Storm Surge on the Open Coast: Fundamentals and Simplified Prediction

by

B. R. Bodine

TECHNICAL MEMORANDUM NO. 35
MAY 1971

U. S. ARMY, CORPS OF ENGINEERS
COASTAL ENGINEERING
RESEARCH CENTER

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ABSTRACT

Open-coast storm-surge computations are of value in planning and constructing engineering works in coastal regions. A quasi-two-dimensional numerical model for such computations is discussed from the standpoint of the model's underlying assumptions, range of validity, calibration, and application. When using simple numerical schemes of this sort, it is possible to make computations manually, although electronic digital calculations are generally preferred.

Elementary aspects of hurricanes and the physical factors governing storm generation processes are discussed. To display the principle characteristics of the model from a physical as well as a mathematical point of view, the basic hydrodynamic equations are given, together with the assumptions generally taken in their development. The equations consistent with the model described here are reduced forms of the basic equations in which several terms have been neglected. These omissions are indicated, and their effects on the resulting numerical scheme are discussed.

The use of design hurricanes for engineering studies is treated. Effects of astronomical tide, initial water level, and atmospheric-pressure setup are considered.

An open-coast storm-surge problem is solved for the Chesapeake Bay Entrance near Norfolk, Virginia. Calculations are made both by computer and manually. The computer program used is listed.

FOREWORD

This report is published to provide a simplified method for computations of open-coast storm-surge to be used by engineers as a basis for construction of protective coastal works. Examples of electronic digital and manual calculations were used to arrive at computations based on a quasi-two-dimensional numerical model.

This report was prepared by B. R. Bodine, an engineer with the Coastal Engineering Research Center, under the general supervision of George M. Watts, Chief, Engineering Development Division and R. A. Jachowski, Chief, Design Branch.

At the time of publication, Lieutenant Colonel Edward M. Willis was Director of CERC; Thorndike Saville, Jr. was Technical Director.

NOTE: Comments on this publication are invited. Discussion will be published in the next issue of the CERC Bulletin.

This report is published under authority of Public Law 166, 79th Congress, approved July 31, 1945, as supplemented by Public Law 172, 88th Congress, approved November 7, 1963.

CONTENTS

ILLUSTRATIONS

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ERRATA

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Page 13 Equation (8) - replace U^2 with V^2

Page 14 Equation (11) - should read:

$$\frac{\partial S}{\partial x} = \frac{1}{gD} \left[f\ V + k\ W^2 \cos\theta \right]$$

Page 16 Equation (15) - lower part should read:

$$t = t_o + \sum_{i=1} (\Delta t)_n$$

Page 19 Starting at the 18th line should read:

Thus, the y-component of volume transport becomes

$$V \leq \sqrt{\frac{D^2 k\ W^2 \sin\theta}{2\ K}}$$

At the new time level, the above equation can be written as

$$\left|V^{n+1}_{i+\frac{1}{2}}\right| \leq \sqrt{\frac{\left|(B_i + B_{i+1})^{n+1}\right| (D^2)^{n+1}_{i+\frac{1}{2}}}{2\ K}}$$

Page 21 Equation (25) - should read:

$$(\Delta S_x)^{n+1}_{n+\frac{1}{2}} = \frac{203\ \Delta x}{D^{n+1}_{n+\frac{1}{2}}} (A_i + A_{i+1})$$

Page 27 First line, last word should be "phasing".

LIST OF SYMBOLS

A, B	kinematic forms of wind stress components for a given position and time.
C	$\sqrt{gd}$ = shallow-water wave speed.
CPI	central pressure index.
d	depth of undisturbed fluid.
D	total depth of fluid for a given position and time.
e	Napierian base = 2.71828.....
f	Coriolis parameter = $2\omega \sin\phi$
g	acceleration of gravity
H_B	height of surface breaking wave
i	ordinal number used in designating discrete position along traverse line.
IM	maximum ordinal number i employed.
j	ordinal number used in designating computational points along traverse line which is positioned at $(i + 1/2)\,\Delta x$
k	dimensionless wind stress coefficient presumed to vary with wind speed.
K_1, K_2	constants used in the relation defining k
K	dimensionless dissipation factor
L	wavelength
M	a term used in describing advection of mementum
n	ordinal number used in defining the time level
NM	maximum ordinal number n employed
p	atmospheric pressure in a hurricane at some radial distance from the storm center
p_n	atmospheric pressure at periphery of storm
p_o	atmospheric pressure at storm center

P	precipitation rate (depth/time)
PMH	Probable Maximum Hurricane
r	radial distance from storm center
R	radius of maximum winds
R_E	radius of earth
S	elevation of water surface relative to datum level at a given position and time.
$S_{\Delta p}$	setup due to atmospheric pressure difference
S_A	setup due to the astronomical tide
S_e	initial water level
S_L	setup at shore due to local features
S_T	total setup at shore
S_W	setup due to breaking waves = αH_B
S_x	x-component of setup
S_y	y-component of setup
SPH	Standard Project Hurricane
t	time
t_o	initial time
u	x-component fluid velocity
U	x-component of volume transport per unit width
v	y-component of fluid velocity
V	y-component of volume transport per unit width
$\mathbb{V}$	fluid velocity
V_F	forward speed of hurricane

V_{gx}	maximum gradient wind speed
V_x	maximum overwater wind speed
W	wind speed
W_c	critical wind speed used in relation for k
x, y, z	Cartesian coordinates

GREEK LETTERS

α	dimensionless coefficient for breaking waves
γ	dimensionless resistance coefficient used in describing bottom and surface stresses
Δ	increment of
θ	angle between wind vector and x-axis
κ	maximum gradient wind speed coefficient
ξ	atmospheric pressure deficit
π	3.14159
ρ	density of water
$\sum$	summation of
τ	force per unit area, or stress
τ_{sx} τ_{bx}	x-component of surface and bottom stress, respectively
τ_{sy} τ_{by}	y-component of surface and bottom stress, respectively
ϕ	earth's latitude
ω	angular velocity of earth = $2\pi/24$ radians per hour

STORM SURGE ON THE OPEN COAST: FUNDAMENTALS AND SIMPLIFIED PREDICTION

by

B. R. BODINE

Section I. INTRODUCTION

Coastal engineers concerned with design problems frequently are required to estimate the storm surge - the rise of water levels on the open coast caused by high winds acting over the Continental Shelf. On the East and Gulf coasts of the United States the most significant rise at the shore is generally associated with the fully developed hurricanes. Here we shall be concerned principally with those hurricanes, although any lesser storm is equally applicable, and surge can readily be estimated by the same methods. The total rise at the shore is dependent on the interactions of the meteorological storm with the sea and the state of the sea during the passage of the storm. Estimating the response of the sea from forces induced by the moving hurricane is complex; practical results are only obtained by accepting approximations. Several open-coast, storm-surge prediction schemes have evolved, particularly in the past three decades, based on various approaches, such as empirical relations, method of characteristics, statistical and numerical schemes. Quantitative agreement between any of the methods and observations is not yet completely satisfactory from the standpoint of coastal engineering design. In the past decade, numerical schemes have generally been used exclusively for predicting storm surge.

High-speed data processing has brought more sophisticated numerical methods to the forefront in many scientific fields. Such methods yield a solution for the more complete and more complex non-linear partial differential equations appropriate to the particular problem. Such techniques have accelerated the study of long-wave motion, and in particular tidal computations. Various schemes, using the method of finite differences, have evolved for resolving the governing hydrodynamic equations in two-dimensions and some in quasi-three dimensions. The open-coast surge problem has been treated among others by Miyazaki (1963), Leendertse (1967), and Jelesnianski (1966, 1967, and 1970). On a smaller scale, Platzman (1958) has used such a method to compute the surge on Lake Michigan resulting from a moving pressure front, and Reid and Bodine (1968) have treated the hurricane-surge problem in Galveston Bay. Such methods describe the storm generation processes in a much more satisfactory manner than those more frequently used by coastal engineers. Such numerical schemes are mentioned here to emphasize their importance, and it is anticipated that in the near future they will replace the less descriptive schemes such as the one which will be discussed here.

