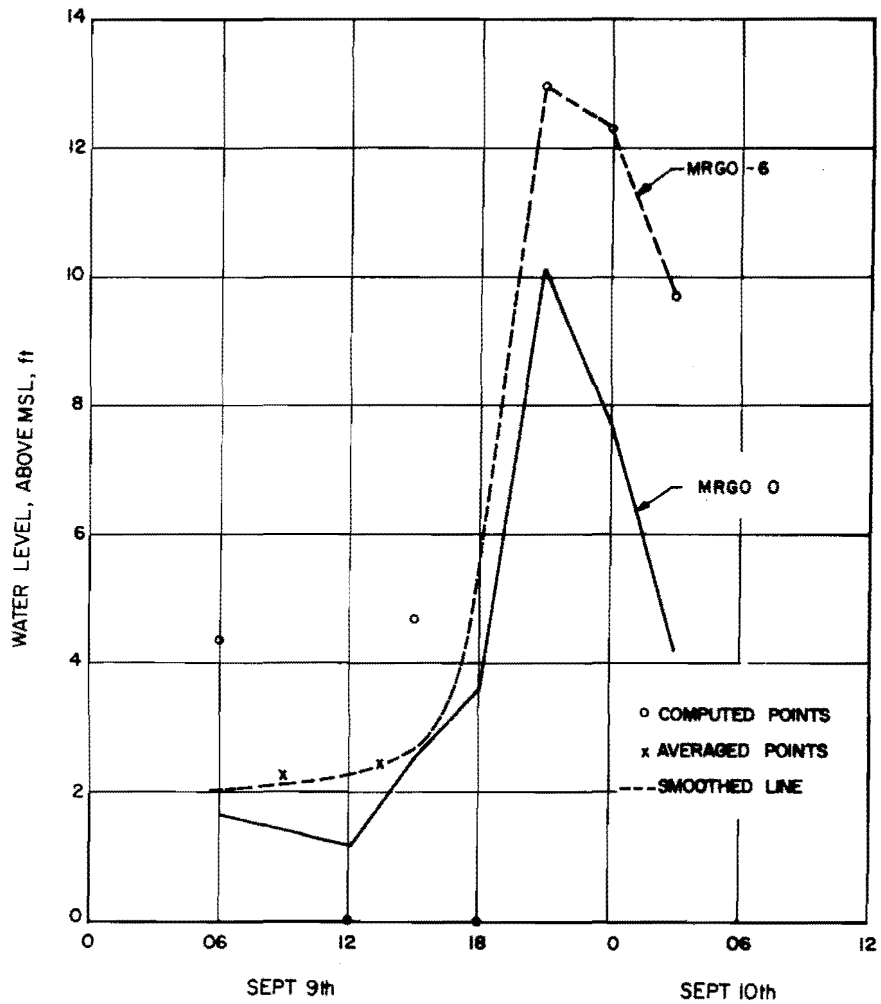


Figure 14

Storm surge computations along Mississippi River-gulf outlet traverse, Hurricane Betsy

PA-3-10301

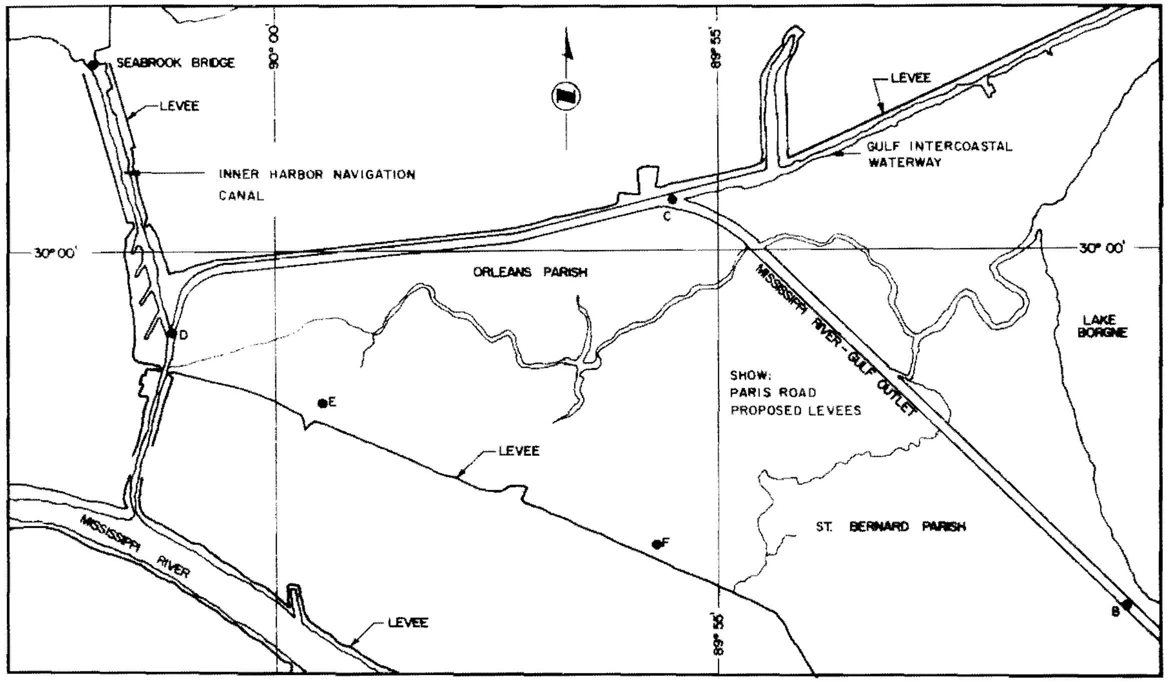


Figure 15
Map illustrating location of points B, C, D, E, and F

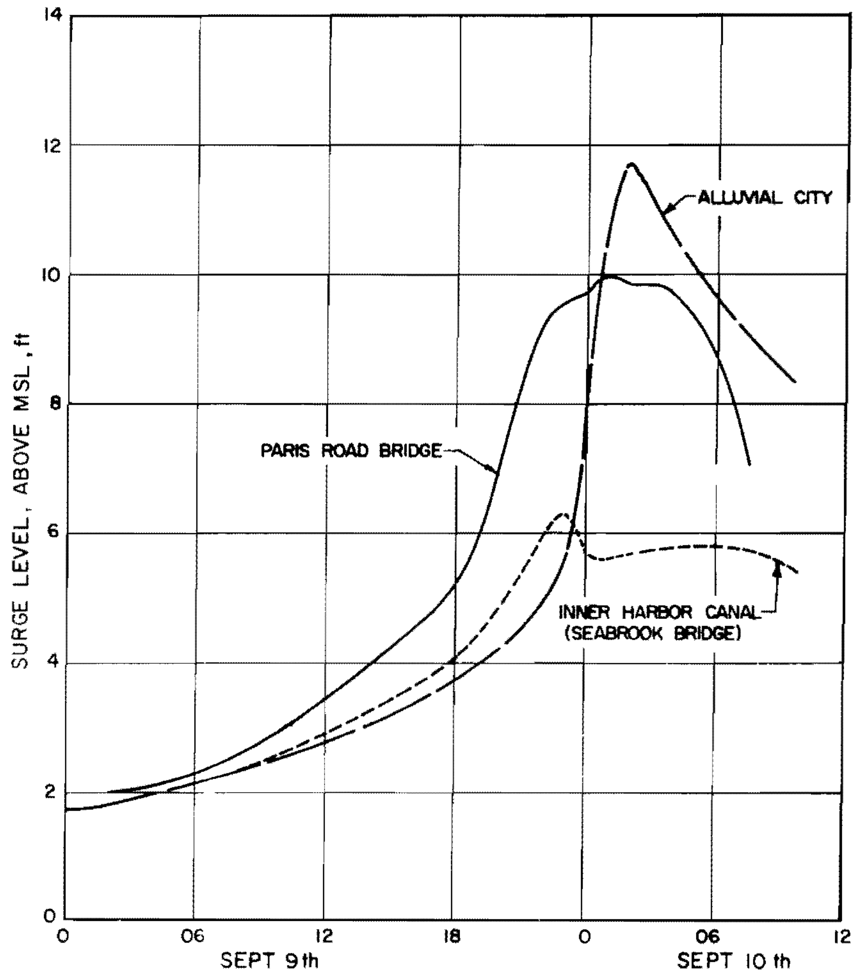


Figure 16
Recorded surge hydrographs in Study Area A,
Hurricane Betsy

PA-3-10303

Bridge record on Fig. 17. The apparent correlations are not too good. Two main reasons are apparent for this discrepancy.

a) The simplification of the complete storm tide equation leaves out almost all inertia effects. The effect of this will be to predict the peak tide much earlier than the observed peak and the predicted fall in water level after the peak will occur at a much too rapid rate. Both of these phenomena are seen on Fig. 17. This phenomenon will be of particular importance for Hurricane Betsy which was a comparatively fast moving storm.

b) No system of equations can really be expected to predict, with a great degree of accuracy, the complex physical phenomenon of flooding over marshland, bayous, houses, trees, etc. The assumptions implied in the equations as used include a vertical integration. That is, the water flows are averaged vertically. The computation of storm surges over semidry land must be regarded as an art rather than a science.

In view of the above limitations and the apparent discrepancies between "first predictions" and observations in Fig. 17, two methods of improving correlations were considered:

a) Regression analysis with assumed predictor equations.

b) Adjustment of surge peaks to agree with observations by means of "surge adjustment factors," as originally proposed in the New Orleans District Interim Survey Reports, "Lake Pontchartrain, Louisiana and Vicinity" and "Mississippi River Delta at and below New Orleans, Louisiana."

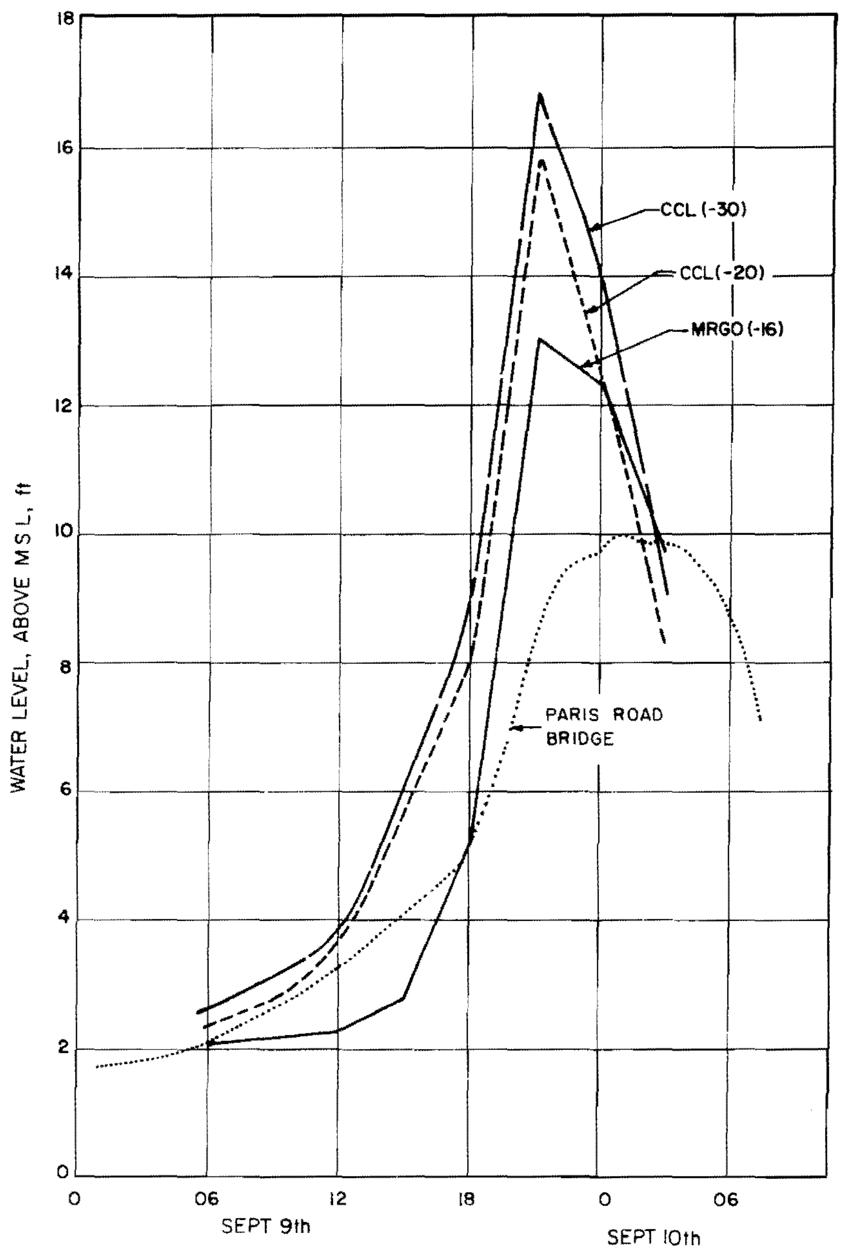


Figure 17
Comparison of computed tides at selected stations with Paris Road bridge record, Hurricane Betsy

PA-3-10304

4.3.4 Regression Correlation

The predictions at three stations were chosen for use in the predictor equation

$$Y(t) \approx X(t) = \alpha_1 A(t) + \alpha_2 B(t) + \alpha_3 C(t) \tag{85}$$

where

- $Y(t)$ is the observed water level at the Paris Road bridge
- $X(t)$ is the predicted water level at Paris Road bridge
- $A(t)$ is the computed water level at the station = 30 n.m. on the Christmas Camp Lake traverse
- $B(t)$ is the computed water level at the station - 20 n.m. on the Christmas Camp Lake traverse
- $C(t)$ is the computed water level at the station - 16 n.m. on the Mississippi River-Gulf Outlet traverse

The first step was taken as a shift in the time axis of the predictions of five hours to compensate for the inertia effect of the water. The values of $Y(t)$, $A(t)$, $B(t)$, $C(t)$ which were used are tabulated in Table VII. The resulting equations, corresponding to Eq. 26, are

$$\begin{aligned} 615.91\,\alpha_1 + 567.02\,\alpha_2 + 547.13\,\alpha_3 &= 446.53 \\ 567.02\,\alpha_1 + 522.99\,\alpha_2 + 504.19\,\alpha_3 &= 412.92 \\ 547.13\,\alpha_1 + 504.19\,\alpha_2 + 490.34\,\alpha_3 &= 407.51 \end{aligned} \tag{86}$$

The solutions of Eq. 86 yield

$$\begin{aligned} \alpha_1 &= -2.045 \\ \alpha_2 &= 0.652 \\ \alpha_3 &= 2.443 \end{aligned}$$

The prediction equation to be used becomes:

TABLE VII

Surge Observations and Predictions used in Correlation Analysis

Day	Time	Observed water level at Paris Road*	Predicted water level at -30 on CCL traverse	Predicted water level at -20 on CCL traverse	Predicted water level at -16 on MRGO traverse
Sept. 9	1100	3.2	2.3	2.6	2.6
	1700	4.6	3.7	3.7	4.0
	2000	6.9	6.2	6.0	6.2
	2300	9.5	8.8	8.1	9.2
Sept. 10	0200	9.8	16.8	15.8	13.9
	0500	9.3	14.1	12.3	12.3

*Peak surge value does not appear because of shift in time axis.

Water level at Paris Road bridge = -2.045 times the water level at -30 on the Christmas Camp Lake traverse + 0.652 times the water level at -20 on the Christmas Camp Lake traverse + 2.443 times the water level at -16 on the Mississippi River Gulf-Outlet traverse.

The results of this prediction scheme for Hurricane Betsy are shown on Fig. 18. Confidence in such a prediction scheme could be expected for a hurricane which has a similar traverse and speed to Betsy. It is apparent that more elaborate prediction schemes can be developed. Because of their empirical nature prediction schemes can only be expected to give reliable results for conditions which are almost repetitive. In particular, for example, any hurricane whose eye passes over one of the traverses will yield too low a storm surge prediction along that particular traverse because the resulting prediction equation is not applicable in this case.