The numerical method covered here is based on the theory developed by Freeman, Baer and Jung (1957) which was referred to as the Bathystrophic

Storm Tide Theory. It can be described as a quasi-two-dimensional numerical scheme for predicting open-coast storm surge. The method is a steady-state integration of the wind stress from the edge of the Continental Shelf, taking into account some of the effects of the alongshore flow caused by the earth's rotation. The development of this scheme was an improvement over the older one-dimensional schemes which neglected the flow alongshore. The simplicity of the Bathystrophic approximation is due to the fact that integration steps can be carried out in a manner analogous to the one-dimensional problem. The advantage of employing such a scheme is that all computations can be made manually without too much mathematical endeavor. The computational procedure can be further simplified by using electronic data processing. Furthermore, the electronic computer used does not require a very large memory capacity.

Bretschneider and Collins (1963) used the theory developed by Freeman, Baer and Jung to predict the open-coast surge at Corpus Christi, Texas, and vicinity. Marinos and Woodward (1968), with some modifications of the model used by Bretschneider and Collins, computed surge hydrographs for various locations along the entire Texas coast. The numerical model described herein is somewhat different than those used by the above investigators.

There are, however, disadvantages to using simplified schemes such as the Bathystrophic approximation since some physical processes are neglected in the storm-generation problem. For some actual conditions this simplified scheme gives a reasonable estimate of the open-coast surge; for other conditions, it may not be satisfactory at all. Thus, at the expense of taking a more simple approach to resolving the open-coast storm surge problem, a computational procedure is obtained which may not always be useful in practice. Consequently, such a procedure is restricted to a certain type of surge problem, depending upon the characteristics of the shelf involved and the behavior of the meteorological storm. To display the limitations of the Bathystrophic theory we will discuss the principal underlying assumptions that lead to the theory and the effects resulting from the various approximations.

Procedures and methods used to compute the open-coast surge for actual hurricanes and hypothetical hurricanes are covered. Also covered are the criteria for establishment of the design water level at a particular site on the coast. A numerical example of computing the open-coast surge is included to further illustrate the method.

Section II. ON PREDICTION OF STORM SURGE

1. General

When a basin of water, such as a sea, lake, bay or estuary is disturbed by some forcing mechanism, there will be a transient motion to at least a portion of the water contained in the system. This sort of fluid motion is referred to as a *surge*, and can produce large variations of the water surface, especially in the shallower regions of the basin. Among the known mechanisms that cause surges are submarine earthquakes which generate tsunamis, a large mass of earth sliding into the water, edge waves, and storms. Here we shall be concerned with tropical storms, and generally with emphasis placed on the surges associated with a hurricane.

The name, hurricane, applies to migratory cyclones which originate in the tropical regions over the oceans near the equatorial zone. Such storms are referred to by different names throughout the world, although their origin, structure, and behavior are essentially the same. A *hurricane* is called a *typhoon* in much of the Pacific Ocean, a *tropical cyclone* in the Bay of Bengal and the Arabian Sea, and a *willy-willy* off the coasts of Australia. A tropical storm is said to become a fully developed hurricane when the maximum wind speed equals 75 miles per hour (65 knots) or more than 12 on the Beaufort scale of wind force. A hurricane is essentially a heat engine, thus implying the existence of a heat source and a cold source. Its development, intensification and dissipation has yet to be fully understood, although considerable knowledge has been gained in our present century. It is beyond the scope of this paper to present the known complex mechanisms which govern the hurricane; however, we will mention some of the elementary characteristics primarily from the standpoint of those related to the induced surge.

Because of the direction of earth's rotation, the hurricane has a cyclonic wind circulation which is counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. The wind system just above the water surface is circular, having an average diameter of about 400 miles across to the gale winds of 40 miles per hour and approximately 100-mile diameter to the hurricane force winds. Moreover, the wind system extends upward in a dome-like configuration to a maximum elevation of about 6 miles or more.

At the center of wind rotation and just above the surface is a region of relative calm called the eye of the hurricane which extends vertically upward through the wind system dome. The eye is cicular or elliptical depending on the characteristics of the hurricane, has an average diameter of about 14 miles, but may vary from about 4 miles to 25 miles (Dunn and Miller, 1964). Atmospheric pressure near the surface of the ocean is minimum in the eye and usually increases in all directions to the storm's periphery. The temperature in the eye is higher than its surroundings, principally at lower levels, which causes the air to rise vertically, thus allowing air from the adjacent wind system to flow into the eye. The warm, moist air flowing into the eye is then heated, ascends, and is dispersed in the upper atmosphere thus providing a vital step in the process of transforming heat to kinetic energy. The more air displaced in the column of the eye, the higher will be the wind speeds. Since the highest pressure gradient is in a region near the eye, the highest wind speeds occur at the place of maximum pressure drop. More specifically, the maximum winds are produced at a region near and to the right of the hurricane center, facing the direction which the eye is moving.

The creation and maintenance of a hurricane requires a delicate balance of all processes; a breakdown in any of these processes will cause the storm to degenerate. The principal source of energy of the tropical cyclone is the release of the latent heat of condensation in the core or center column; thus, the hurricane can only be maintained over the warm ocean waters. As hurricanes move overland, they lose their cyclonic characteristics rapidly and transform into less intense storms which may move over distances of several hundred miles before completely dissipating. A transformation of wind speeds and direction takes place when a hurricane moves into a coastal area due to frictional drag overland. This will be seen later to have an effect on the water level variation at shore.

According to Dunn and Miller (1964), the East and Gulf Coasts of the United States can expect a hurricane to cross the coast on the average of about 2 to 3 per year. Any reaches along these coastlines are susceptible to tropical cyclone crossings. On the West Coast, only California can expect a hurricane, and only infrequently. About six tropical storms per year develop off the west coast of Central America or Mexico and only about one-half of those become full-scale hurricanes. Only about one in 50 of these hurricanes hits California. Tropical storms spawned in the North Atlantic Ocean, including the Gulf of Mexico and the Caribbean Sea, on the average, number about eight per year, and only 58 percent of these reach hurricane intensity.

Three characteristics of hurricanes are important in establishing their capacity for producing storm-induced wind tides and surface waves, and these may be identified as: pressure differential (Δp), the difference in pressure at the storm periphery (p_n) from that at p_o, the central pressure (i.e. in the eye); radius of maximum winds (R), the distance from the eye to the region of maximum winds; and the forward speed (V_F), the speed at which the eye moves. The central pressure index is commonly used for tagging the hurricane intensity, and is abbreviated as CPI. All of these characteristics appear to be dependent to some degree upon the storm's latitude, and they usually vary throughout the storm's life span.

2. Factors Influencing the Maximum Surge

The high winds of a hurricane which moves over the Continental Shelf and crosses the coast not only generate high waves but drag a large quantity of water along in the process. For a relatively straight coastline the water transported shoreward causes the water level to rise both to the left and right of landfall of the storm center. Transport in the shoreward direction occurs in the right quandrants of the storm, and winds in the leading left quadrant set up a current to the left alongshore prior to the eye advancing into shore thus giving a rise in water level to the left as well as the right. For the relatively straight coastline the offshore winds in the left quadrants will seldom provide sufficient offshore transport to depress the water level below the initial level because of the alongshore currents developed in the leading left quadrant of the storm. However, if a landmass juts out into the sea such as the southern part of Florida, and a hurricane center moves into the southern tip, then the storm driven currents alongshore become discontinuous at the leeward side of the landmass. Moreover when the winds in the leading quadrants of the storm pass over the landmass, they have a seaward direction on the leeward coast side, and these offshore winds can depress the water level by several feet. All levels of surge along the coast during the passage of a hurricane are of concern. But from the aspect of coastal engineering design, it is of primary interest to know the peak surge or the highest surge. For the relatively straight coastline, the peak surge is generally assumed to occur in the vicinity of landfall of the region of maximum winds. This has never been fully verified from actual observations because of inadequacy of water level recorders on the open coast, but merely based on the physical over-water structure of the hurricane. Jelesnianski (1967) has numerically shown that for a model coast of uniform and straight contours, the location of the peak surge relative to the storm system is dependent on the angle at which the storm approaches the coast. Irregularities in shelf and coastline configurations would also govern the exact location of the peak surge.

The highest level to which the water will rise on the open coast during the passage of a hurricane is dependent upon several factors or causes. In general, these factors can be attributed to the initial state of the sea, the properties of the seawater over which the storm runs, the behavior and characteristics of the storm, the characteristics of the basin and forces which act external to the system. The initial sea state refers to the level of the sea on the shelf heralding the approach of a hurricane. Generally, sea level is above normal before the arrival of a hurricane, especially along the coasts adjacent to the Gulf of Mexico and lower latitudes of East Coast. Such abnormal levels have yet to be fully understood, but commonly are called "forerunners", and are attributed to transport caused by winds in advance of the hurricane. Harris (1963) indicates that the initial rise may be related to short-period anomalies in the mean sea level which are not related to the hurricane. In any event, whatever the cause, the initial water level can be an important factor when attempting to account for the total rise at the open coast.

A hurricane moving over the Continental Shelf affects the buildup of water on the coast in accordance with its intensity, path, pressure effect, forward speed, size, and associated rainfall. The greater the onshore wind speeds and usually the longer the winds act over the water, the greater will be the rise of water at the coast. The forward speed, however, can be an important factor in the total rise. If there is a gradual pressure change, the water level will rise in regions of low pressure and fall in regions of high pressure, thus the pressure is one of the important components of the surge. The size of the storm relative to the size of the basin is also an important factor, since a storm too large for the basin could limit the hurricane's growth as well as intensity because of the interference of the outskirt winds with the land. An example of a very large storm relative to the basin size was Hurricane Carla (1961) which made landfall near Port O'Connor, Texas. When this storm was approximately centered in the western end of the Gulf of Mexico basin, its winds at the edge were sweeping the coastal terrain of the east Coast of Mexico as well as the Coasts of Texas and Louisiana.

Rainfall associated with the hurricane can contribute to the rise of surge on the open coast because of the volume added to the system; however, since the sea basin is such a large reservoir, the rise caused by precipitation is generally neglected. For semienclosed bays and estuaries, rainfall can be an extremely important factor in estimating the surge for any location within the system. In fact, in a semienclosed basin, the peak surge height may be increased as much as 3 feet due to direct rainfall on the water surface when coupled with the surface rainfall runoff from the watersheds located adjacent to the basin. Although the direct effect of rainfall on the open sea can be usually neglected in estimating the maximum storm surge along the open coast, streams discharging large quantities of water in the sea may affect the maximum water level locally.

When wind-generated surface waves of a hurricane move into the nearshore regions and break on the sloping beach more or less parallel to the depth contours, they may be responsible for a significant water transport shoreward. As the water moves back seaward by gravity, the momentum of the water particles is substantially decreased, resulting in a water surface gradient extending from the breaker region to the shore. Thus, the kinetic energy of the particles is increased as the wave breaks and moves shoreward, and decreases when the particles move back seaward. Part of the kinetic energy is transformed to potential energy and some energy is lost in the form of friction and turbulence. However, the gain in potential energy results in an increased water level at the shore. Wave setup is the superelevation of the water surface over normal surge elevation due to onshore mass transport of the water by wave action alone (Saville, 1962).

Model studies of wave setup have been made by Fairchild (1958) and Saville (1962); theoretical studies of wave setup were made by Dorrestein (1962), Fortak (1962) and Longuet-Higgins and Stewart (1962, 1963, 1964). All of these studies show that the water level is depressed below the stillwater level (SWL) at the point of maximum wave amplitude or where the wave peaks up and breaks. Saville (1962) indicates that waves breaking on a beach face, with the crests parallel to the depth contours, produce a wave setup at the shore of about 10 to 15 percent of the incident wave height for seabed profiles 1 on 15 or gentler. Waves breaking at an oblique angle to the depth contours probably produce less setup at the shore. Wave setup is also dependent on the configuration of the foreshore and the configuration of the coastline. An estimate of the influence on wave setup of such irregularities is difficult, and would vary for each different configuration.

The maximum storm-induced surge at the coast is also affected by the fluid properties over the total depth beneath the storm system. Fluid stratification is present due to the vertical density gradients, and strong currents in the nearshore regions cause bed materials to be propelled into suspension thus increasing the fluid density. Since water is a real fluid, there is lateral friction between the fluid stream lines. Such complexities are generally ignored in estimates of the maximum open-coast surges, although accounted for in some overall gross manner. However, the properties of the fluid are important in the storm generation process, and it is not always completely satisfactory to disregard the various modes of internal motion caused by the disturbance of real fluid.

The height of the hurricane surge is also governed by the characteristics of the basin, such as the size, coastline and bed formation, and the roughness of the Continental Shelf. As mentioned previously, a basin too small for the storm system can cause a reduction in intensity while the storm is positioned far out at sea, thereby reducing the surge at the open coast. The water level at the shore is also dependent upon the hydrographic configurations of the shelf and the shape of the coastline. Thus, the water level is affected by the presence of submerged barriers, submarine canyons and any other formations which may abet or impede the flow. Normally, there is an amplification of the storm-induced surge wave if the shelf is relatively flat or shallow. However, this may not always be the case, since bottom-friction stresses may predominate over the surface stresses. Bottom stresses are important principally in shallow water and are dependent on the roughness of the seabed in respect to the size of the bottom material as well as the configuration of the bed. When estimating the surge which moves over the low-lying terrain adjacent to the sea, the bottom stresses become extremely important due to vegetation and other obstructions.

The maximum surge on the open coast is also affected by the astronomical tide. The degree of effect depends on the amplitude of the tide and the phasing of the tide with the storm-induced surge. When maximum storm surge at the coast coincides with a maximum tide, the highest water level will be produced at the shore. The water level will be reduced when a low tide occurs simultaneously with the maximum surge. The vertical departure of the water surface from its mean position for any particular location because of tides depends on geographical location, basin configuration, and the magnitude of the tidal forces at a particular time. The tide range can be as great as 18.2 feet at Eastport, Maine, while only 1.3 feet at Key West, Florida. Generally, the tides along the Gulf Coast are diurnal while those on the East Coast are semidiurnal. For some locations, the tide may be the principal component of the total rise at shore during a hurricane.

Coriolis effect also plays an important role in the fluid motion beneath the storm system. Coriolis acceleration exists only when a mass has velocity relative to the earth's surface. The effect acts to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. For large basins such as the ocean, and for fluid motion propagating at relatively slow speeds, the Coriolis acceleration becomes quite important.

Section III. THEORETICAL ASPECTS

Bathystrophic Storm-Tide theory can be described as a quasi-two-dimensional method for evaluating the change of water level along a single traverse line over the Continental Shelf. Unlike the older one-dimensional schemes, it takes into account some of the effects of the earth's rotation. However, Bathystrophic theory is only an approximation to the complete storm-generation process, and its usefulness in predicting actual storm surge depends upon the problem being considered. For some situations, the Bathystrophic approximation appears to give a reasonable estimate of the open-coast surge, but for others the estimate could be in error by a factor of two or more. Usefulness of this theory requires some knowledge of its underlying assumptions and the hydrodynamic processes neglected in its development. To display the underlying principles of the approximation, the initial conditions imposed and basic hydrodynamic relations appropriate to the problem follow.

1. Preliminary Conditions Imposed

Although the basic equations which govern storm surge generation will not be derived here, it is important to mention the conditions imposed at the outset of their development. A knowledge of these conditions gives a better understanding of the resulting equations. The conditions are:

a. It is assumed for a disturbance of intermediate horizontal scale that $L >> D$ and $L << R_E$, where L is the wave length; D is the fluid depth; and R_E is the radius of the earth. This also implies that:

(1) The vertical components of velocity and acceleration can be neglected. Thus the vertical pressure gradient is hydrostatic, and vertical Coriolis effects can be ignored.