The above method has been presented to illustrate the use of correlation techniques based on storm surge predictions for an area for a specific hurricane track utilizing the available hydrographs and hurricanes traveling close to that track. For conditions of sparse data and several completely different hurricane tracks the method appears to be impractical, and it was therefore necessary to return to the "surge adjustment factor" based on matching peak surges.

4.3.5 Surge Prediction Factors

The surge prediction factor can be considered as a special case of the regression-correlation technique in which only one point correlation is made. The least squares criterion reduces to the choice of zero error for one point--the peak surge--at which the surge factor is computed.

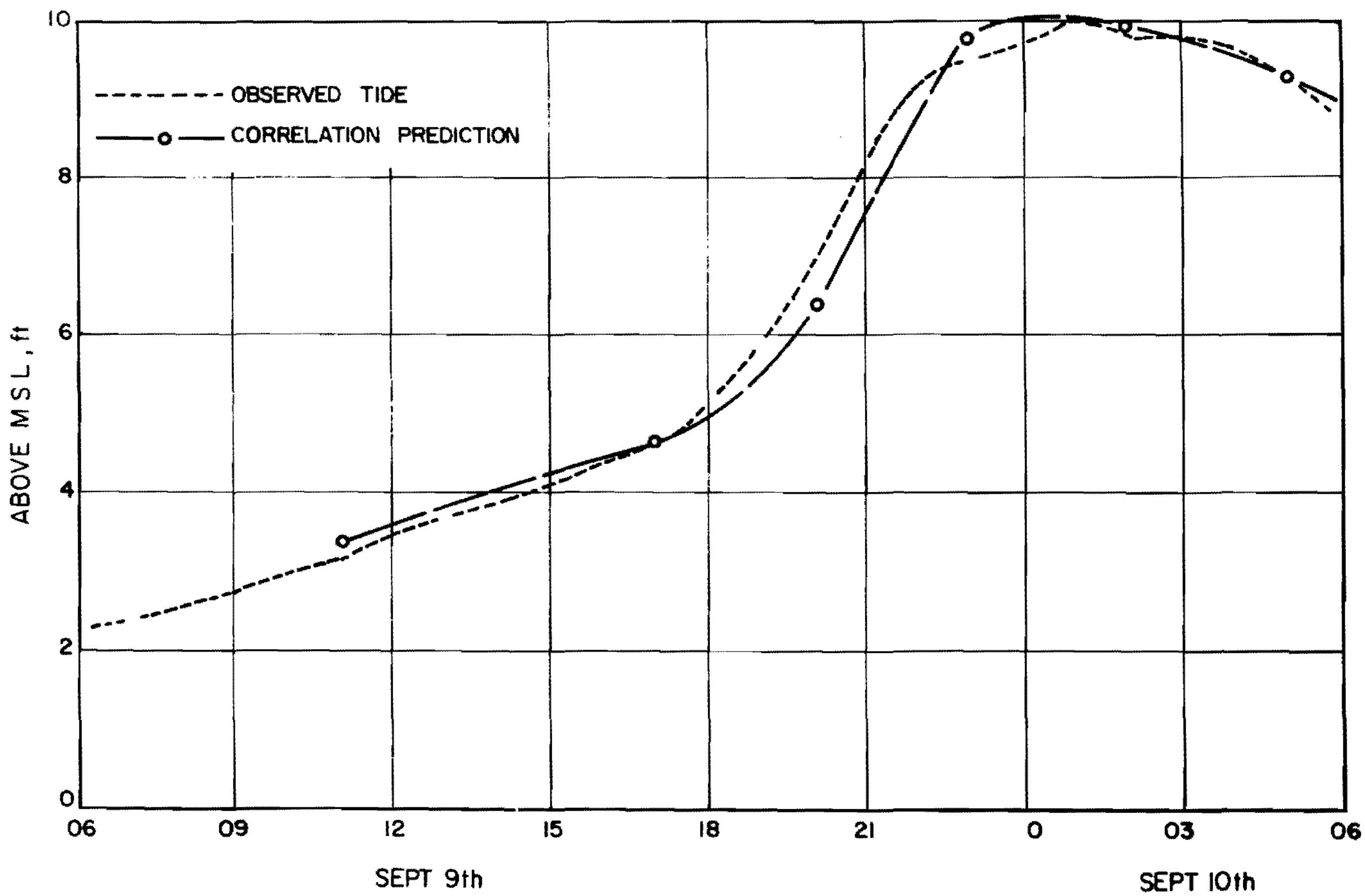


Figure 18
Comparison of observed and predicted water levels at Paris Road bridge during Hurricane Betsy

PA-3-10305

The factor was defined as the peak surge observed at a location divided by the peak surge predicted by the theory at a nearby location. This yields surge adjustment factors Z_{ij} where i is the station for which predictions are required and j is the station for which computations were made. Table VIII presents the results of the determination of these factors for the locations B, C, D, E and F on Fig. 15 from the computations made for stations 0 and -16 on the Mississippi River-Gulf Outlet (MRGO) traverse and for stations 0, -20 and -30 on the Christmas Camp Lake (CCL) traverse.

4.4 Results for Synthetic Hurricanes

4.4.1 Wind Fields, Pressures and Hurricane Track

Two synthetic hurricanes were considered: the standard project hurricane (SPH) and the probable maximum hurricane (PMH). The hurricane tracks were chosen, after discussions with New Orleans District personnel, such as to produce critical storm surge elevations in the vicinity of the Inner Harbor Navigation Canal (Fig. 18). The hurricane coordinates, forward speed and maximum winds for the SPHs are given in Tables IX through XI. The radius to maximum winds was taken as 30 nautical miles and the forward speed was 11 knots for all storms. The hurricanes corresponding to PMH conditions are identical with the SPHs in many characteristics. The differences are:

a) The maximum (and all other) wind speeds are increased 14 percent.

b) The CPIs are reduced from the typical SPH values of 27.6 to 26.9 inches of mercury.

The wind fields for the SPHs and PMHs were computed using the computer program given in Appendix C. This program produces cards as output with the wind stress components along and perpendicular to a chosen traverse for each point specified on that traverse.

TABLE VIII

Surge Prediction Factors for Hurricane Betsy

Required Station / Computed Station	B	C	D	E	F
MRGO (0)	1.00	1.02	0.885	0.885	0.990
MRGO (-16)	0.691	0.705	0.612	0.612	0.683
CCL (0)	0.905	0.925	1.03	0.915	0.895
CCL (-20)	0.610	0.621	0.692	0.615	0.602
CCL (-30)	0.572	0.585	0.650	0.578	0.567

TABLE IX

Hurricane Parameters for SPH on Track Sigma

Time, Hours before Land	H Long, degree	H Lat, degree	V_{max}, knots
30	83.83	27.18	89.4
27	84.37	27.40	89.4
24	84.95	27.63	89.4
21	85.54	27.86	89.4
18	86.12	28.09	89.4
15	86.69	28.47	89.4
12	87.29	28.55	89.4
10	87.65	28.69	89.4
8	88.03	28.84	89.4
6	88.42	28.99	89.4
5	88.61	29.07	88.5
4	88.80	29.14	88.5
3	89.00	29.22	88.5
2	89.19	29.29	88.5
1	89.30	29.36	88.5
0	89.57	29.44	87.5
-1	89.77	29.51	87.5
-2	89.96	29.59	86.8
-3	90.15	29.66	86.8
-4	90.34	29.73	86.8
-5	90.53	29.80	83.4

TABLE X

Hurricane Parameters for SPH on Track Epsilon

Time, Hours before Land	H Long, degree	H Lat, degree	V_{max}, Knots
30	84.87	25.82	89.4
27	85.34	26.17	89.4
24	85.82	26.52	89.4
21	86.47	26.87	89.4
18	86.78	27.21	89.4
15	87.26	27.56	89.4
12	87.75	27.72	89.4
10	88.07	28.15	89.4
8	88.40	28.38	89.4
6	88.73	28.61	89.4
5	88.89	28.73	88.5
4	89.05	28.85	88.5
3	89.20	28.96	88.5
2	89.38	29.08	88.5
1	89.54	29.20	88.5
0	89.70	29.32	87.5
-1	89.87	29.43	87.5
-2	90.03	29.59	86.8
-3	90.19	29.66	86.8
-4	90.35	29.77	86.8
-5	90.51	29.88	83.4

TABLE XI

Hurricane Parameters for SPH on Track Chi

Time, Hours before Land	H Long, degree	H Lat, degree	V_{max}, Knots
30	84.28	26.51	89.4
27	84.81	26.80	89.4
24	85.34	27.08	89.4
21	85.86	27.36	89.4
18	86.39	27.65	89.4
15	86.93	27.93	89.4
12	87.47	28.22	89.4
10	87.83	28.41	89.4
8	88.19	28.60	89.4
6	88.55	28.79	89.4
5	88.73	28.89	88.5
4	88.91	28.99	88.5
3	89.09	29.08	88.5
2	89.27	29.18	88.5
1	89.45	29.27	88.5
0	89.62	29.37	87.5
-1	89.80	29.46	87.5
-2	89.98	29.56	86.8
-3	90.16	29.65	86.8
-4	90.34	29.75	86.8
-5	90.52	29.85	83.4

4.4.2 Storm Tide Computations for the SPH and PMH

The unadjusted, open coast storm surges, as predicted by the computer program, are plotted in Figs. 19 through 24. (These are the values taken directly from the computer program and need to be adjusted by the prediction factors of Table VIII.)

The wind and bottom friction stress coefficients were identical with those used for Hurricane Betsy. The same wind fields were used for the PMH as for the SPH but the wind stress was increased by $(1.14)^2$

Adjusted predictions for the synthetic hurricanes for points B, C, D, E, and F with and without the Gulf-Outlet Channel and with the proposed protection works are summarized in Table II. The four separate cases are:

- I Existing levees with no Gulf Outlet Channel
- II Existing levees with the Gulf Outlet Channel
- III Proposed levees with the Gulf Outlet Channel
- IV Proposed levees with no Gulf Outlet Channel

The first predicted peak surge levels in Table II were computed by applying the surge prediction factors of Table VIII to the peak surges shown in Figs. 19 through 24. The three stations used to fix these surge levels were CCL-30, CCL-20, and MRGO-16. The three predicted values for each point, B, C, D, E, and F, averaged to yield the values in Table II. The surge levels at point A were used as MRGO-0 with no prediction factor.

Further adjustments for the various conditions for the various conditions (Cases I, II, III, and IV) were made. These adjustments were made on the basis of the numerical results shown in Fig. 8 since its surges were "shear rising." The peak surge levels for cases II, III and IV are identical.