(2) The curvature of the earth can be neglected.

b. The acceleration due to earth's rotation is a constant.

c. The fluid is homogenous and incompressible, thus the water density ρ is a constant.

d. The fluid is inviscid. Thus, internal forces due to viscosity are neglected.

e. The seabed is regarded as fixed and impermeable.

f. The effects of surface waves are considered linearly superimposable on the storm surge.

Thus, it is assumed that only horizontal flow takes place, the traditional approach when dealing with this type of fluid motion. Such flows have been referred to as *nearly horizontal flows* (Birkhoff, 1960). In the context of wave motions, such wave motions are often referred to as *waves of long period* or simply *long waves*. Wave motions in which the vertical accelerations have a marked influence on the wave behavior are called *short-period waves* or *gravity waves*. Surface waves referred to in item f above are of this type.

The water motion which accompanies the propagation of long waves is unsteady, and is in a continuous state of change. This change, however, is not abrupt, and the motion can be considered as gradually changing.

2. Basic Notation

Figure 1 shows the various notations used in the discussions. The value D is the total depth of the fluid at time t. Moreover, $D = S + d$ where S is the disturbance height of the free surface, and d is the depth of the undisturbed fluid. The Cartesian axes x and y are situated in a horizontal reference plane at the undisturbed water level, with z directed vertically upwards. The x and y axes are chosen counterclockwise with x directed shoreward and perpendicular to the shoreline.

3. The Differential Equations

The hydrodynamic equations may be written in either of the two equivalent forms: (1) the mean current velocities and (2) the volume transport. Preference for the particular form depends on the individual investigator, but generally the second form is preferred when an electronic computer carries out the computations. Here the volume-transport form is taken. This form is obtained by integrating the governing equations in the vertical over the total depth. Integrations of the primitive equations appropriate for the storm surge problem have been shown by Haurwitz (1951), Weylander (1961), Fortak (1962), Platzman (1963), Reid (1964), and Harris (1967). These derivations show more clearly the actual approximations involved. Here, the equations are taken directly in integrated form, since it is the purpose co display only the principal approximations taken.

The governing two-dimensional equations are:

$$\frac{\partial U}{\partial t} + \frac{M_{xx}}{\partial x} + \frac{M_{xy}}{\partial y} = fV - gD\,\frac{\partial S}{\partial x} + gD\,\frac{\partial \xi}{\partial x} + \frac{\tau_{sx} - \tau_{bx}}{\rho} - W_x P \qquad (1)$$

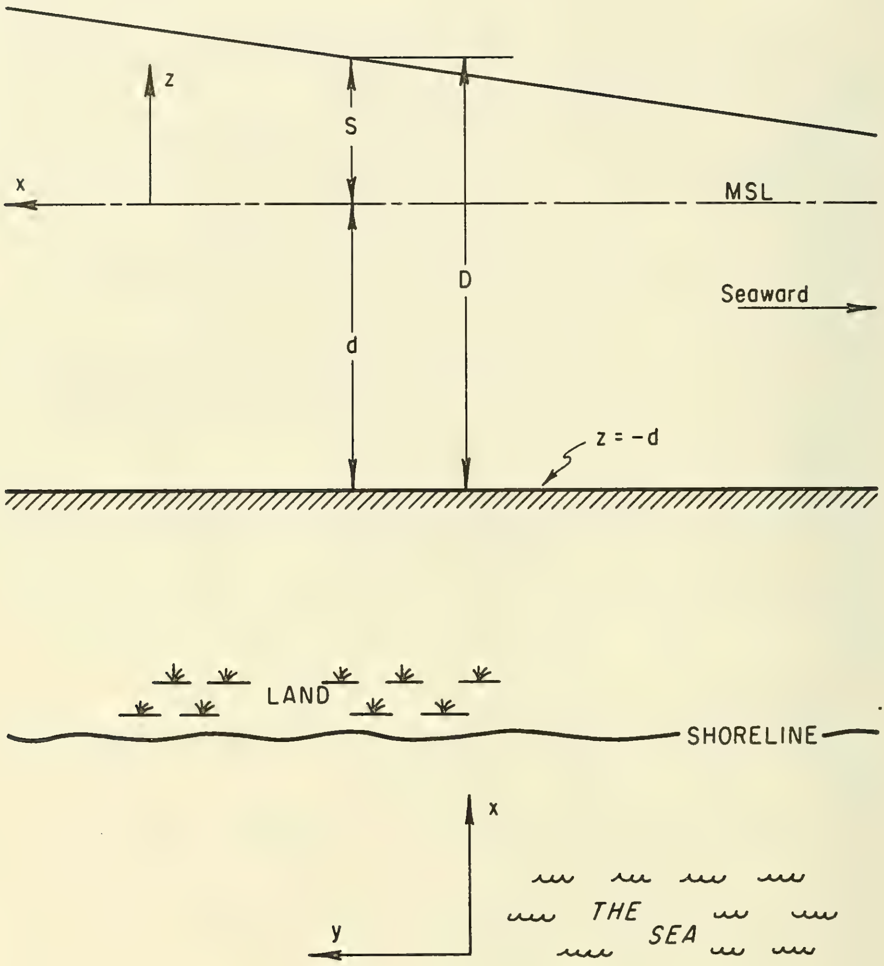

Figure 1. Notation and Reference Frame

$$\frac{\partial V}{\partial t} + \frac{\partial M_{yy}}{\partial y} + \frac{\partial M_{xy}}{\partial x} = -fU - gD\frac{\partial S}{\partial y} + gD\frac{\partial \xi}{\partial y} + \frac{\tau_{sy} - \tau_{by}}{\rho} - W_y P \qquad (2)$$

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

$$M_{xx} = \int_{-d}^{S} u^2 \, dz; \qquad M_{yy} = \int_{-d}^{S} v^2 dz; \qquad M_{xy} = \int_{-d}^{S} uvdz;$$

$$U = \int_{-d}^{S} udz; \qquad V = \int_{-d}^{S} vdz$$

The symbols used are defined as follows:

U, V = x and y components, respectively, of volume transport per unit width.

t = time

M_{xx}, M_{yy}, M_{xy} = Momentum transport quantities

f = $2\omega \sin \phi$ = Coriolis parameter

ω = angular velocity of earth = $2\pi/24$ radians per hour:

ϕ = geographical latitude

τ_{sx}, τ_{sy} = x and y components of surface wind stress.

τ_{bx}, τ_{by} = x and y components of bottom stress

ρ = density of water.

W_x, W_y = x and y components of wind speed.

ξ = Atmospheric pressure deficit in head of water.

u, v = x and y components, respectively, of current velocity.

P = Precipitation rate (depth/time).

g = gravity

Equations (1) and (2) are the expressions for conservation of momentum and often referred to as the equations of motion. These equations are based on Newton's law, force = mass times acceleration. Equation (3) is the expression for conservation of mass for an incompressible fluid, generally referred to as the equation of continuity.

4. The Bathystrophic Approximation

The assumptions made by Freeman, Baer and Jung (1957) in the development of the Bathystrophic Storm Tide Theory implied that: the volume transport perpendicular to the shore could be neglected; the onshore winds give an instantaneous rise of the sea surface; advection of momentum (field acceleration) is negligible; the sea surface is uniform, and parallel to the depth contours; and precipitation can be neglected. These assumptions indicate that:

$\frac{\partial U}{\partial t}$, fU, $\frac{\partial U}{\partial x}$, $\frac{\tau_{bx}}{\rho} \rightarrow 0$, no onshore transport,

M_{xx}, M_{yy}, $M_{xy} \rightarrow 0$, momentum values neglected,

$\frac{\partial S}{\partial y}$, $\frac{\partial V}{\partial y} \rightarrow 0$, alongshore sea surface uniform,

$P \rightarrow 0$, Precipitation neglected.