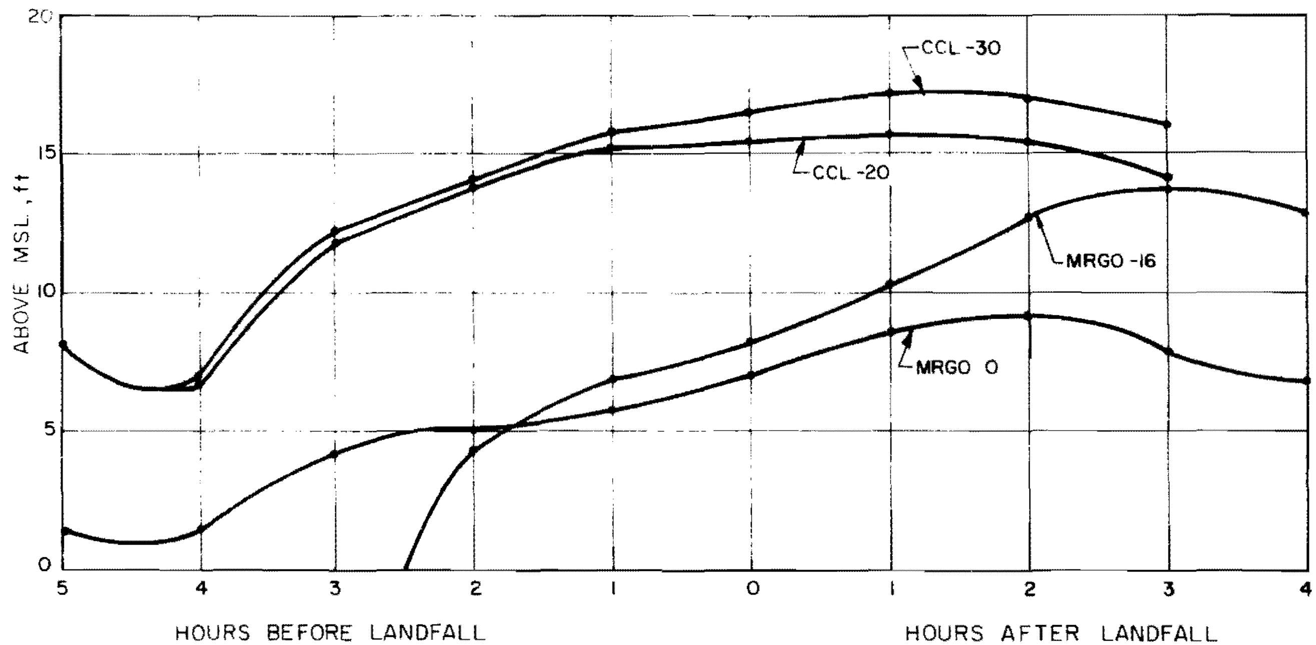


Figure 19

Computed, unadjusted open coast storm surges for SPH on track sigma

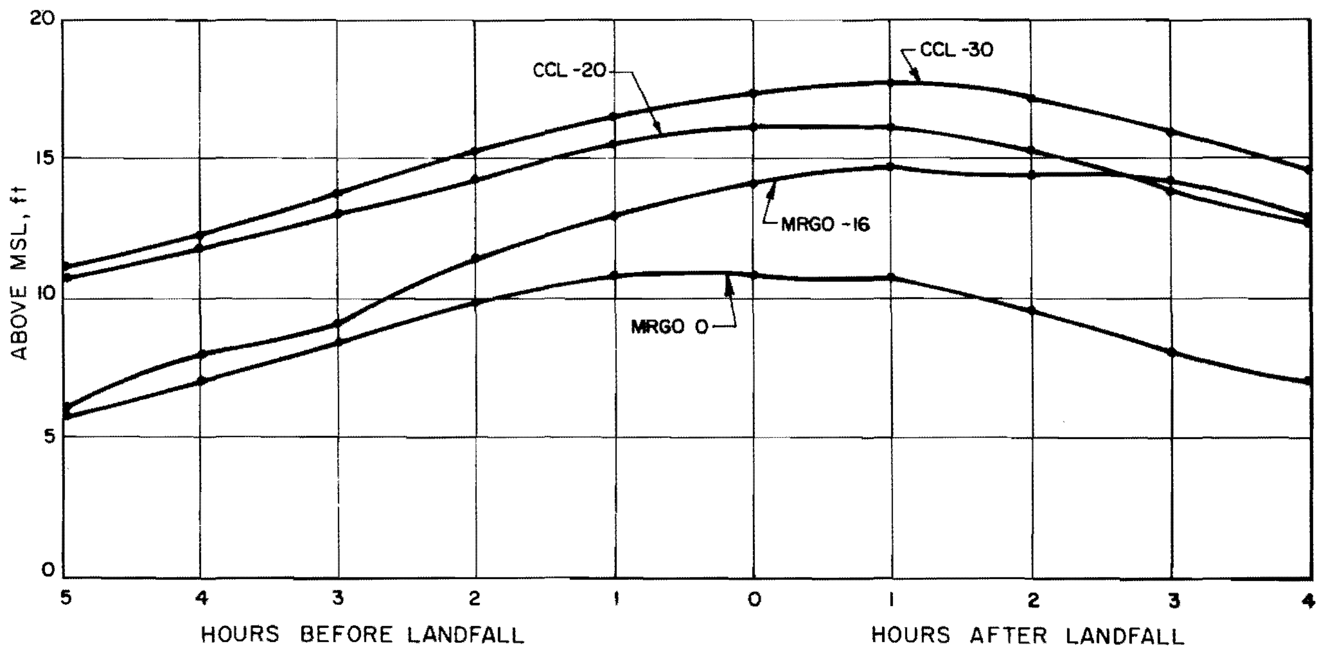


Figure 20

Computed, unadjusted open coast storm surges for SPH on track epsilon

PA-3-10307

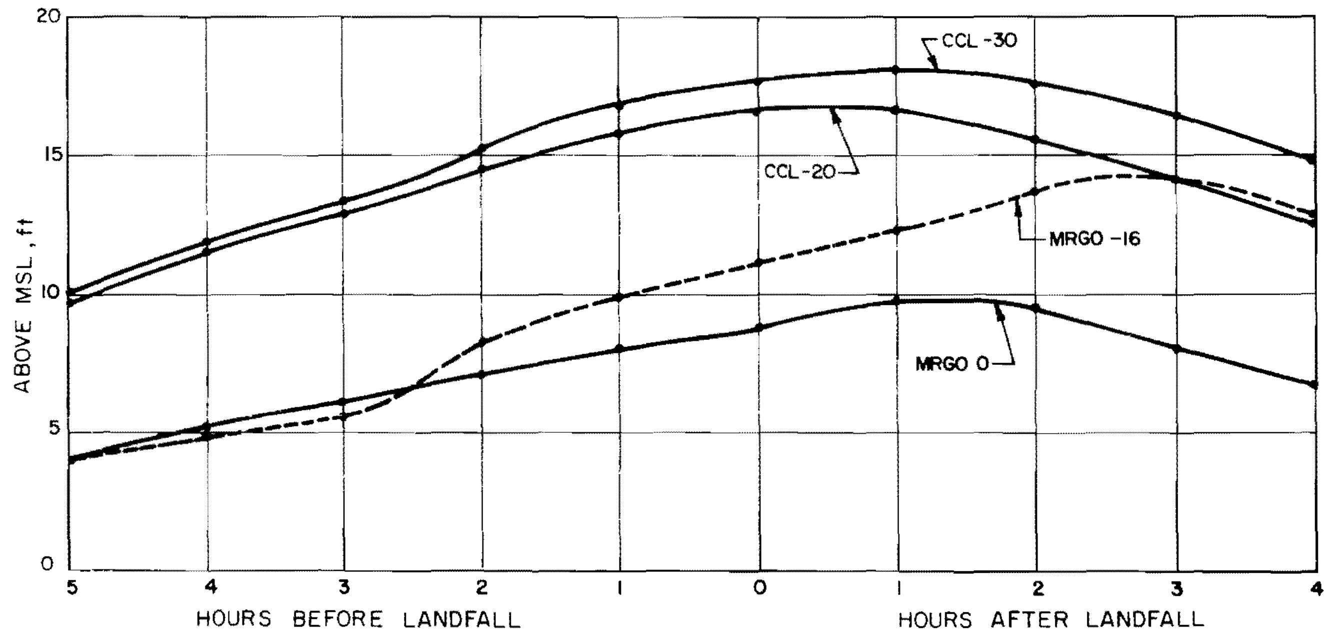


Figure 21

Computed, unadjusted open coast storm surges for SPH on track chi

PA-3-10308

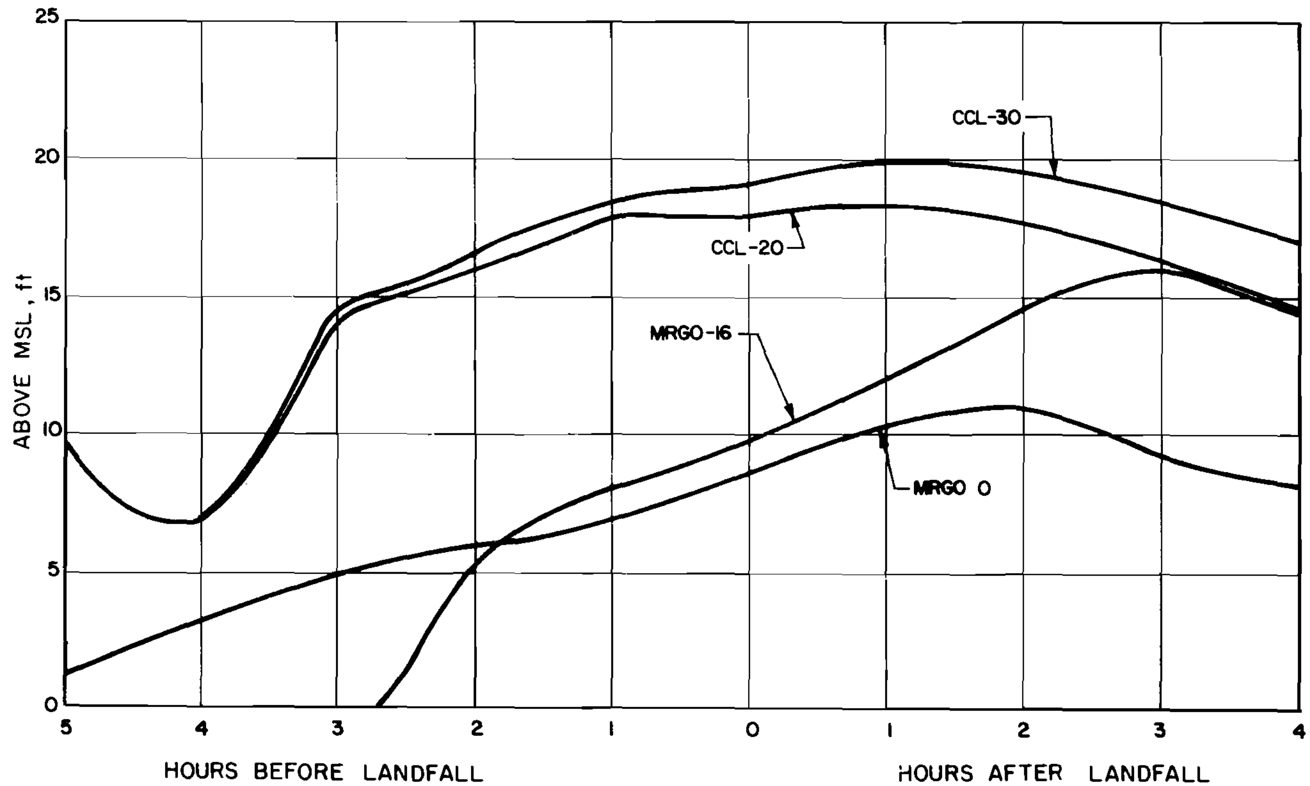


Figure 22

Computed, unadjusted open coast storm surges for PMH on track sigma

PA-3-10309

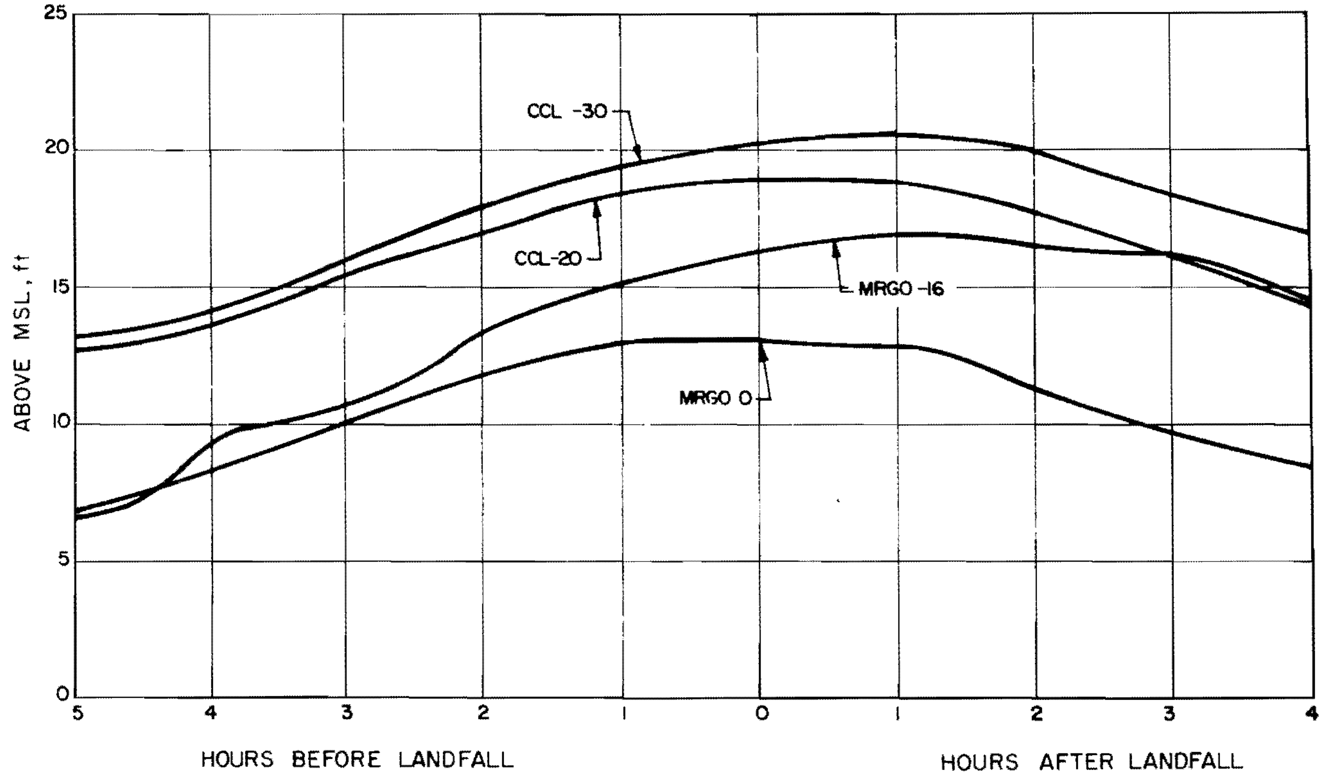


Figure 23

Computed, unadjusted open coast storm surges for PMH on track epsilon

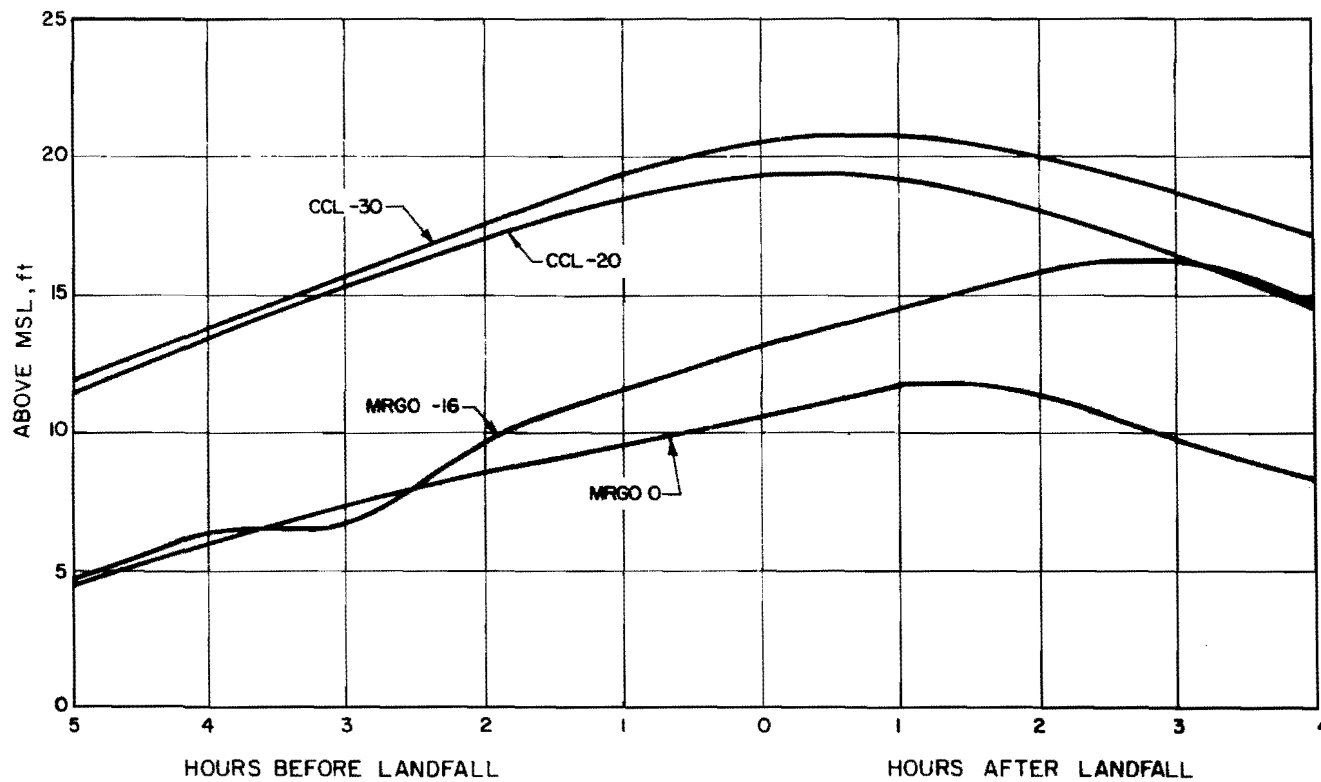


Figure 24

Computed, unadjusted open coast storm surges for PMH on track chi

PA-3-10311

The predictions of the synthetic hurricane storm surge peaks for point C (Paris Road Bridge) using the correlation equation derived in Section 4.3.4 are summarized in Table XII. Values of Case II, point C, taken from Table II are also listed in Table XII for comparison purposes.

TABLE XII

Comparison of Correlation Method with Surge Prediction Method for Point C, Case II

Hurricane	Track	Surge Peak Using Correlation Equation	Surge Peak Using Prediction Factor
SPH	Sigma	10.4	10.3
SPH	Epsilon	11.0	10.5
SPH	Chi	10.6	10.7
PMH	Sigma	11.8	12.0
PMH	Epsilon	12.5	12.4
PMH	Chi	12.2	12.3

5. REFERENCES

Dronkers, J. J. (1964). Tidal Hydraulics in Rivers and Coastal Waters. North Holland Publishing Co. (Div. of John Wiley & Sons, Inc.)

Freeman, J. C., L. Baer and G. H. Jung (1957). "The Bathystrophic Storm Tide." J. Marine Research, Vol. 16, No. 1.

Hellstrom, B. (1941). "Wind Effect on Lakes and Rivers." Inst. of Hydraulics, Roy. Inst. Tech., Stockholm, Bulletin No. 41.

Keulegan, G. H. (1951). "Wind Tides in Small Closed Channels." Nat. Bur. Standards, Res. Paper 2207, Vol. 46, No. 5.

Langhaar, H. L. (1951). "Wind Tides in Inland Waters." Proc., Mid-Western Conference on Fluid Mechanics.

Reid, R. O. (1964). Corps of Engineers, Storm Tide Course, Summer 1964 (Unpublished).

Saville, T. (1952). "Wind Set Up and Waves in Shallow Water." Beach Erosion Board, U. S. Army Corps of Engineers, T. M. 27.

APPENDIX A

COMPUTER PROGRAM FOR BATHYSTROPHIC STORM TIDE EQUATIONS

Logic Flow

1. Read number of stations NX, number of time steps NT, bottom friction factor, wind stress factor, coriolis factor, bottom friction factor for marsh.
2. Read shoreline parameters: azimuth, longitude, latitude and normal pressure.
3. Read hydrography d versus x.
4. Read time card.
5. Read hurricane parameters: longitude, latitude, radius to maximum winds, C.P.I., astronomical tide.
6. Read wind stress components WW_X, WW_Y versus X.

6A. Read initial surge and longshore flow (never used in this study — inserted as a comment card).

7. Repeat from 4 through 6 for number of time steps.
8. Determine X, Y coordinates relative to position of hurricane center and compute the term ΔP in inches of mercury.
9. Write out all input data.
10. Compute Δt. Do through 23 NT times; J = 1, NT.
11. Compute Δx. Do through 22 NX times; I = 1, NX.
12. Compute best estimate of total water depth including astronomical tide, 1.14 ΔP, and storm surge from previous station at this time.
13. Check total water depth. On negative to go 14; on positive go to 15.