$\frac{\partial \xi}{\partial x}$, $\frac{\partial \xi}{\partial y}$ Barometric effects are not considered here, but will be accounted for from a separate source. This effect is discussed later.

Based on these assumptions, Equations (1) and (2) reduce to

$$gD \frac{\partial S}{\partial x} = fV + \frac{\tau_{sx}}{\rho} \tag{4}$$

$$\frac{\partial V}{\partial t} = \frac{\tau_{sy} - \tau_{by}}{\rho} \tag{5}$$

and the continuity relation, Equation (3), is disregarded in the Bathystrophic approximation because of the assumptions taken. Thus the reduced equations are quasi-two-dimensional since computations are restricted to a single axis, the x-axis; however, the rate of change of transport along the y-axis is retained to account for the effects of earth's rotation.

5. Bottom and Surface Stresses

Relations are now introduced which describe approximately the stresses that occur when there is water motion in the neighborhood of the seabed and the interaction of the winds with the sea surface. Formulas based on experiments and theoretical considerations have been introduced which give reasonably reliable values provided that the frictional forces at the surface or at the bed are not influenced by each other. However, in shallow water, the problem is more involved since the wind effects on the water will influence the vertical velocity distribution over the total depth. Consequently, the slope of the water surface due to the winds is also influenced by bottom stresses. Moreover, in the vincinity of the shore, the velocity at the surface may have a different direction from that at the bottom. Friction models which take into account the combined effects of surface and bottom stresses have been proposed by Reid (1957) and Platzman (1963).

Here, the simplified stress laws are used, and the influence of the vertical velocity distribution is neglected. Moreover, similar formulas are adopted for representing the surface stress and bottom stress and this form is given by:

$$\tau = \gamma \rho \forall^2 \tag{6}$$

where τ is the shear stress at the boundary; γ is a dimensionless resistance coefficient; ρ is the water density; and $\forall$ is the fluid velocity. More specifically, the shear stress at the bottom is divided by water density, and consistent with the stress term required for Equation (5) is:

$$\frac{\tau_{by}}{\rho} = K\ V^2 \tag{7}$$

Here K and V replace γ and $\forall$, respectively, in Equation (6), and K is the bed friction coefficient and V as defined previously is the y-component of the water velocity. The bottom-stress relation given here is a different form than the one originally proposed by Freeman, Baer and Jung (1957) and subsequently used by many investigators. As implied by the above authors, the bed friction coefficient had dimensions of length to the minus one-third power. This is in accordance with Manning's (1890) relation which implies that the friction coefficient should be inversely proportional to $D^{1/3}$. However, on the other hand, Prandtl-von Karman boundary-layer theory implies that the friction coefficient is dimensionless (Prandtl, 1935; von Karman, 1935). For simplicity in computation, the latter theory is chosen.

Equation (7) written in transport form is

$$\frac{\tau_{by}}{\rho} = K\ U^2\ D^{-2} \tag{8}$$

For typical seabed conditions, it has been found that K generally lies in a range from 10^{-3} to 5×10^{-3}.

The surface stress due to the wind formula adopted in the form of Equation (6) is

$$\tau_s = \rho k \, W^2 = \rho k \, W|W| \tag{9}$$

where W is the wind velocity. For convenience is using standard observations, the wind velocity is taken to be at 30 feet above the wave surface, based on 10-minute averages. The square of the wind velocity is written in Equation (9) as $W|W|$ to retain the proper sign consistent with the coordinate system employed. In the example calculations presented, the dimensionless coefficient k is taken as a function of the wind speed as implied by the Van Dorn (1953) relation for wind stress. Thus, it is assumed that

$$\begin{aligned} k &= K_1 && \text{for } W \leq W_c \\ k &= K_1 + K_2 \left(1 - \frac{W_c}{W}\right)^2 && \text{for } W \geq W_c \end{aligned} \tag{9a}$$

where the constants K_1 and K_2 are 1.1×10^{-6} and 2.5×10^{-6}, respectively, and W_c is a critical wind speed taken as 14 knots (about 16 miles per hour).

Finally, surface-stress equations for introduction into Equations (4) and (5) can be written as:

$$\begin{aligned} \frac{\tau_{sx}}{\rho} &= k \, W^2 \cos \theta \\ \frac{\tau_{sy}}{\rho} &= k \, W^2 \sin \theta \end{aligned} \tag{10}$$

where θ is the angle between the x-axis and the wind vector.

Equations (4) and (5) can now be written as follows:

$$\frac{\partial S}{\partial x} = \frac{1}{gD} \qquad f \, V + k \, W^2 \cos \theta \tag{11}$$

$$\frac{\partial V}{\partial t} = k \, W^2 \sin \theta - K \, V^2 \, D^{-2} \tag{12}$$

Thus, two simple differential equations are obtained which can readily be resolved by the method of numerical integration. However, simplifying the more complete hydrodynamic relations (i.e., Equations (1), (2) and (3) for the storm-surge problem, results in formulas which are restricted to certain classes of problems.

6. Limitations of Reduced Equations

The Bathystrophic equations reveal that the time-dependent surge can be determined only spatially along the x-axis or a single line, often referred to as the *traverse line*. Orientation of this line becomes very important for valid computations due to the restrictions brought about by the simplifications of the resulting formulas. Since all transport along the x-axis is neglected, the computational axis must be oriented perpendicular to the bed contours. The onshore wind stress is then assumed to give an instantaneous setup of water where the deep basin beyond the Continental Shelf acts as a relatively infinite reservoir for replenishing the volume being set up. The orientation of the traverse line for shelves that have contours which are straight and parallel to the coastline presents no problems. Actual shelf formations do not have such a simple configuration; many are quite complex in shape. If the shelf configurations are not unusually complex, particularly in the shallow nearshore regions, it appears that a reasonable estimate might be obtained by orienting the traverse line which on the average would be perpendicular to the bed contours, and by giving special weight to those contours in the nearshore region. It is emphasized that a line along which numerical computations are made *must always* be taken straight and perpendicular on the average to the bed contours for valid resolution.

There are also restrictions for placement of the traverse line with respect to the storm system. Use of the Bathystrophic approximation is invalid for estimating storm surge in the left quadrants of the hurricane, because of the water motions due to the offshore wind components coupled with the effects of earth's rotation. Furthermore, the formula is generally not considered appropriate for traverses to the left of the region of maximum winds. A traverse line can be taken at the region of maximum winds and anywhere to the right of this position, although previous studies indicate that surge predictions are not too reliable if the traverse line is selected in the vicinity of the outskirts of the storm. Care is needed in computing the surge along a traverse line when a storm moves over the Shelf with a large crossing angle. Consequently, it is seen that one can only investigate the dispersion of the surge at and to the right of maximum winds when using the Bathystrophic formulas.

Generally, in connection with storm-surge problems, predicting the height of the water surface is of primary interest; predicting the associated volume transport or current velocities is of only casual interest. The simplified prediction technique covered here neglects all x-component transport, and only partially describes the y-component of transport. Thus, the Bathystrophic relations should be used only for predicting the height of the water surface.

This prediction scheme is considered more appropriate for determining storm surge for slow moving hurricanes, because of the resulting quasi-steady state relation. More specifically, $\partial U/\partial t$ is neglected while $\partial V/\partial t$ is retained. For fast-moving hurricanes, inertial effects become important, and can contribute significantly to the total setup at the shore.