14. Dry land. Set surge, discharge and water level to zero. Go to 11.

15. Check depth value. On negative use coefficients for marsh. On positive use coefficients for offshore.

16. Compute longshore discharge, Q(I, J).

17. Compute storm surge, S(I, J).

18. Compute water level above mean sea level, WL(I, J).

19. Check to see if water level plus depth is negative. If yes go to 20. If no go to 21.

20. Dry land. Set water level to zero. Go to 11.

21. Store discharge, surge and water level.

22. Is I = NX? If yes go to 23. If no go to 11.

23. Is J = NT? If yes go to 24. If no go to 10.

24. Write out values of Q(I, J), S(I, J), WL(I, J) for each station and time step.

25. End

Preparation of Input Data for Computer

All input data is on IBM cards prepared according to the following list.

1. Title Card: Any combination of traverse name, numbers, hurricane name, etc. up to 72 characters. Called for in A-Format statement.

2. Coefficients Card:

   a) Number of stations as a fixed point number ending in column 5.

   b) Number of time steps as a fixed point number ending in column 10.

   c) Coefficients of normal bottom friction, wind stress, coriolis and marshland bottom friction. All used as exponential format numbers ending in columns 25, 40, 55, and 70, respectively.

3. Shoreline Parameter Card:

   a) Azimuth of traverse, longitude and latitude. All in floating point format using 10 columns each. Decimal point location is arbitrary.

   b) Normal pressure. 10 digit floating point number, decimal point location is arbitrary.

4. Hydrography Cards: Program requires the number of cards specified in 2 a containing two numbers each: water depth and distance offshore at arbitrary values but in sequence starting from furthest offshore. 10 digit floating point numbers with arbitrary decimal point location. Negative values of depth and distance offshore are permitted.

5. Time Card:

   a) Time of day in hours and decimals. A 10 digit floating point number with arbitrary decimal point location.

   b) Month, day and year contained in columns 11 through 28. A-Format is used such that any combination of 18 letters and numbers is permitted.

6. Hurricane Parameter Card:

   a) Longitude and latitude of hurricane eye. 10 digit floating point numbers with arbitrary decimal point location.

   b) Radius to maximum winds and C.P.I. 10 digit floating point numbers with arbitrary decimal point location.

   c) Astromonical tide. 10 digit floating point number with arbitrary decimal point location.

7. Wind Stress Cards: Number of cards is specified by 2 a. They must be in the same sequence as the hydrography cards (item 4).

The onshore stress component must be listed first and the longshore component second. 10 digit floating point numbers with arbitrary decimal point location.

Cards 5, 6 and sets 7 form one time block. The number of time blocks is specified in item 2b.

The program is set up to perform as many consecutive cases as are loaded at one time. It automatically proceeds with the computation of further storm tide cases starting with item 1. If no more cases are loaded, computing stops.

The total core capacity used by the program in its current form is approximately 17,000 on an IBM 704.

<u>Fortran Listing (following pages)</u>

```
      PROGRAM TIDES
C                                STORM TIDE ( TWO DIMENSIONS )
      DIMENSION DATE(30,3)
      DIMENSION TITLE(12)
      DIMENSION    X(80), T(30), D(80), WWY(80,30), WWX(80,30),
     1 WL(80,30),                      S(80,30),    Q(80,30),   DP(80,30)
      DIMENSION  A(30),HLONG(30),HLAT(30),R(30),PZ(30),XT(80),YT(80)
 9999 CONTINUE
      READ           (5,900)(TITLE(I),I=1,12)                           SRMY
      IF(EOF,5)222,333
  222 CALL EXIT
  333 WRITE             (6,901)(     TITLE(I),I=1,12)
  900 FORMAT(12A6)
  901 FORMAT(1H1,17HSTORM TIDE ALONG ,12A6,8HTRAVERSE//)
      READ           (5, 700) NX, NT, BIGK, SMALLK, F,BIGKL
  700     FORMAT (2I5,4E15.4)
                    WRITE               (6,902)NX,NT,BIGK,SMALLK,F ,BIGKL
  902 FORMAT(///////////4H NX=I5,/4H NT=I5,/4H BK=E15.8,/4H SK=E15.8,/3H
     XF=E15.8,/7H BIGKL=E15.8,/////)
      READ           (5,704)ALFA,SLONG,SLAT,PN
  704 FORMAT(4F10.0)
      WRITE             (6,705)ALFA,SLONG,SLAT,PN
  705 FORMAT(10X,5HALFA=E15.8/10X,6HSLONG=E15.8,/10X,5HSLAT=E15.8,/10X,
     X3HPN=E15.8//)
      NX = NX + 1
      READ           (5, 701) (D(I), X(I),   I=2,NX )
  701     FORMAT (2F10.1)
      DO 1   J=1,NT
      READ           (5, 702) T(J)    ,DATE(J,1),DATE(J,2),DATE(J,3)
  702 FORMAT(F10.0,3A6)
      READ           (5,706)HLONG(J),HLAT(J),R(J),PZ(J),A(J)
  706 FORMAT(5F10.0)
    1 READ           (5, 703) ( WWX(I,J), WWY(I,J), I=2,NX)
  703 FORMAT(2F10.0)
C     READ           (5,703)(Q(I,1),S(I,1),I=2,NX)
C     UPON REMOVAL OF C IN ABOVE CARD ,REMOVE ME (CARD)
      X(1) = X(2)
      E703 = 7.0 / 3.0
C     DEVELOP DP
      COSPHI=COS ((SLAT+HLAT(1))/2.0/57.2958)
      DO 800 J=1,NT
      HLAT(J)=(SLAT-HLAT(J)   )*60.0
  800 HLONG(J)=(SLONG-HLONG(J))*COSPHI*60.0
      ALFA=ALFA/57.2958
      ALFAS=SIN (ALFA)
      ALFAC=COS (ALFA)
      DO 801 I=2,NX
      XT(I)=X(I)*ALFAS
  801 YT(I)=X(I)*ALFAC
      DO 802 I=2,NX
      DO 802 J=1,NT
      DP(I,J)=PN-PZ(J)
      VOILA=SQRT ((HLONG(J)-XT(I))**2+(HLAT(J)-YT(I))**2)
      IF(VOILA-1.0E-15) 802,802,805
  805 DP(I,J)=(DP(I,J)-(PN-PZ(J))*EXP (-R(J)/VOILA))
  802 CONTINUE
C     END DP
C                        -----WRITE OUT INPUT DATA-----
      WRITE             (6,750)
  750 FORMAT(1H1,10X,4HD(I),16X,4HX(I),/)
      WRITE             (6,751)(D(I),X(I),I=1,NX)
```

```
751 FORMAT(2E20.8)
    WRITE              (6,752)(T(J),A(J),HLONG(J),HLAT(J),R(J),PZ(J), J=
   X1,NT)
752 FORMAT(///9X,2H1T,14X,1HA,14X,5HHLONG,10X,4HHLAT,11X,1HR,14X,2HPZ,
   X//(6E15.6))
    WRITE              (6,753)(Q(I,1),S(I,1),XT(I),YT(I),X(I),I=2,NX)
753 FORMAT(1H1,9X,6HQ(I,1),13X,6HS(I,1),14X,5HXT(I),15X,5HYT(I),14X,4H
   1X(I)//(5E20.8))
    DO 666 J=1,NT
    WRITE (6,755) T(J),DATE(J,1),DATE(J,2),DATE(J,3)
755 FORMAT(1H1,10X,F10.0     ,3A6,/,9X,9H WWY(I,J),12X,8HWWX(I,J),12X,
   17HDP(I,J),14X,4HX(I),/)
754 FORMAT(4E20.8)
    WRITE             (6,754) (WWY(I,J),WWX(I,J),DP(I,J), X(I),I=2,NX)
666 CONTINUE
777 J = NT
  2 T(J) = T(J) - T(J-1)
                               IF (T(J)) 3, 3, 4
  3 T(J) = T(J) + 24.0
  4 T(J) = 3600.0* T(J)
    J = J - 1
                               IF ( J - 2 ) 5,2,2
  5 I = NX
 12 X(I) = 6080.0 * ABS   (X(I) - X(I-1) )
    I = I - 1
                               IF ( I - 2 ) 15,15,12
 15 X(2) = X(3)
                               DO  6 J= 2, NT
                               DO  6 I= 3, NX
    PTD1=D(I)-A(J)+1.14*DP(I,J)
    PTD=PTD1+S(I-1,J)
    IF (PTD-0.5)9,9,77
 77 IF(D(I))22,66,66
 22 Q(I,J) = (SMALLK*(WWY(I,J-1)+WWY(I,J))*T(J)/2.0+Q(I,J-1)) /
   1          ( 1.0 + BIGKL* T(J)/PTD**E703 * ABS ( Q(I,J-1)))
    S(I,J) = (SMALLK/(64.34*PTD) *(WWX(I-1,J) + WWX(I,J)) + F* Q(I,J)/
   1                         (32.17 * PTD ) ) * X(I) + S(I-1,J)
    WL(I,J)=PTD1+S(I,J)-0.76-D(I)
    GO TO 33
 66 Q(I,J) = (SMALLK*(WWY(I,J-1)+WWY(I,J))*T(J)/2.0+Q(I,J-1)) /
   1          ( 1.0 + BIGK * T(J)/PTD**E703 * ABS ( Q(I,J-1)))
    S(I,J) = (SMALLK/(64.34*PTD) *(WWX(I-1,J) + WWX(I,J)) + F* Q(I,J)/
   1                         (32.17 * PTD ) ) * X(I) + S(I-1,J)
    WL(I,J)=PTD1+S(I,J)-0.76-D(I)
 33 IF(WL(I,J)+D(I))44,6,6
 44 WL(I,J)=0.0
    GO TO  6
  9 Q(I,J)=0.0
    S(I,J)=0.0
    WL(I,J)=0.0
  6 CONTINUE
             X(2) = X(1)
             DO  7  I = 3, NX
  7          X(I) = X(I-1) - X(I)/6080.0
    DO 8  J=2,NT
             T(J) =AMOD (T(J-1) + T(J)/3600.0 , 24.0)
    IT1=T(J)*100.0
    WRITE              (6,1900)IT1,DATE(J,1),DATE(J,2),DATE(J,3)
1900 FORMAT (1H1,I5,1X,3HCST,1X,3A6,5X,/////1X,10X,1HX,14X,2HWL,14X,
   11HS,14X,1HQ)
    WRITE              (6,2900)(X(I),WL(I,J),S(I,J),Q(I,J),I=3,NX)
```

```
2900 FORMAT (F15.2,2F15.3,F15.2)
   8 CONTINUE
     GO TO 9999
     END
```

APPENDIX B

SYNTHETIC HURRICANE WINDFIELDS

by

M. J. Viehman

In predicting water wave and surge phenomena, a knowledge of the distribution of wind speeds and directions over the interface is essential.

Here a numerical method is developed, utilizing the technique of Goodyear, Nunn, and others to compute the wind speed and direction along a coordinate line through a Standard Project Hurricane in Zones B and C in the Gulf of Mexico, as modified by Hydromet Memo HUR-7-85.

Hydromet Memo HUR-7-85 (November 1965) modified the Standard Project Hurricane (SPH) of National Hurricane Research Project Report No. 33 in Zones B and C in the Gulf of Mexico, with moderate translational speed (MT) to conform with historical data given in Fig. B-1 from Nunn. This figure is a plot of R, the radius of maximum winds in nautical miles against the dimensionless ratio V/V_{max} at some distance from the storm r (also in nautical miles) on semilog paper with lines of constant r drawn to the right of 90 percent of the historical data for the area.

It is seen that any of the lines of equal r are of the form

$$\log_{10} R = m \frac{V}{V_{max}} + \log b \qquad \text{(B-1)}$$

Values of m and b obtained from the lines in Fig. B-1 for the various values of r are plotted in Fig. B-2. The lines are seen to be well described by equations of the form

$$\log m = k \log r + \log C_1 \qquad \text{(B-2)}$$

and

$$\log b = n \log r + \log C_2 \qquad \text{(B-3)}$$

Fitting Eqs. B-2 and B-3 by the least squares criteria gives

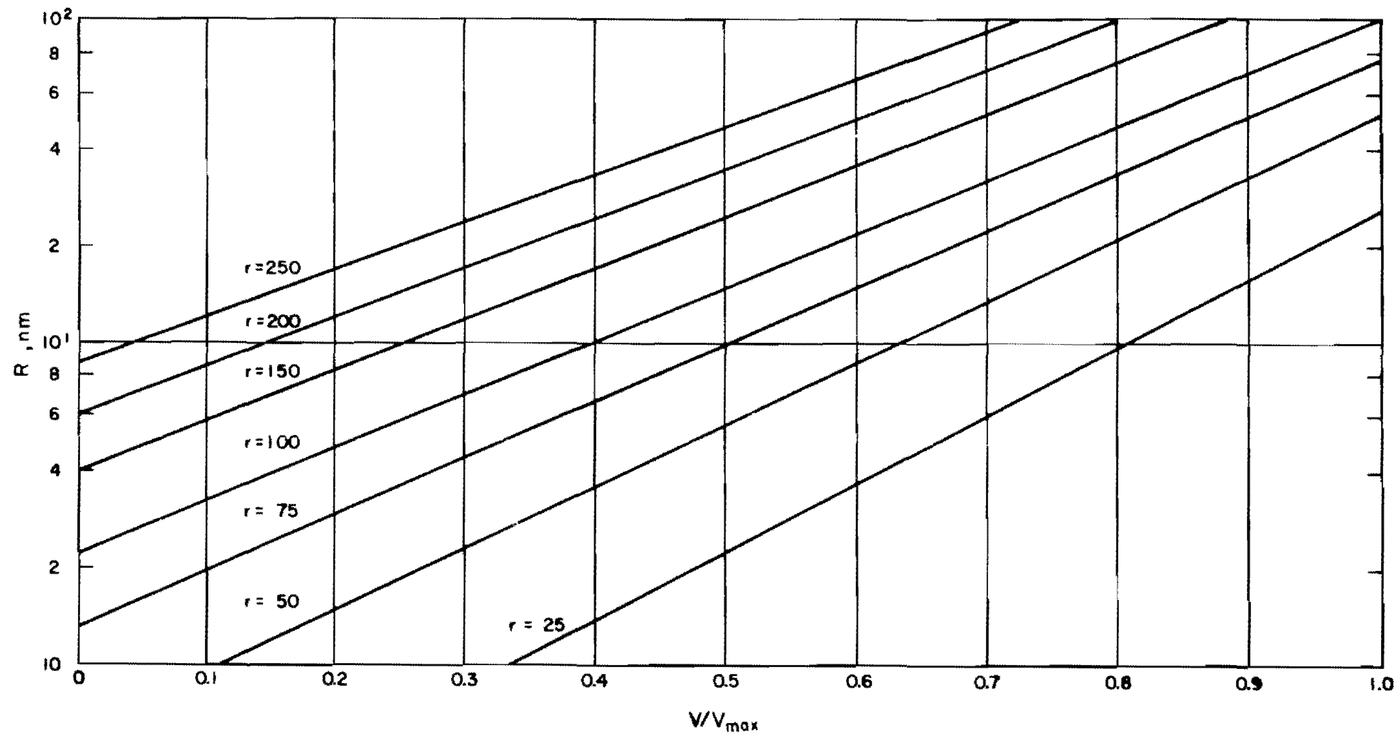


Figure B-1

Hurricane wind field nomograph

PA-3-10312

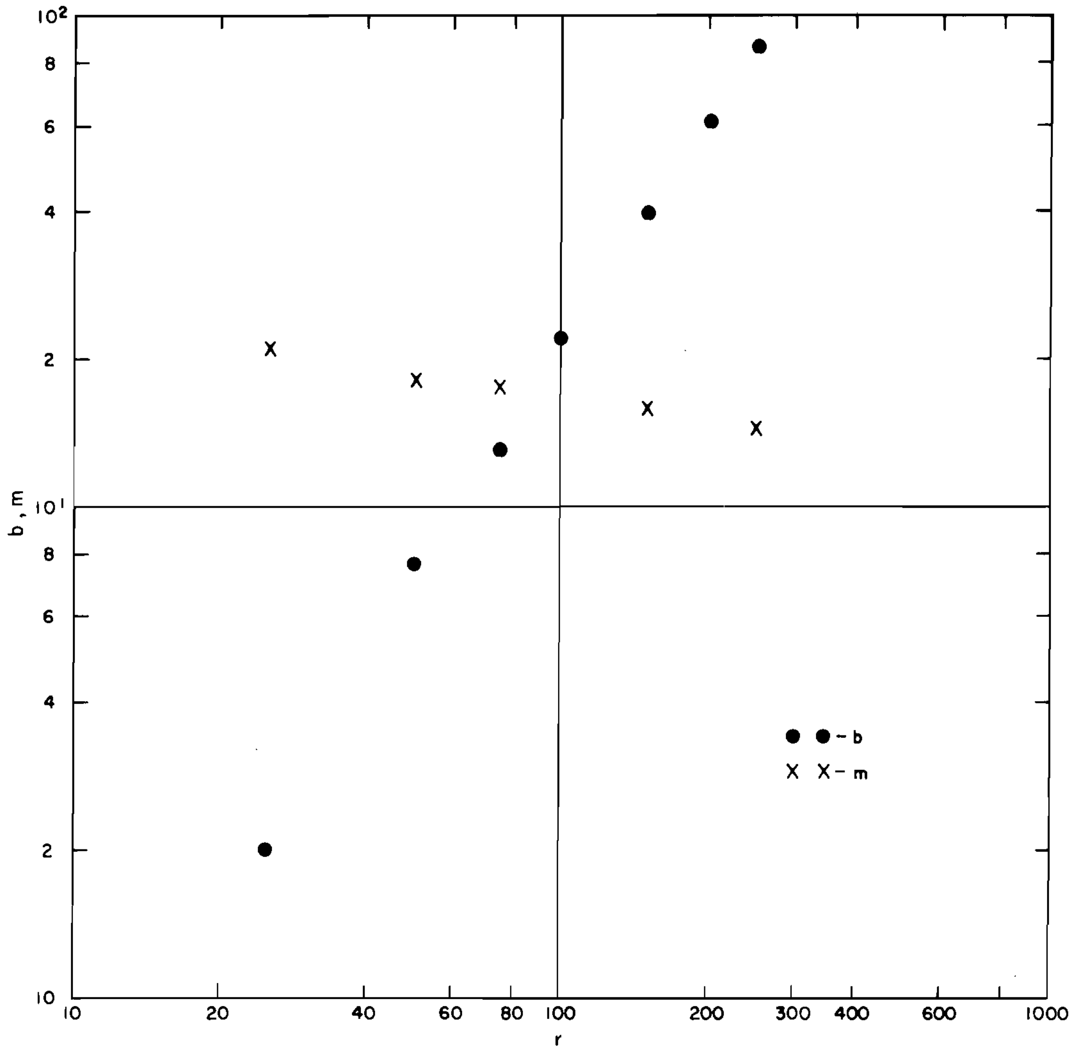


Figure B-2
b and m versus r

PA-3-10313

$$k = -0.15128$$
$$C_1 = 3.354$$
$$n = 1.607$$
$$C_2 = 1.265 \times 10^{-3}$$

yielding from Eq. B-1

$$\log_{10} R = C_1 r^k \frac{V}{V_{max}} + \log_{10} C_2 r^n$$

or

$$V(r) = \frac{V_{max}}{C_1 r^k} \log \frac{R}{C_2 r^n} \qquad \text{(B-4)}$$

where the values k, C_1, C_2, and n were given above.

Equation B-4 evaluates the wind speed along the radial direction from the storm center through the point of maximum wind speed (since at $r = R$, $V = V_{max}$). Figure B-3 shows this direction. For the SPH, which has a wind incurvature angle of 25 degrees, the direction of the section is 115 degrees measured clockwise from the storm direction.

This direction through the maximum wind is taken as $\theta = 0$ degrees and the wind speed distribution around the storm at a constant r is taken to be

$$V(r,\theta) = V_{(r)} - \frac{V_H}{2} (1 - \cos\theta) \qquad \text{(B-5)}$$

so that for equal values of r the wind on the opposite side of the storm ($\theta = 180$ degrees) will be the maximum wind minus the storm velocity.

Equations B-4 and B-5, assuming the incurvature angle of 25 degrees, are sufficient to describe the wind anywhere outside the radius of maximum winds of the storm.

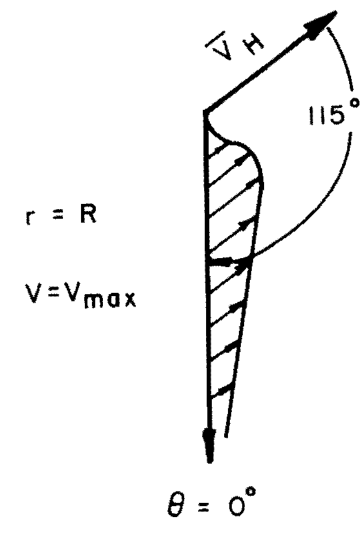


Figure B-3
Radial direction through the maximum wind

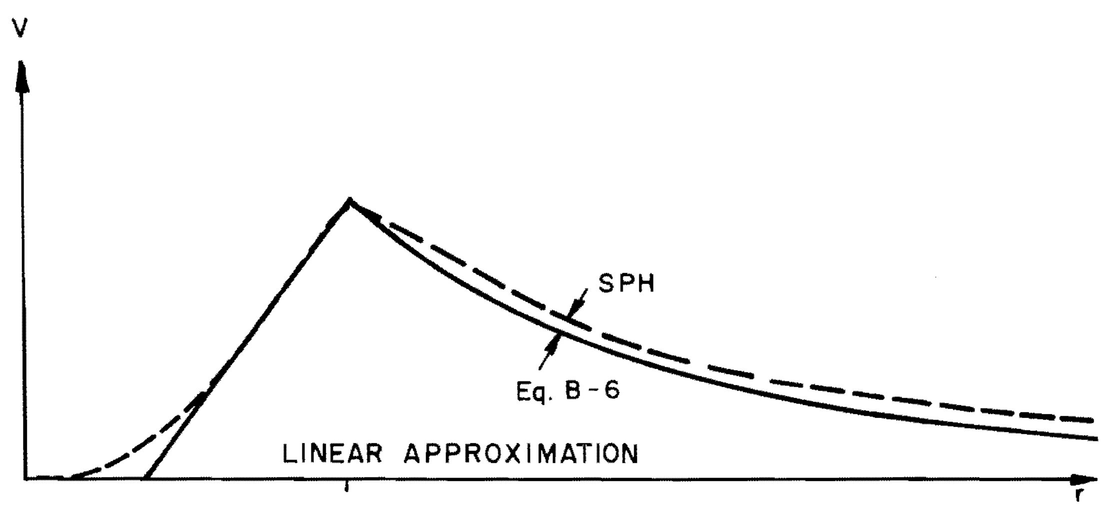


Figure B-4
Sketch of wind profiles for SPH and Eq. B-6

PA-3-10314

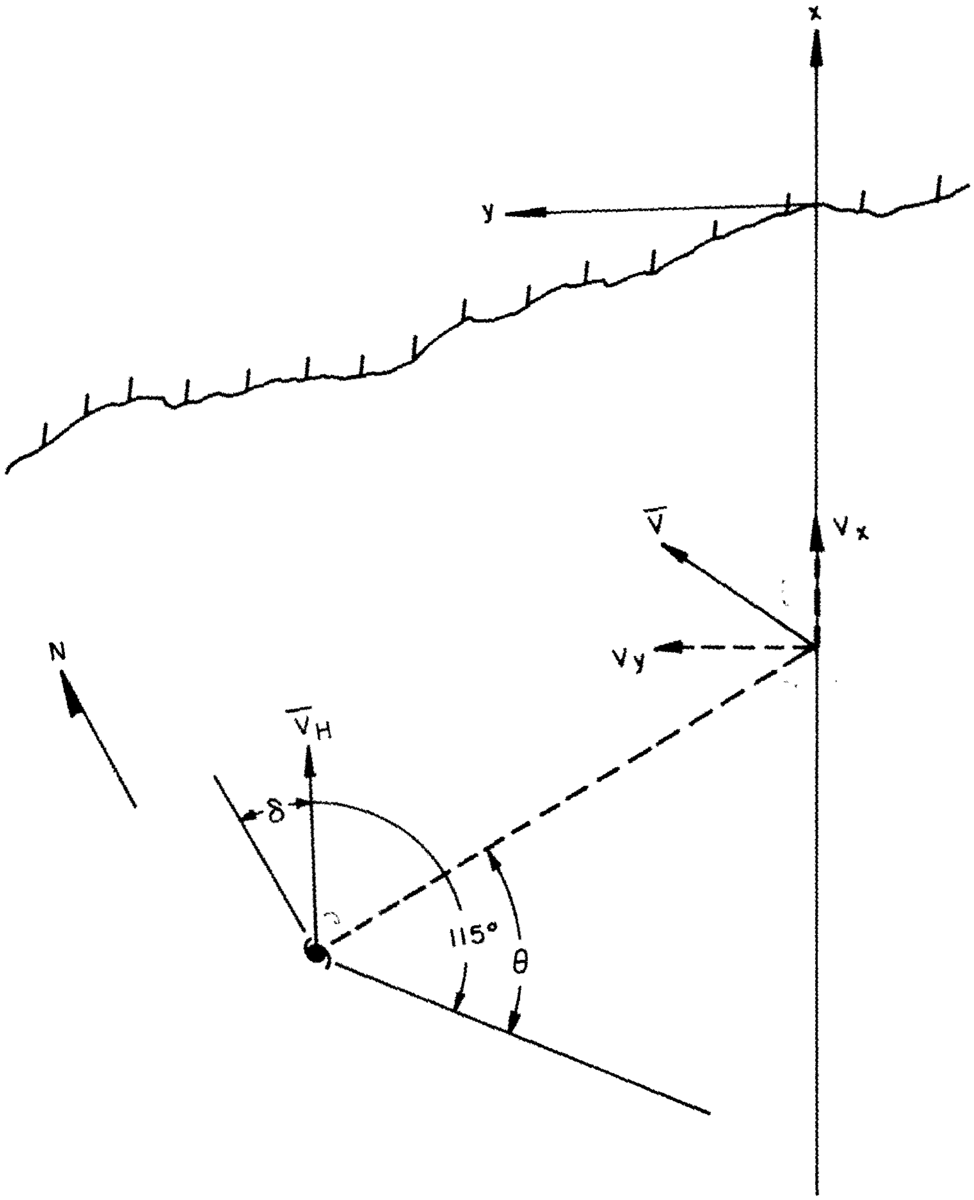


Figure B-5

PA-3-10315

Inside the radius of maximum winds a linear falling off of the velocities will yield a close approximation for surge calculations. Figure B-3 shows this approximation.

It is frequently found useful to specify the wind direction and magnitude by giving its components in some orthogonal system chosen relative to an offshore traverse. Such a system is shown in Fig. B-5.

In order to complete a computational scheme to compute the wind along (V_x) and perpendicular (V_y) to an arbitrary traverse, the relationships between the various angles in Fig. B-5 need to be developed. A relationship between the storm position, specified as the storm's latitude H_{lat} and longitude H_{long}, the position x where the wind is to be computed with the angle θ needs to be derived. Simple addition and subtraction will yield

$$\theta = \delta + 115 \text{ deg} - \gamma \tag{B-6}$$

where

$$\gamma = \tan^{-1} \frac{d_{long}}{d_{lat}}$$

$$d_{long} = H_{long} - X_{long}$$

$$d_{lat} = X_{lat} - H_{lat}$$

and X_{lat} and X_{long} are the position where the wind is to be computed. These are shown in Fig. B-6.

To compute $\cos\theta$ directly without using an inverse function $\left(\text{i.e. } \tan^{-1} \frac{d_{long}}{d_{lat}}\right)$, the trigonometric identity for $\cos(a - b)$ is used where $a = \delta + 115$ degrees (the cosine and sine of a may be calculated once and used through the calculation), and $b = \gamma$. Cos γ is seen to be

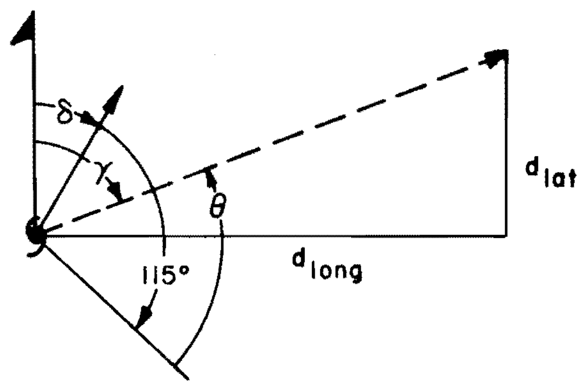


Figure B-6

PA-3-10316

equal to $\frac{d_{lat}}{r}$ and $\sin\gamma$ equal to $\frac{d_{long}}{r}$ if d_{lat} and d_{long} are in nautical miles. To effect this, multiply d_{lat} by 60 and d_{long} by $60 \cos\phi$, where ϕ is the latitude of the hurricane. The result is:

$$\cos\theta = \left[\cos(\delta + 115 \text{ deg})\, d_{lat} + d_{long} \sin(\delta + 115 \text{ deg}) \cos\phi\right] \frac{60}{r} \tag{B-7}$$

Now the angle β that the wind is making with the traverse $(+x)$ must be found. Figure B-7 shows the angles necessary to make the computation. Figure B-8 shows these angles superimposed on one another so it may be seen that

$$\beta = \alpha - \gamma + 90 \text{ deg} + 25 \text{ deg} \tag{B-8}$$

Again, the sine and cosine identities for sums and differences of angles are used giving

$$\cos\beta = \frac{60}{r}\Big[D_{long} \cos\phi\,(\cos\alpha \cos 25 \text{ deg} - \sin\alpha \sin 25 \text{ deg}) - D_{lat}(\cos\alpha \sin 25 \text{ deg} + \sin\alpha \cos 25 \text{ deg})\Big] \tag{B-9}$$

$$\sin\beta = \frac{60}{r}\Big[D_{lat}(\cos\alpha \cos 25 \text{ deg} - \sin\alpha \sin 25 \text{ deg}) + D_{long} \cos\phi\,(\sin\alpha \cos 25 \text{ deg} + \cos\alpha\ 25 \text{ deg})\Big] \tag{B-10}$$

The computer program given in Appendix C uses the aforementioned scheme to compute the wind V, its components V_x and V_y, and the wind stress $V^2 \cos\beta = UU_x$ and $V^2 \sin\beta = UU_y$.