7. The Numerical Scheme

Frequently, it is of interest to know how much of the setup can be attributed to the onshore effects and how much can be attributed to the alongshore effects. To determine these two separate and distinct effects in the computational scheme, Equation (11) can be written in the equivalent forms as follows:

$$\frac{\partial S_x}{\partial x} = \frac{k\ W^2 \cos\theta}{gD} \tag{13}$$

$$\frac{\partial S_y}{\partial x} = \frac{fV}{gD} \tag{14}$$

where the total setup along the x-axis is simply

$$\frac{\partial S}{\partial x} = \frac{\partial S_x}{\partial x} + \frac{\partial S_y}{\partial x}$$

Equations (12), (13), and (14) can be solved by computing in increments of time and space provided that the increments taken are not too large. Furthermore, the functional relationships as given by the above equations are taken as continuous over the entire interval. In the numerical analog of the equations, Δx and Δt are taken as nonuniform spacing and time steps. This will allow taking coarse spacing, Δx, where the seabed is relatively flat, and fine spacing where the bed slope changes more rapidly near shore. Nonuniform time steps, Δt, allow more frequent storm-surge computations during the period when the maximum rise in water level is anticipated which is sometimes useful in developing the storm surge hydrograph. The discrete position, x, along the traverse line and the time level, t, are defined as:

$$\begin{aligned} x &= x_o - \sum_{i=1} (\Delta x)_i \\ t &= t_o + \sum_{i+1} (\Delta t)_n \end{aligned} \tag{15}$$

where x_o is the distance from the shoreline to the most seaward position prescribed on the traverse line. The summation of Δx for all i's up to and including IM, the maximum value of i at shore, is simply x ; thus at the shore x = 0. Actually, according to the coordinate system taken, x would be negative seaward of the shoreline; however, taking x positive does not effect the computation scheme, and furthermore such a choice is consistent with the computational schemes presently used. Normally, t_o will be taken as zero and the time level is simply the summation of Δt for all n's up to, and including, some specified value of $n = NM$.

For the present numerical scheme, the values of wind stress, seabed depths below the undisturbed level, and coriolis effects are presumed supplied at all discrete positions of i, while S, D, and V are evaluated at i + 1/2. On this basis the numerical analogs of Equations (12), (13), and (14) can be written as follows:

$$(\Delta S_x)^{n+1}_{i+\frac{1}{2}} = \frac{\Delta x}{2gD^{n+1}_{i+\frac{1}{2}}} (A_i + A_{i+1})^{n+1} \tag{16}$$

$$(\Delta S_y)^{n+1}_{i+\frac{1}{2}} = \frac{\Delta x}{2gD^{n+1}_{i+\frac{1}{2}}} (f_i + f_{i+1}) \; V^{n+1}_{i+\frac{1}{2}} \tag{17}$$

$$V^{n+1}_{i+\frac{1}{2}} = \frac{1/2[\overline{(B_i + B_{i+1})}^{n} + \overline{(B_i + B_{i+1})}^{n+1}] \Delta t + V^{n}_{i+\frac{1}{2}}}{[1+K| V^{n}_{i+\frac{1}{2}} |\Delta t(D^{-2})^{n+\frac{1}{2}}_{i+\frac{1}{2}}} \tag{18}$$

where the overbar signifies the spatial average of B at the specified time levels and A and B are defined as

$$A = k\ W^2 \cos\theta$$

$$B = k\ W^2 \sin\theta$$

The ordinal number n represents the previous time level and n + 1 represents the new time level. The values of D can be regarded as the total water depth at a position centered between x_i and x_{i+1}. The total water depth at any specified position not only depends upon the mean water depth and storm-induced setup, but also on the effects of setup due to pressure, astronomical forces, and the initial sea level - provided there is a departure from the normal level. Thus, the total water depth at a time midway between two time levels is given by

$$D^{n+\frac{1}{2}}_{i+\frac{1}{2}} = \frac{d_i + d_{i+1}}{2} + S_e + \frac{S^n_A + S^{n+1}_A}{2} + (S_x + S_y)^n_{i+\frac{1}{2}}$$

$$+ 1/4 \quad [(S_{\Delta p})_i + (S_{\Delta p})_{i+1}]^n + [(S_{\Delta p})_i + (S_{\Delta p})_{i+1}]^{n+1} \tag{19}$$

where S_e = initial setup

S_A = setup due to astronomical forces

$S_{\Delta p}$ = atmospheric pressure setup.

Specification or determination of these setups will be discussed in more detail later. The total water depth at the new time level is given by

$$D_{i+\frac{1}{2}}^{n+1} = \frac{d_i + d_{i+1}}{2} + S_e + S_A^{n+1} + (S_x + S_x)_{i+\frac{1}{2}}^{n}$$

$$+ 1/2 \left[(S_{\Delta p})_i + (S_{\Delta p})_{i+1}\right]^{n+1} \tag{20}$$

The components of storm setup, S_x and S_y, are

$$S_x = \sum_{j=1} (\Delta S_x)_j \tag{21}$$

$$S_y = \sum_{j=1} (\Delta S_y)_j \tag{22}$$

In other words, the total wind setup for any discrete position along the traverse is the setup in that reach and the accumulation of setups in all reaches seaward of that reach. It should be noted that in Equations (19) and (20), an error is introduced each time D is evaluated since the term $(S_x + S_y)$ is taken at the previous time level and should be the value at time level $n+\frac{1}{2}$ for Equation (19) and at n+1 for Equation (20). This is, of course, due to the fact that the correct values are unknown at those time levels and an approximation is taken. This error, however, is small provided that increments in time and space are not taken too large.

For problems of this sort it is customary to assume for initial conditions that the system at $t = t_o$ is at equilibrium state which infers that the current velocities are zero and the water surface is uniform. For the present case, this implies that V is zero and S is uniform for the system. Although for actual conditions the system seldom, if ever, would be in a complete state of equilibrium. After a suitable lapse of time, this is usually of little consequence, since eventually the response of the system reflects only the effects of the forcing functions.

Calculations are initiated at the seaward boundary, and then stepped forward through all prescribed spatial positions to the boundary at the shore. The same process is repeated by commencing again at the seaward boundary. This procedure is continued for the entire temporal range. For any discrete position along the traverse line, V, at the new time level is first evaluated based on V at the previous time level as well as B and D as the average value in the domain of $x + \Delta x$ and $t + \Delta t$. A knowledge of V at the new time level (Equation (18)) allows determination of x and y components of setup (Equations (16) and (17)). The total water level rise at the coast can then be evaluated by a summation of the components - those related directly to the meteorological storm and those unrelated - as follows:

$$S_T = S_x + S_y + S_{\Delta p} + S_e + S_A + S_W + S_L \tag{23}$$

where $S_W = \alpha H_B$ is the wave setup at the shore due to breaking waves, H_B is the height of the breaking wave, and α is a coefficient which normally ranges from about 0.1 to 0.2. The local setup or setdown S_L is the deviation of the water surface from the computed water level due to a local effect such as inland runoff or shape of the hydrography in the nearshore region. Figure 2 shows a profile of the various components of set over the Continental Shelf at a typical coastal region.

Since numerical calculation of V is based on a repeating formula, it is subject to the round-off errors, that is, each computed value will influence the values which are yet to be determined. To ensure that the value does not exceed the maximum possible value, it is useful to employ the following derived relationship. Equation (12) can be written incrementally as

$$\Delta V = k\ W^2 \sin\theta\ \ \Delta t - K\ V^2 D^{-2}\ \ \Delta t$$

or

$$K\ V^2 D^{-2}\ \Delta t = k\ W^2 \sin\theta\ \Delta t - \ \Delta V.$$

For small ΔV, $K\ V^2 D^{-2} \leq k\ W^2 \sin\theta$.

Thus, the y-component of volume transport becomes

$$V \leq \frac{D^2 k\ W^2 \sin\theta}{2\ K}$$

At the new time level, the above equation can be written as

$$\left|V_{i+\frac{1}{2}}^{n+1}\right| \leq \frac{\left|(B_i + B_{i-1})^{n+1}\right| (D^2)_{i+\frac{1}{2}}^{n+1}}{2\ K} \tag{24}$$

Thus, the absolute value of the flux must never exceed the term on the right-hand side of the equation. This relation should always be used as a check, and if it exceeds this value, the flux at the new time level, as an estimate, can be set equal to the value given by right-hand side of Equation (24).