Equations B-8 and B-9 were also used to compute back the V/V_{max} from which they were derived. Samples are shown in Fig. B-9. It is seen that the results tend to be a little low for large values of r in some cases. However, the contribution to the surge or wave phenomena at these low wind speeds is small. Even if the storm is considered stationary,

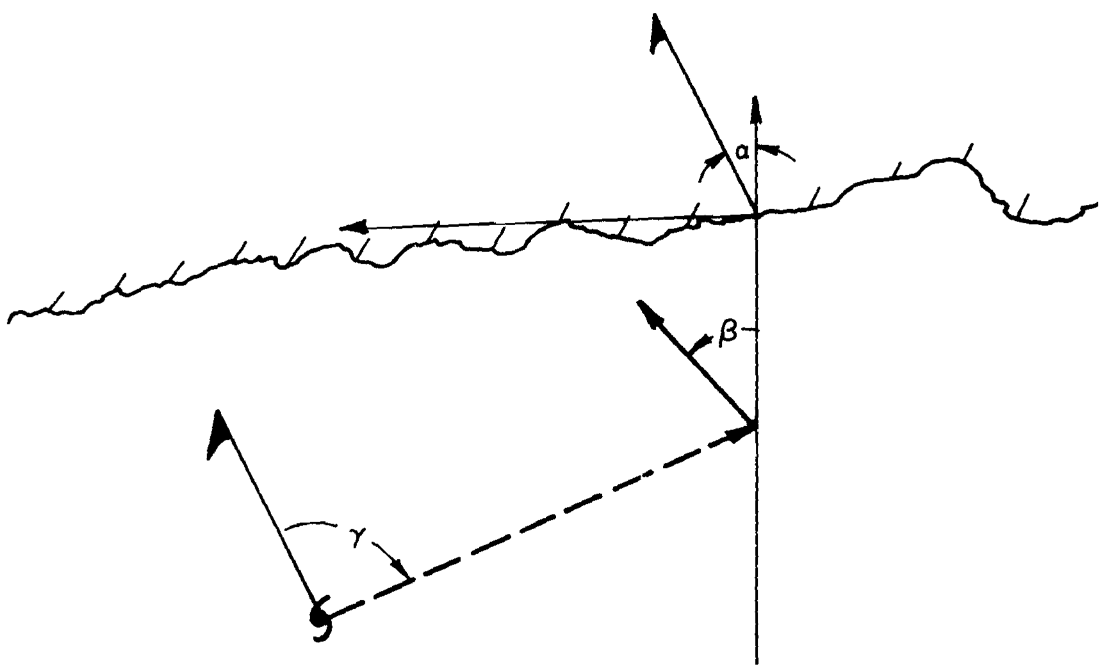


Figure B-7
Angle wind makes with traverse

PA-3-10317

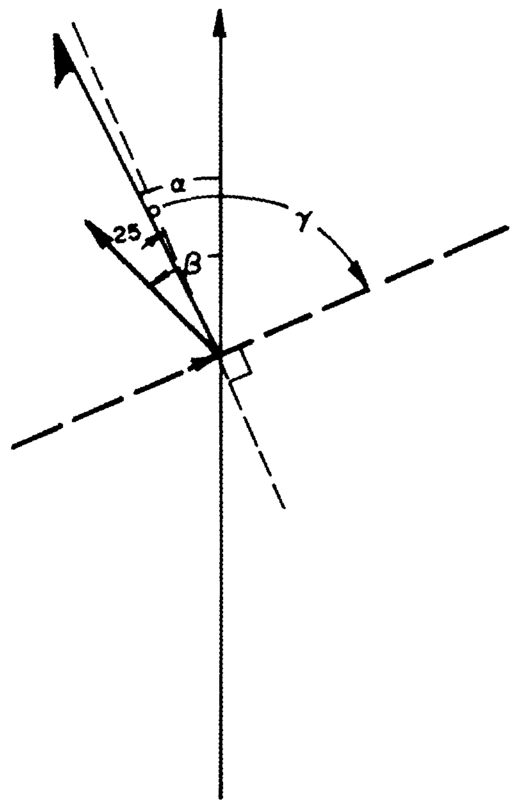


Figure B-8
Superposition of the angles

PA-3-10318

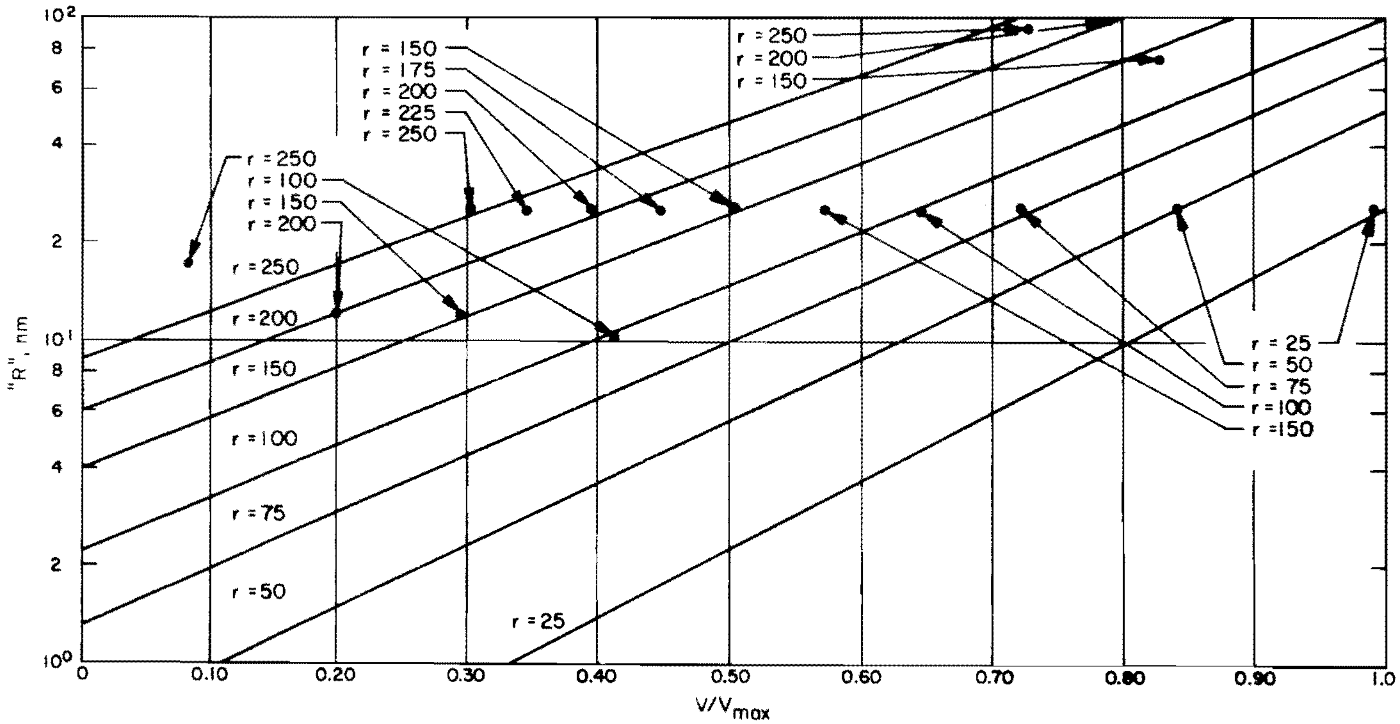


Figure B-9

Comparison of sample point computations using derived equations with hurricane wind speed nomograph

PA-3-10319

which is in violation of the premise, the speed of translation is moderate (MT), steady state values of either surge or wind waves are approached quickly and differences (in heights) are small at these wind speeds.

APPENDIX C

COMPUTER PROGRAM FOR GENERATION OF WIND STRESS COMPONENTS ALONG A TRAVERSE

Introduction

This program is written to solve the equations developed in Appendix B to determine onshore and longshore wind stress components for a project hurricane along a specified traverse. The project hurricane is specified in terms of its latitude, longitude, radius to maximum winds, forward speed, and azimuth of direction of travel. The traverse is specified by its shoreline coordinates and azimuth. Points on the traverse are specified by their distance offshore. The wind stress components are put out on cards which are then used in the storm tide program described in Appendix A.

Logic Flow

1. Read number of time steps, number of stations along traverse, longitude and latitude of traverse and azimuths.
2. Read values for distances offshore of stations for which stress components are required.
3. Write out heading and shoreline parameters.
4. Compute various constants and coefficients required in the equations.
5. Read hurricane parameters at time specified. Repeat through for number of times specified in 1 (N = 1, NT).
6. Write out hurricane parameters.
7. Compute wind stress at point specified. Repeat through for number of stations specified in 1 (I = 1, NX).
8. Write out wind stress components.
9. Punch card containing wind stress components.

10. Return to 7 if station counter is less than NX; otherwise go to 11.

11. Return to 5 if time counter is less than NT; otherwise go to 12.

12. End.

Preparation of Input Data

1. Card Containing:

   a) Number of time steps: fixed point number ending in column 5.

   b) Number of stations on traverse: a fixed point number ending in column 10.

   c) Longitude and latitude of shoreline station (X = 0): two 10-digit floating point numbers. The position of the decimal point is arbitrary.

   d) Azimuth of traverse measured clockwise from the north to the onshore vector: a 10-digit floating point number with arbitrary decimal point location.

2. One card for each station on the traverse. The number of cards is specified in 1 (b). Each card contains the water depth and distance offshore: two 10-digit floating point numbers with arbitrary decimal location. (The water depth is not used in this program but these cards exist from the storm surge program described in Appendix A.) Negative numbers are permitted for overland stations.

3. One card for each time step specified in 1 (a):

   a) Forward speed of hurricane in knots: a 10-digit floating point number with arbitrary decimal point location.

   b) Azimuth of vector of direction of travel of hurricane measured clockwise from north: a 10-digit floating point number with arbitrary decimal location.

c) Longitude and latitude of hurricane eye: two 10-digit floating point numbers with arbitrary decimal location.

d) Radius to maximum winds and maximum wind speed: two 10-digit floating point numbers with arbitrary decimal location.

e) Time: a 10-digit floating point number used to identify the time. In the case of the project hurricanes this was chosen as the number of hours before landfall.

Fortran Listing (following pages)

```
      PROGRAM  WINDS
C     GENERATION OF WIND STRESSES ALONG A TRAVERSE
C     NO. OF TIMES = NT , STATIONS = NX
C     COORDINATES OF SHORE LINE (SLONG, SLAT)
C     AT AZIMUTH ALPHA DEGREES
C     HURRICANE TRAVELLING AT AZIMUTH DELTA, SPEED VH, CENTERED AT HLONG
C         HLAT
C     HURRICANE PARAMETERS, R, CAPR, VMAX,VH
      DIMENSION X(100), TITLE(12)
10000 CONTINUE
      READ INPUT TAPE 5,80,NT,NX,SLONG,SLAT,ALPHA
   80 FORMAT (2I5,3F10.0)
      IF (EOF,5) 1113, 1112
 1112 CONTINUE
      DO 222 I=1,NX
  222 READ INPUT TAPE 5,81,D,X(I)
   81 FORMAT (2F10.0)
      WRITE OUTPUT TAPE 6,83,NT,NX,SLONG,SLAT,ALPHA
   83 FORMAT(     4X,26HWIND STRESS ALONG TRAVERSE,/// 5X,4HNT =,I5,2X,4H
     1NX =,I5,/ 5X,7HSLONG =,F10.3,4X,6HSLAT =,F10.3,/ 5X,7HALPHA =,
     2F10.3)
      RADIAN=0.0174532925
      TENLE=0.4342944819
      C1=3.354
      C2=0.001265
      FK=0.15128
      FN=1.60727
      COSAL=COSF(RADIAN*ALPHA)
      SINAL=SINF(RADIAN*ALPHA)
      SIN25=0.42261826
      COS25=0.90630779
      DO 1111  N=1,NT
      READ INPUT TAPE 5,82,VH,DELTA,HLONG,HLAT,CAPR,VMAX,TIME
   82 FORMAT (7F10.0)
      WRITE OUTPUT TAPE 6,84,VH,DELTA,HLONG,HLAT,CAPR,VMAX,TIME
   84 FORMAT(/ 4X,39HHURRICANE TRAVELLING WITH FORWARD SPEED,F8.2,1X,
     15HKNOTS,/ 5X,10HAT AZIMUTH,F10.3,7HDEGREES,/
     25X,16HCENTERED AT LONG,F10.3,3X,3HLAT,F10.3,/
     35X,21HRADIUS OF MAX WINDS =,F10.3,/
     45X,17HMAX WIND SPEED IS,F10.3,1X,5HKNOTS,/,5X,F10.3,25H  HOURS BEF
     5ORE LANDFALL)
      WRITE OUTPUT TAPE 6,92
   92 FORMAT(// 5X,3HWWX,7X,3HWWY,7X,1HX,9X,1HV,9X,2HVY,6X,2HVX)
      COD115=COSF(RADIAN*(DELTA+115.0))
      SID115=SINF(RADIAN*(DELTA+115.0))
      DO 1111  I=1,NX
      XLAT=SLAT-X(I)*COSAL/60.0
      XLONG=SLONG+X(I)*SINAL/(60.0*COSF(XLAT*RADIAN))
      DLAT=XLAT-HLAT
      PHIBAR=0.5*(XLAT+HLAT)*RADIAN
      DLONG=HLONG-XLONG
      COSPHI=COSF(PHIBAR)
      R=60.0*SQRTF(DLAT**2+(DLONG*COSPHI)**2)
      IF (R-CAPR)1,1,2
    1 IF (R-CAPR/3.0) 3,3,4
    3 V=0.0
      GO TO 5
    4 COSTH=(COD115*DLAT+SID115*DLONG*COSPHI)*60.0/R
      V=((3.0*R-CAPR)/(2.0*CAPR))*(VMAX-VH/2.0*(1.0-COSTH))
      GO TO 5
    2 COSTH=(COD115*DLAT+SID115*DLONG*COSPHI)*60.0/R
```

```
      V=TENLE*VMAX*R**FK/C1*ALOG (CAPR/(C2*R**FN))-VH/2.0*(1.0-COSTH)
    5 VY=V*60.0/R*(DLAT*(COSAL*COS25-SINAL*SIN25)+DLONG*COSPHI*
     1(SINAL*COS25+COSAL*SIN25))
      VX=V*60.0/R*(DLONG*COSPHI*(COSAL*COS25-SINAL*SIN25)-DLAT*
     1(COSAL*SIN25+SINAL*COS25))
      WWX=V*VX
      WWY=V*VY
      WRITE OUTPUT TAPE 2,90,WWX,WWY,X(I),V,VY,VX
      WRITE OUTPUT TAPE 6,91,WWX,WWY,X(I),V,VY,VX
   90 FORMAT (6F10.3)
   91 FORMAT (6F10.2)
 1111 CONTINUE
      GO TO 10000
 1113 CALL EXIT
      END
```

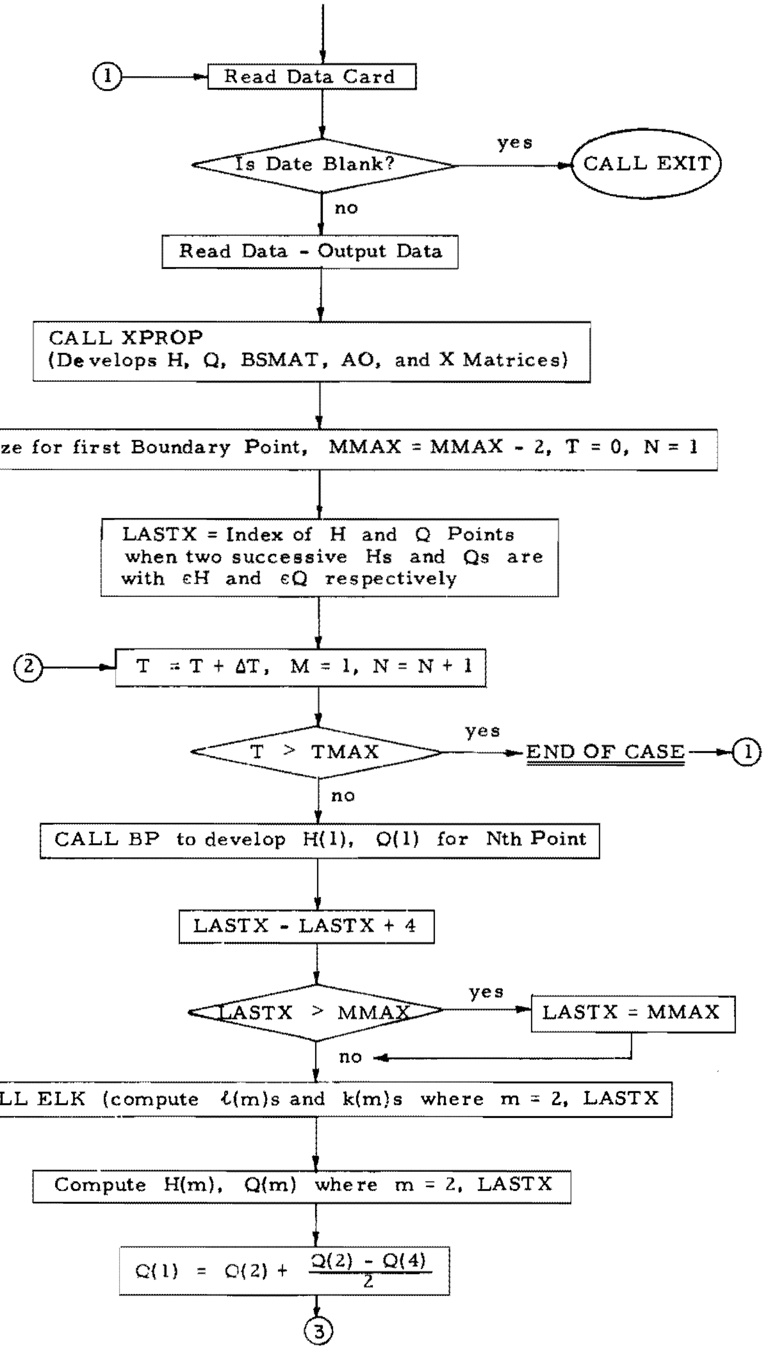
APPENDIX D

COMPUTER PROGRAM FOR SURGE ROUTING IN A CHANNEL

by

Mariann Moore

703A
CHANNEL (Downstream Conditions)



(3)

Set upstream conditions if LASTX = MMAX

$$H(MMAX) = H(MMAX - 1) + \frac{H(MMAX - 1) - H(MMAX - 2)}{2}$$

$$H(MMAX + 1) = H(MMAX - 1)$$

$$Q(MMAX - 1) = \frac{Q(MMAX - 2)}{2}$$

$$Q(MMAX) = 0 \qquad Q(MMAX + 1) = - Q(MMAX - 1)$$

H(M) > 1000 — yes → ERROR MESSAGE → (1)

If it is time to print output results for time = T, and if IDEBMP - 1, ℓ k results will be printed.

LASTX = Index of H and Q Points when two successive Hs and Qs are within εH and εQ respectively when values from LASTX - 4 to LASTX are checked.

(2)

```
      PROGRAM CHANNEL
C     DOWNSTREAM VERSION  (705A)
C      CHANNEL SURGE IN THE MISSISSIPPI RIVER GULF OUTLET-SN526-705
C     STORAGE OF L AND K MATRICES L1,M-1     L1,M     L1,M+1  ,ETC
C                                 L2,M-1     L2,M     L2,M+1  ,ETC
C                                 L3,M-1     L3,M     L3,M+1  ,ETC
C                                 L4,M-1     L4,M     L4,M+1  ,ETC
C     IF CHANGE IN TWO SETS OF H AND Q LESS THAN EPS, VALUES OF LS AND
C     KS ARE ASSUMED EQUAL AT THE TWO POINTS
C     NTABLE=NO OF ENTRIES IN THE TABLES B,AZERO,AND THE INITIAL VALUE
C     MATRICES HH(X) AND QQ(X) -- T=0
C     A(H,X) DEFINED AS BS(X) .H
C     NHO=NO OF ENTRIES IN THE INITIAL VALUE MATRIX HO(T)--X=0
C     MMAX = NUMBER OF GIVEN X STATIONS
      DIMENSION HH(100),QQ(100)
      DIMENSION XX(100),AZERO(100),B(100),TT(100),C2(600),A0(600),
     1HO(100),H(600),Q(600),ELMAT(4,600),CAYMAT(4,600),X(600),AMAT(600),
     2 BSMAT(600)
      COMMON A0,AZERO,B,C2,XX,FMARSH, FCHANN,IC2,
     1HO,TT,X,H,Q,ELMAT,CAYMAT,AMAT,BSMAT,ALPHA,ACON,G
    1 READ (5,8000) NDA,NMO,NYR
      IF (NDA) 99,99,2
    2 READ (5,8000) NTABLE,NHO,MMAX,NPRTX,        IDEBBP,IDEBMP
      READ (5,8001) G,ALPHA,ACON,DT,DX,XMAX,TMAX,DTPRT,EPSH,EPSQ,FMARSH
     1,FCHANN ,CASEK,C2ZERO
 8001 FORMAT(7F10.0)
 8000 FORMAT (7I10)
      READ (5,8001) (XX(I),I=1,NTABLE)
      READ (5,8001)(  B(I),I=1,NTABLE)
      WRITE (6,2000) NMO,NDA,NYR,ALPHA,FCHANN,FMARSH,DT,DX,TMAX,XMAX,
     1DTPRT,EPSH,EPSQ,G
 2000 FORMAT (1H1,27X,     51H CHANNEL SURGE IN THE MISSISSIPPI RIVER GUL
     1F OUTLET,5X,I2,1H/,I2,1H/,I2,//,  15H  INERTIA COEF.,8X,6HFCHANN,
     211X,27HFMARSH           T INCREMENT   ,  4X,11HX INCREMENT,8X,12HTIME
     3MAXIMUM,6X,9HX MAXIMUM/,1X,7E17.8/,1H0,25HPRINTING INCREMENT IN T
     4=,E14.4,5X,25HQUITTING TOLERANCE IN H =,E14.4,5X,25HQUITTING TOLER
     5ANCE IN Q =,E14.4,/,51X,4H G =,E15.8,//)
 2001 FORMAT (37X,2E20.8)
      WRITE (6,2002)
 2002 FORMAT (1H1,48X,1HX,12X,16HSURFACE WIDTH BS,/)
      WRITE (6,2001) (XX(I),  B(I),           I=1,NTABLE)
      READ (5,8001) (TT(I),I=1,NHO)
      READ (5,8001) (HO(I),I=1,NHO)
      WRITE (6,2007)
 2007 FORMAT (1H1,47X,24HINITIAL CONDITION AT X=0,/,49X,2H T,17X,5HHO(T)
     1,/)
      WRITE (6,2008) (TT(I),HO(I),I=1,NHO)
 2008 FORMAT (37X,2E20.8)
      READ (5,8001)(HH(I),I=1,NTABLE)
      READ (5,8001)(QQ(I),I=1,NTABLE)
      DO 30 I=1,MMAX
      H(I)=0.0
   30 Q(I)=0.0
C     DEVELOP H(X), Q(X),BS(X),AND A0(X) MATRICES AND X(M) MATRIX
      CALL XPROP (MMAX,NTABLE,DX,HH,QQ)
      WRITE (6,2009)
 2009 FORMAT (1H1,38X,24HINITIAL CONDITION AT T=0,/,19X,2H X,19X,1HH,
     1 19X,1HQ,18X,2HBS,18X,2HA0,/)
      WRITE (6,2011) (X(I),H(I),Q(I),BSMAT(I),A0(I),I=1,MMAX)
 2011 FORMAT( 7X,5E20.8)
      WRITE (6,2012)
```

```
 2012 FORMAT(1H1)
C      INITIALIZE FOR FIRST BOUNDARY POINT
       ISTART=1
       MMAX=MMAX-2
       T=0.0
       TPRINT=DTPRT
       N=1
       HA=H(1)
       X=0.0
C      FIND LAST POINT IN H,Q LINE AT T=0
       IQUIT=-1
       DO 290 I=1,MMAX
       INDEX=I
       IF (ABS(H(I+1)-H(I))-EPSH) 211,211,300
  211  IF (ABS(Q(I+1)-Q(I))-EPSQ) 220,220,300
  220  IQUIT=IQUIT+1
       IF (IQUIT) 290,290,300
  290  CONTINUE
       LASTX=MMAX
       GO TO 310
  300  LASTX=INDEX
C      RETURN LOOP FOR NEW T(N)
  310  IQUIT=-1
       T=T+DT
       IF (T-TMAX) 320,320, 315
  315  WRITE (6,2030) T,TMAX,DT
 2030  FORMAT(1H1,24H****CASE FINISHED****T =,E15.8,5X,6HTMAX =,E15.8
      1,5X,4HDT =,E15.8,/,1H1)
       GO TO 1
  320  HOLD=H(1)
       QOLD=Q(1)
       QOLDER = QOLD
       M=1
       INDEX=1
       N=N+1
C      OBTAIN BOUNDARY POINT X=0, M=1, H=HO(T)
       CALL BP(N,HOLD,QOLD,QOLDER,T,ISTART,NHO,IDEBBP)
       HNEW=H(1)
       IF (HNEW-1000.0 ) 322,322,321
  321  WRITE (6,2031) INDEX,T
 2031  FORMAT(34H ****ERROR****HO(T) BLOWS UP AT M=,I4,6H    T =,E15.8)
       GO TO 1
  322  QNEW=Q(1)
       H(1)=HOLD
       Q(1)=QOLD
       LIST=0
       IF (TPRINT-T) 330,330,340
  330  LIST=1
       TPRINT=TPRINT+DTPRT
  340  LASTX=LASTX+4
       IF (LASTX-MMAX)360,350,350
  350  LASTX=MMAX
  360  CALL ELK(LASTX,DX,DT,MMAX,CASEK,C2ZERO)
       L4=LASTX-4
       IPRINT=0
       H(1)=HNEW
       Q(1)=QNEW
  362  DO 365 M=2,LASTX
       H(M)=H(M)   +( ELMAT(1,M)   + ELMAT(4,M)   +2.0*( ELMAT(2,M)
      1  +ELMAT(3,M)   ))/6.0
       Q(M)=Q(M)   +(CAYMAT(1,M)   +CAYMAT(4,M)   +2.0*(CAYMAT(2,M)
```

```
     1 +CAYMAT(3,M)   ))/6.0
 365 CONTINUE
     Q(1)=Q(2)+0.5*(Q(2)-Q(4))
     IF (LASTX-MMAX) 371,370,370
 370 MM=MMAX-1
     MP=MMAX+1
     H(MMAX)=H(MM)+0.5*(H(MM)-H(MM-2))
     H(MP)=H(MM)
     Q(MM)=0.5*Q(MM-1)
     Q(MMAX)=0.0
     Q(MP)=-Q(MM)
 371 DO 500 M=1,LASTX
     INDEX=M
     IF (H(M)-1000.0)  374,374,321
 374 IPRINT=IPRINT+1
     IF (LIST) 400,400,375
 375 IF (IPRINT-NPRTX) 400,380,380
 380 IF (M-1) 381,381,382
 381 WRITE (6,2010) T,DT
2010 FORMAT( //,4H T =,F10.1,5X,4HDT =,F10.1,//6X,2H M,6X,4HX(M),9X,
    14HH(M),13X,4HQ(M),10X,12HA(H(M),X(M)),4X,13HC2(H(M),X(M)),10X,
    21HE,13X,1HK,/)
 382 WRITE (6,2020)M,X(M),H(M),Q(M),AMAT(M),C2(M)
2020 FORMAT(I9,F10.1,2E17.7,E18.6,E17.6)
     IPRINT=0
     IF (IDEBMP) 400,400,390
 390 WRITE (6,2025)                   (ELMAT(K,M),CAYMAT(K,M),K=1,4)
2025 FORMAT(91X,2E14.5)
 400 CONTINUE
     IF (M-1) 500,500,396
 396 IF (M-L4)500,395,395
 395 IF (ABS(H(M)-H(M-1))-EPSH) 410,410,500
 410 IF (ABS(Q(M)-Q(M-1))-EPSQ) 420,420,500
 420 IQUIT=IQUIT+1
     IF (IQUIT) 500,500,430
 430 DO 450 I=INDEX,LASTX
     H(I)=H(LASTX)
 450 Q(I)=Q(LASTX)
     LASTX=INDEX
     GO TO 310
 500 CONTINUE
     GO TO 310
  99 CALL EXIT
     END
     SUBROUTINE BP(N,HOLD,QOLD,QOLDER,T,ISTART,NHO,IDEBBP)
C    DOWNSTREAM VERSION   (703A)
     DIMENSION XX(100),AZERO(100),B(100),TT(100),C2(600),A0(600),
    1HO(100),H(600),Q(600),ELMAT(4,600),CAYMAT(4,600),X(600),AMAT(600),
    2 BSMAT(600)
     COMMON A0,AZERO,B,C2,XX,FMARSH, FCHANN,IC2,
    1HO,TT,X,H,Q,ELMAT,CAYMAT,AMAT,BSMAT,ALPHA,ACON,G
C    BP FINDS THE FIRST POINT AT X=0,M=1, H=HO(T(N))
C    BP SETS UP THE NEXT ISTART, AOLD, AND BSOLD
C    ISTART=STARTING PLACE IN TABLE HO(T)
     DO  100 I=ISTART,NHO
     INDEX=I
     IF (T-TT(I)) 130,110,100
 100 CONTINUE
 110 H(1)=HO(INDEX)
     ISTART=INDEX
     GO TO 150
```

```
130 IM=INDEX-1
    H(1)=HO(IM)+(HO(INDEX)-HO(IM))*(T-TT(IM))/(TT(INDEX)-TT(IM))
    ISTART=IM
150 HH=H(1)
    BS=BSMAT(1)
    AMAT(1)=BS*HH +ACON
    DH=H(1)-HOLD
    ELMAT(1,1)=DH
    IF (N-1) 160,160,170
160 CAYMAT(1,1)=0.0
    GO TO 175
170 CAYMAT(1,1)=QOLD-QOLDER
175 DO 200 I=2,4
    CAYMAT(I,1)=CAYMAT(1,1)
200 ELMAT(I,1)=DH
 99 RETURN
    END
    SUBROUTINE ELK(LASTX,DX,DT,MMAX,CASEK,C2ZERO)
C     DOWNSTREAM VERSION   (703A)
    DIMENSION XX(100),AZERO(100),B(100),TT(100),C2(600),A0(600),
   1HO(100),H(600),Q(600),ELMAT(4,600),CAYMAT(4,600),X(600),AMAT(600),
   2 BSMAT(600)
    COMMON A0,AZERO,B,C2,XX,FMARSH, FCHANN,IC2,
   1HO,TT,X,H,Q,ELMAT,CAYMAT,AMAT,BSMAT,ALPHA,ACON,G
C     ELK DEVELOPS L1 THROUGH 4 AND K1 THROUGH 4 AT POINTS X(M=2)
C     THROUGH X(M=LASTX) FOR ONE VALUE OF T(N)
    DX2=2.0*DX
    DO 500 K=1,4
    JSTART=1
    DO 500 M=2,LASTX
    IF (M-LASTX) 90,50,50
 50 IF (K-1)90,90,60
 60 LAST=LASTX+1
    KM=K-1
    IF (LASTX-MMAX) 80,85,85
 80 ELMAT(KM,LAST) = ELMAT(KM,LASTX)
    CAYMAT(KM,LAST)=CAYMAT(KM,LASTX)
    GO TO 90
 85 CAYMAT(KM,LAST)=-CAYMAT(KM,LASTX-1)
    ELMAT(KM,LAST) =  ELMAT(KM,LAST-2)
 90 GO TO (100,200,200,300),K
100 ADDL=0.0
    ADDK=0.0
    ADDDH=0.0
    ADDDQ=0.0
    GO TO 400
200 ADDK=0.5 * CAYMAT(K-1,M)
    ADDL=0.5 *  ELMAT(K-1,M)
    ADDDH=0.5*( ELMAT(K-1,M+1)  - ELMAT(K-1,M-1))
    ADDDQ=0.5*(CAYMAT(K-1,M+1)  -CAYMAT(K-1,M-1))
    GO TO 400
300 ADDK=CAYMAT(3,M)
    ADDL= ELMAT(3,M)
    ADDDH= ELMAT(3,M+1)- ELMAT(3,M-1)
    ADDDQ=CAYMAT(3,M+1)-CAYMAT(3,M-1)
400 XARG=X(M)
    HARG=H(M)+ADDL
    BS=BSMAT(M)
    A=BS*HARG +ACON
    IF (HARG) 401,402,402
401 C2(M)=C2ZERO
```

```
      GO TO 403
  402 ETA=(((BSMAT(M)-CASEK)*(FMARSH**1.5)+CASEK*(FCHANN**1.5))/BSMAT(M)
     1)**0.66666667
      C2(M)=((1.486/ETA)**2)*((A0(M)+HARG)**0.3333333)
  403 IF (K-1) 410,410,420
  410 AMAT(M)=A
  420 DHDX=(H(M+1)-H(M-1)+ADDDH)/DX2
      DQDX=(Q(M+1)-Q(M-1)+ADDDQ)/DX2
      QATM=Q(M)+ADDK
  440 ELMAT(K,M)=-DT*DQDX/BS
  450 APLUSH=A0(M)+H(M)+ADDL
      FRICT=1.0/C2(M)
      CAYMAT(K,M)=DT*(-G*A*DHDX-QATM*(G*ABS(QATM)*FRICT/APLUSH+
     1 ALPHA*DQDX)/A)
  500 CONTINUE
   99 RETURN
      END
      SUBROUTINE XPROP (MMAX,NTABLE,DX,HH,QQ)
C     DOWNSTREAM VERSION   (703A)
      DIMENSION HH(100),QQ(100)
      DIMENSION XX(100),AZERO(100),B(100),TT(100),C2(600),A0(600),
     1H0(100),H(600),Q(600),ELMAT(4,600),CAYMAT(4,600),X(600),AMAT(600),
     2 BSMAT(600)
      COMMON A0,AZERO,B,C2,XX,FMARSH, FCHANN,IC2,
     1H0,TT,X,H,Q,ELMAT,CAYMAT,AMAT,BSMAT,ALPHA,ACON,G
C     XPROP DEVELOPS THE MMAX VALUES OF THE VECTORS A0,BSMAT,H,Q(X) ANDX
C     GIVEN THE NTABLE VALUES OF THE VECTORS AZERO,B,HH,QQ,AND XX
      X(1)=0.0
      ISTART=1
      DO 500 K=1,MMAX
      DO 300 I=ISTART,NTABLE
      INDEX=I
      IF (X(K)-XX(I)) 350,250,300
  300 CONTINUE
  250 BSMAT(K)=B(INDEX)
      H(K)=HH(INDEX)
      Q(K)=QQ(INDEX)
      ISTART=INDEX
      GO TO 400
  350 IM =INDEX-1
      FACTOR=(X(K)-XX(IM))/(XX(INDEX)-XX(IM))
      BSMAT(K)=B(IM)+(B(INDEX)-B(IM))*FACTOR
      H(K)=HH(IM)+(HH(INDEX)-HH(IM))*FACTOR
      Q(K)=QQ(IM)+(QQ(INDEX)-QQ(IM))*FACTOR
      ISTART=IM
  400 FACTOR=K
      KP=K+1
      A0(K)=ACON/BSMAT(K)
  500 X(KP )=FACTOR*DX
   99 RETURN
      END
```