8. Computational Formulas

Here, we shall give the formulas in a more compact and generally more usable form by absorbing invariant coefficients and values caused by inconsistency of units into a constant for each equation. Thus, in the United States, wind speeds associated with hurricanes are usually reported in miles per hour while distances taken from hydrographic maps

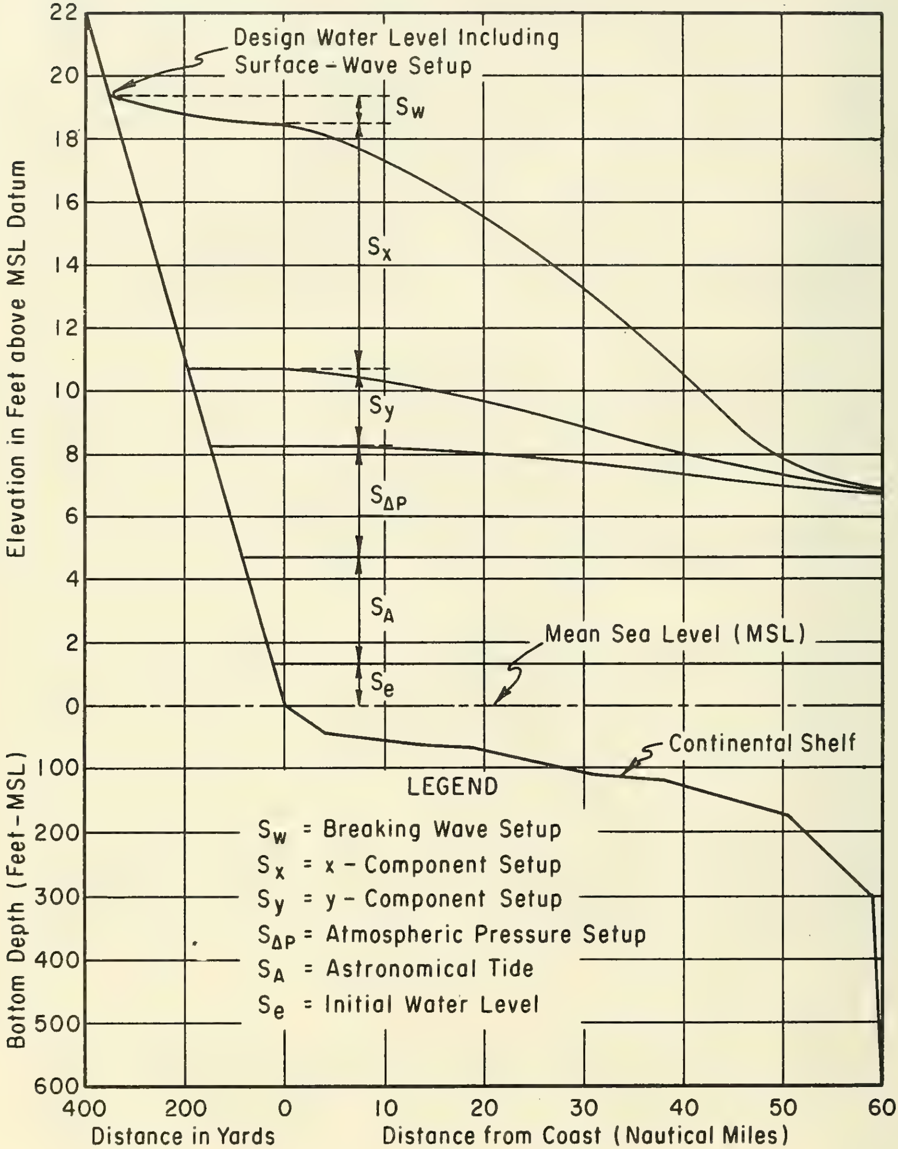

Figure 2. Setup Components Over the Continental Shelf

are given in nautical miles. To eliminate conversion of units from the basic data, we take as follows:

ΔS_x, ΔS_y → feet

Δx → nautical mile

g → ft/sec^2

D → feet

A, B → mi^2/hr^2

V → mi^2/hr

f → 1/hr

Δt → hr

On this basis the pertinent equations become

$$(\Delta S_x)^{n+1}_{n+\frac{1}{2}} = \frac{203\ \Delta x}{D^{n+1}_{i+\frac{1}{2}}} \quad (A_i + A_{i=1}) \tag{25}$$

$$(\Delta S_y)^{n+1}_{i+\frac{1}{2}} = \frac{106\ \Delta x}{D^{n+1}_{n+\frac{1}{2}}} \left\{ (\sin\theta)_i + (\sin\theta)_{i+1} \right\} V^{n+1}_{i+\frac{1}{2}} \tag{26}$$

$$V^{n+1}_{i+\frac{1}{2}} = \frac{1/2\ [(\overline{B_i + B_{i+1}})^n + (\overline{B_i + B_{i+1}})^{n+1}]\ \Delta t + V^n_{i+\frac{1}{2}}}{1 + (5280)^2\ |V^n_{i+\frac{1}{2}}|\ \Delta t\ K(D^{-2})^{n+\frac{1}{2}}_{i+\frac{1}{2}}} \tag{27}$$

$$V^{n+1}_{i+\frac{1}{2}} \leq \sqrt{\frac{|(B_i + B_{i+1})^{n+1}|\ (D^2)^{n+1}_{i+\frac{1}{2}}}{2\ (5280)^2\ K}} \tag{28}$$

When using the above equation, one should ensure that the units used are consistent with those specified above.

Section IV. DESIGN STORMS

1. General

From the coastal engineering viewpoint, it is necessary to define the design hurricane prior to discussing the actual application of the numerical scheme previously described. Design analysis of coastal projects by engineers must provide the degree of protection necessary for the purpose of the project. A high degree of protection is required when a coastal structure provides protection of lives. A high degree of protection is also required when extensive property damage can be caused by a hurricane. When the risks are small, it may be better to accept a lower degree of protection to obtain lower costs for the project. Thus, the selection of a design hurricane for a coastal protection project is dependent on the economics of providing the required degree of protection.

To give the most probable degree of protection required for a particular study area, it has been the practice to select a hurricane with a given set of characteristics for the particular geographical location. Since the characteristics are specified, the storm is called a Hypothetical Hurricane or Hypo-Hurricane, USA-CERC (1966). Furthermore, for such a storm the characteristics are taken as invariant, and the storm is presumed to follow a prescribed path. Two design storms, which are dependent upon geographical location, have been established for practical application in the analysis of the design of coastal structures. These are referred to as the Standard Project Hurricane (SPH) and Probable Maximum Hurricane (PMH). The establishment of these design storms was carried out jointly by the U. S. Weather Bureau and the U. S. Army Corps of Engineers.

2. Standard Project Hurricane

Graham and Nunn (1959) developed the criteria for defining the SPH through a detailed analysis of past documented hurricanes. The objective for developing such a design storm was to provide a standard or criterion which would serve as a basis in the design of coastal structures subject to hurricane surges. In this analysis, statistical quantities were compiled for the experienced hurricane characteristics for various delineated zones along the Atlantic and Gulf Coasts of the United States. The characteristics considered were: central pressure index (CPI), radius of maximum winds (R), forward speed (V_F), maximum gradient wind speed (V_{gx}), and maximum wind speed (V_x). The SPH is based on a CPI having an occurrence probability of once in 100 years.

Furthermore, the radius of maximum winds and forward speed are to be taken in such a manner that the highest surge is produced at the coast being investigated. The CPI, as well as R and V_F, are representative of positions for the various zones. More specifically, Graham and Nunn defined the SPH as "A hypo hurricane that is intended to represent the most severe combination of hurricane parameters that is reasonably characteristic of a region excluding extremely rare combinations."

The maximum gradient wind speed and maximum wind speed in the belt of maximum winds in miles per hour were determined by the following formulas:

$$V_{gx} = \kappa(P_n - P_o)^{\frac{1}{2}} - R(0.575\ f) \tag{29}$$

$$V_x = 0.865\ V_{gx} + 0.5\ V_F \tag{30}$$

where κ is taken as 73 for the SPH, P_n and P_o are the peripheral and central pressures in inches of mercury, respectively, R is the radius of maximum winds in nautical miles, f is Coriolis parameter in units per hour, and V_F is the forward speed in miles per hour. V_x is the maximum wind speed 30 feet above the water.