APPENDIX E

DERIVATION OF THE PLANFORM FACTOR

In a converging channel such as Study Area A, there will be a change in tide from one end to the other, depending on the degree of convergence. Although Study Area A is an open-end channel, it will be convenient to consider the problem as a closed channel, and then make the necessary allowances.

Langhaar (1951) discussed the problem of a closed channel and defined a planform factor N which could be applied to a channel of constant width and depth in order to arrive at the wind setup for a channel of variable width and depth. The wind setup was given by

$$S = N \frac{k\, U^2\, L}{2\, g\, D} \qquad \text{(E-1)}$$

where

S is the setup

L is the length of the channel

D is the depth.

The planform factor N is equal to unity for a channel of constant width and depth. 2S is the total difference in elevation between the downwind and the upwind end of the channel as shown in Fig. E-1.

Langhaar considered a number of special geometrically shaped closed channels, including those having converging sides and sloping bottoms. However, for the marshland of Study Area A, the depth is constant, and it appears that the sides can be represented by the simply mathematical expression

$$B = B_o\, e^{-2aX} \qquad \text{(E-2)}$$

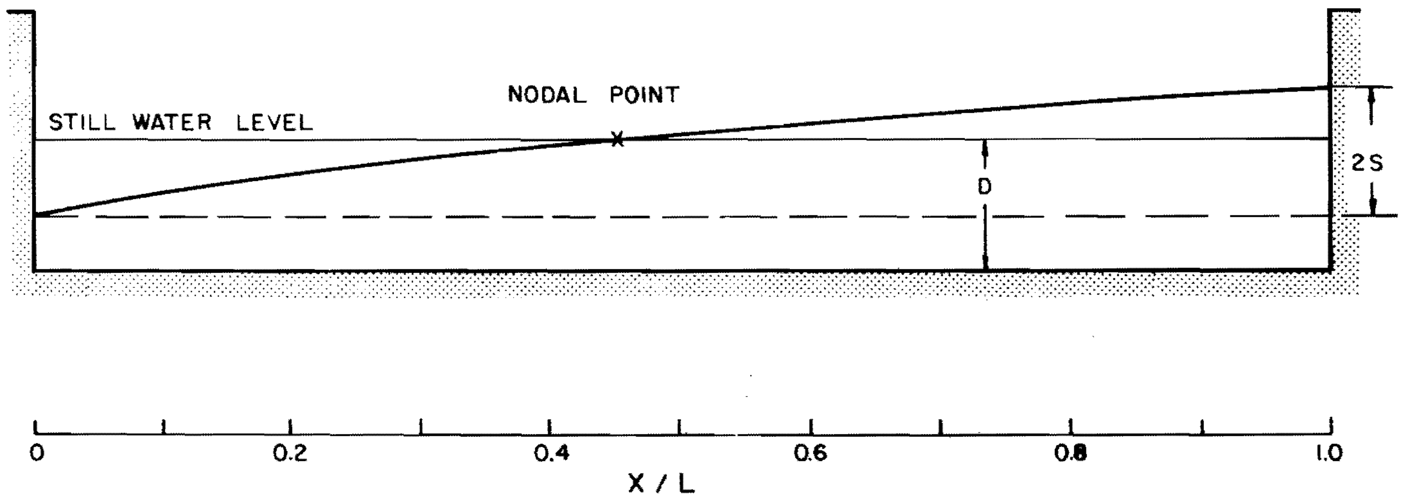


Figure E-1
Wind setup in close channel

where B is the width of the channel at distance X measured from B_o, the width at the beginning of the channel.

The integration of the above equation results in

$$S = \frac{k\,U^2\,X}{gD} + \text{const} = \frac{N\,k\,U^2 L}{2\,g\,D} \tag{E-3}$$

where L is the length of the channel. The constant of integration can be determined from

$$\int_0^L B\,S\,d\,X = A_s\,D \tag{E-4}$$

where A_s is the area of the surface (A_s D = volume of water).

If we let a = α/L in Eq. E-2, by use of Eq. E-4 one obtains, after minor algebra,

$$S = \frac{k\,U^2\,L}{2\,g\,D}\left[1 - \frac{(e^{2\alpha} - 1) - 2\alpha}{2\alpha\,(e^{2\alpha} - 1)}\right] \tag{E-5}$$

whence

$$N = 2\left[1 - \frac{(e^{2\alpha} - 1) - 2\alpha}{2\alpha\,(e^{2\alpha} - 1)}\right] \tag{E-6}$$

For $\alpha = 0$, the planform is rectangular $B_L/B_o = 1.0$ and N = 1.0.

The above development is one for a channel closed at both ends. If we consider a channel open at the entrance to the marshland, then an approximation (linear relationship) can be given by shifting the surface profile so that the original (- S) coincides with the mean water level, thus, the setup at the upper end of the marshland will be twice that given for the open channel. This is illustrated in Fig. E-2.

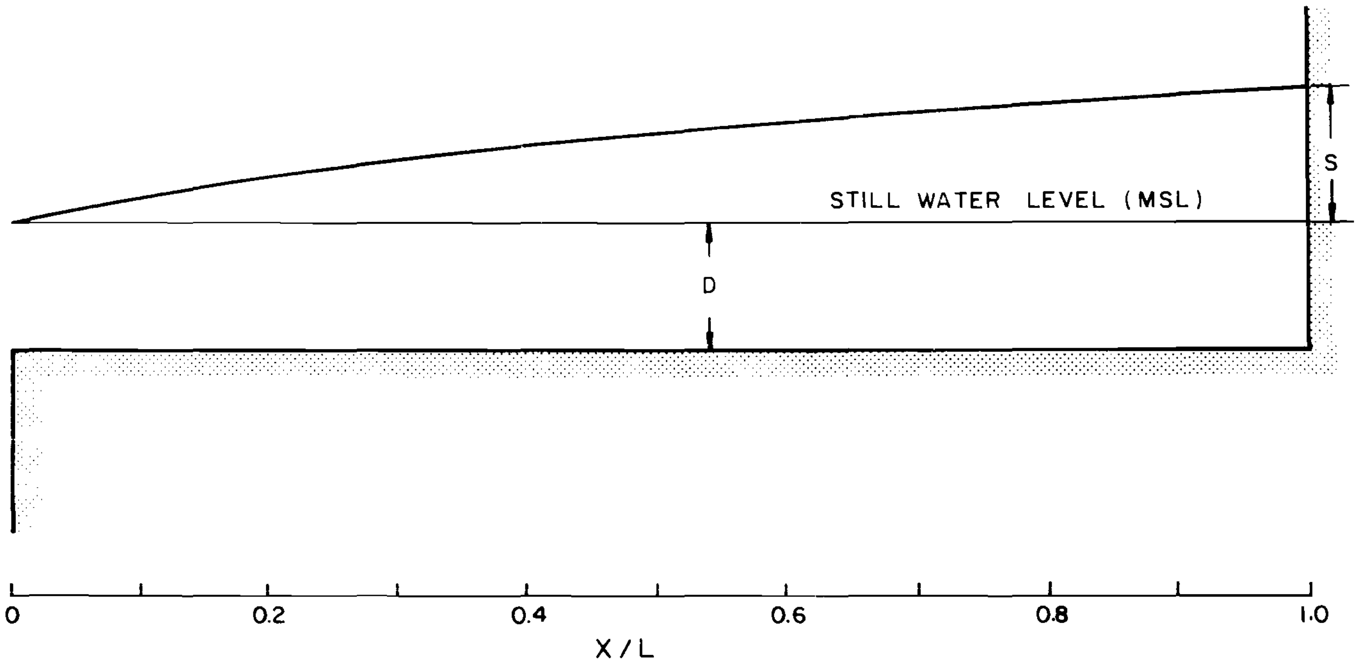


Figure E-2

Wind setup in channel with open entrance

PA-3-10321

Another way to look at the problem (Fig. E-2) is to take $L = L/2$ since the nodal point is shifted from the middle of the closed channel (Fig. E-1) to the entrance of the open channel (Fig. E-2). In either case, dS/dX is assumed to be the same for both the closed and the open channel for the same wind speed.

Thus, for an open rectangular channel of constant width and depth, the setup will be twice that given by Eq. E-5 whence

$$S = \frac{k\,U^2\,L}{g\,D}\left[1 - \frac{(e^{2\alpha} - 1) - 2\alpha}{2\alpha\,(e^{2\alpha} - 1)}\right] \tag{E-7}$$

and the planform factor is still the same as given by Eq. E-6.

A partial planform factor $N\,(X/L)$ can be found by solving the integral of Eq. E-4 between 0 and X, in which case α of Eq. E-6 is replaced with $\alpha\,(X/L)$.

The planform factor N can be solved for by assuming α and calculating b_o/L_L from Eq. E-2 for $X/L = 1.0$, whence $B_o/B_L = e^{2\alpha}$ or $\alpha = 1/2\ \ell n\ B_o/B_L$. Figure E-3 shows relationships for N as a function of B_o/B_L.

For the marshlands of Study Area A, it appears that B_o and B_L are approximately 11 miles and 1.1 miles wide, respectively. At least using these values there seems to be reasonable agreement of the real boundaries with the theoretical boundaries given by Eq. E-2. From Fig. E-3 it is seen that there can be a large change in B_o for large B_o/B_L values without having much effect on the planform factor.

For the special case of $B_o/B_L = 0.1$, the partial planform factor $N\,(X/L)$ is shown in Fig. E-4. From this, it is seen that the maximum value of the planform factor, the upper reach of the marsh, is about 1.36; a considerable tolerance is permitted for the exact value of V_o since N does not change much for B_o/B between about 0.9 and 1.2, for example.

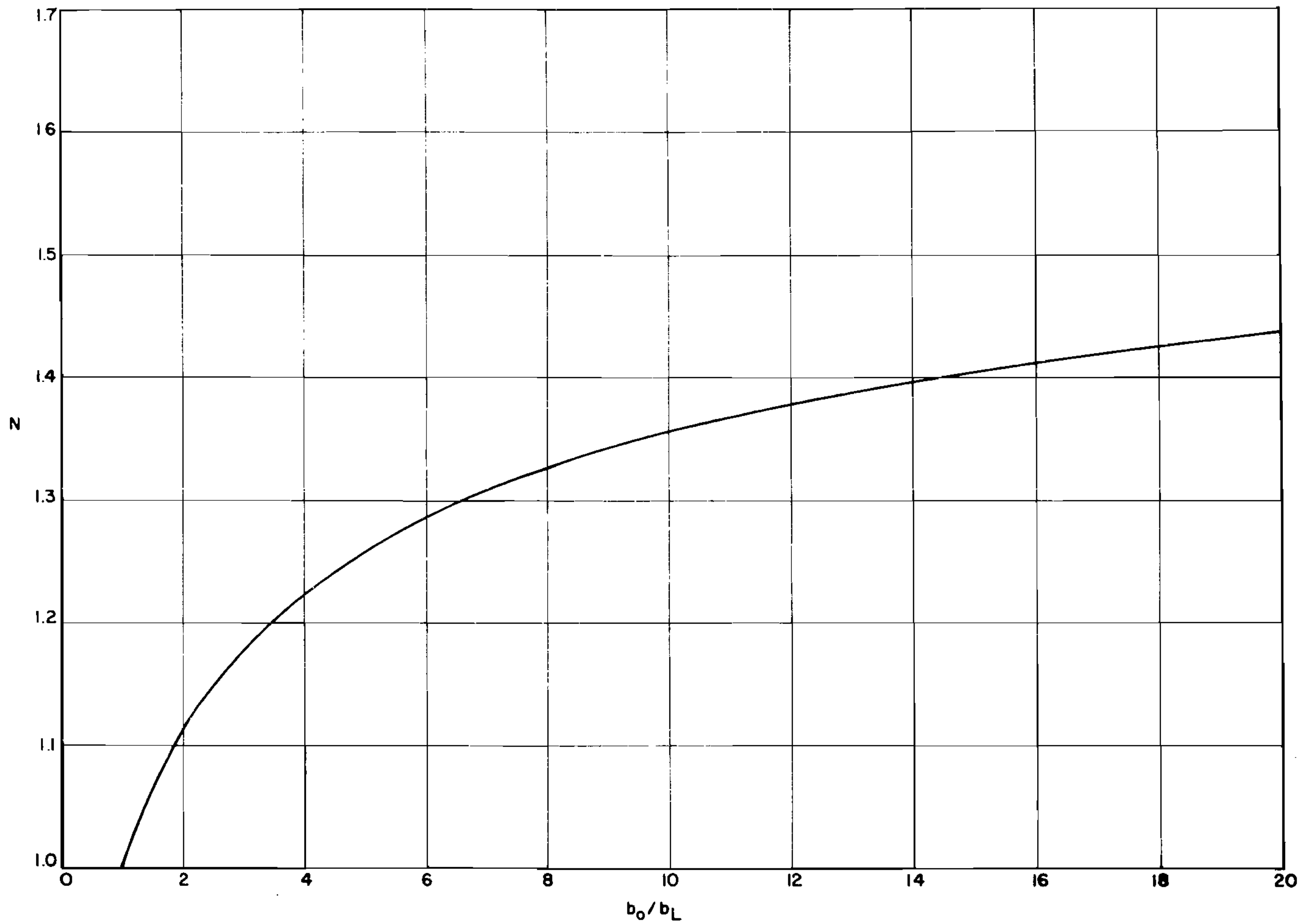


Figure E-3

PA-3-10322