A knowledge of these variables for a given location allows computation and graphical construction of the storm's entire isovel field.

3. Probable Maximum Hurricane

In the past several years, many nuclear-powered electrical generating stations have been constructed or proposed. Many of these have been sited along the Atlantic and Gulf Coasts of the United States where they may become vulnerable to hurricane surge and surface waves. To ensure that these power plants would not be flooded by hurricane surges, including the wind-generated surface waves, with the exception of extremely rare events, the Atomic Energy Commission (AEC) established a criterion which would provide adequate safety for public health. AEC concluded that adequate safety would be provided if the plant site would not be flooded by the surge and surface waves associated with a Probable Maximum Hurricane.

The Hydrometeorological Branch of the Weather Bureau in an Interim Report, HUR 7-97 (1968), developed the characteristics of the PMH which is substantially more severe than the SPH. The PMH was defined as "A hypothetical hurricane having that combination of characteristics which will make the most severe storm that can probably occur in the particular region involved. The hurricane should approach the point under study along a critical path and at optimum rate of movement."

HUR 7-97 not only developed the characteristics for defining the PMH, but updated the experience hurricane data originally carried out by Graham and Nunn (1959). Development of the isovel fields is essentially the same for the PMH as that given for the SPH. The difference is that P_n is taken as the standard sea level pressure of 29.92 inches of mercury for the SPH, while P_n is considered as a function of the latitude for the PMH. Moreover, κ is considered a function of the latitude for the PMH while κ for the SPH was taken as a constant.

4. Design Storms other than SPH and PMH

It may be advantageous in some cases to select a design storm other than the SPH or PMH based on the risks or economics of a particular coastal structure. In such circumstances, the information presented in HUR 7-97 can be used to obtain a different probability of occurrence of the CPI, and obtain hurricanes of various intensities. HUR 7-97 is recommended instead of Graham and Nunn's earlier investigation (1959) because of the updating of the basic data. It should be noted that the CPI for a PMH was not assigned to any particular probability of occurrence, but was taken as only an extreme event because of the relatively small amount of data presently available. Generally, if a design storm is selected other than SPH and PMH, it would be a storm less severe than the SPH. For instance, a coastal structure such as a stone jetty which offers protection only for normal conditions, could for some cases be designed for a storm less severe than the SPH. This is because it may be more economical to provide occasional maintenance than to build a much more costly and stable structure initially. A design storm for such a condition would be selected according to the CPI frequency considered satisfactory for the particular project. The radius of maximum winds R and the forward speed V_F would be taken as those values considered appropriate for that particular geographical location.

Section V. ESTIMATING THE PRESSURE EFFECT, INITIAL WATER LEVEL AND ASTRONOMICAL TIDE

1. Pressure Setup

The effect of atmospheric-pressure setup, $S_{\Delta p}$, which enters in the total depth calculation in space and time is evaluated separate from the relations previously described. Although several methods have evolved for estimating the pressure effect, none appear to be completely satisfactory for all storm-surge problems. The method presented here appears to be satisfactory for some cases, but for other cases the approximation may not be very reliable. Prior to giving the pressure-setup relation, a discussion will be made of the total problem to clarify the limitations of the relation presented.

The atmospheric pressure, p, acting on the water surface during a hurricane is a function of position in the storm field and time, or symbolically $p = f(x,y,t)$. In general, the atmospheric pressure is minimum at the hurricane eye, where $p = p_o$, and increases radially outward to the edge of the storm, or storm periphery where $p = p_n$. Because of the pressure variation in the open sea, water will rise in regions of low pressure and fall in regions of high pressure. The higher pressure region depresses the sea level by transporting the water to the lower pressure region where it causes the sea level to rise.

To move water from one region to the other requires time, thus the process is time-dependent. If the pressure change is rapid, there may be insufficient time for very much transport to take place resulting in only a small change of the water level. If there is sufficient time, an equilibrium state can be reached where the pressure forces are in balance with the gravitational forces. In the deeper regions of the sea, equilibrium state occurs more rapidly than in the shallow regions near the coast. In the nearshore regions, transport is impeded due to bed friction; more time is required to transfer the water. For actual hurricanes, the pressure disturbance moves with the speed of the storm, and can vary with the time elapsed. Hurricanes which move at very high speeds may not allow sufficient time for the water surface to reflect maximum and minimum levels that are associated with the actual pressure difference.

Consequently, the speed of the hurricane may play a role in the actual amount of water being set up. Harris (1963) indicates that the difference in water level between any two points in the storm field is proportional to the difference in atmospheric pressure provided that the storm speed (V_F) is small compared to the shallow-water wave speed, $\sqrt{gD}$. When the storm speed is comparable to the shallow-water wave speed, the water level will be amplified by resonance (Harris,1957).

The difficulty in establishing a relation which gives the actual amount of water set up during a hurricane is because the value has never been observed for past hurricanes. The total rise at shore, even with the best measurement devices, is only an estimate. Separating pressure setup from other components of the total rise is impossible. Thus, methods which give only a reasonable approximation of this effect must be used. One such approximation that has been used frequently in practice was developed by Myers (1954). He based his analysis on the mean radial pressure distribution of 69 historical hurricanes. The pressure p was defined as

$$p = p_o + (p_n - p_o)\, e^{-R/r} \tag{31}$$

based on the mean values of the experienced hurricanes. Here the pressure p is the pressure at a radial distance, r, from the storm center, p_o is the central pressure, R is the radius of maximum winds, and p_n is the peripheral pressure (theoretically at $r = \infty$). Subtracting p_n from both sides of the equation the relation can be written as

$$p_n - p_o = (p_n - p_o)\,(1 - e^{-R/r}) \tag{32}$$

When pressure is in inches of mercury, the setup of water in feet due to the pressure difference based on the above equation is given by

$$S_{\Delta p} = 1.14\,(p_n - p_o)\,(1-e^{-R/r}) \tag{33}$$

This relation provides a method of estimating the pressure setup on the traverse line. However, Equation (33) does not reflect the effect of the speed of the storm nor does it reflect the restrictions to flow. Thus, it is assumed that the sea is in a state of equilibrium when considering only the effects of atmospheric-pressure variation. For rapid storms, the estimate may be much too high, and when resonance occurs, the estimate may be too low. The best estimate possible would appear to occur when the storm speed is slow compared to the shallow-water wave speed.

2. Initial Water Level and Astronomical Tide

Because water level is often above the normal level prior to the arrival of a hurricane, this condition must be taken into account when making open-coast surge estimates for hypothetical hurricanes. It has been observed for past hurricanes in the Gulf of Mexico that in the absence of predicted astronomical tides, the water level has been as much as 2 feet and more above the normal level at shore just before the approach of the hurricane. Initial water levels observed for hurricanes experienced along the East Coast of the United States are substantially less than those in the Gulf and generally decrease with higher latitude. At present there are no precise methods for prescribing the initial water level that should be used for a particular location in conjunction with a hypothetical hurricane. It has been the practice to base this initial level on those previously observed in the region. This appears to be the most satisfactory approach at this time. On this basis, when an open-coast surge estimate is to be made for some specific location, all pertinent storm and water-level data should be analyzed to arrive at a reasonable value. The final value selected should also reflect the probability of occurrence of the hurricane event being studied. Thus, for an extremely rare event such as the PMH, a more conservative (i.e., a higher initial water level) value should be adopted provided that the value selected is reasonable for the area.

Normally, in application to hypothetical hurricanes, the astronomical tidal rise is taken in phase with maximum level of the storm surge. For an SPH, the spring high tide is usually taken; for the PMH, that tide exceeded by only 10 percent of the spring tides is taken. The specific tide amplitude chosen depends on the particular geographical location being studied.

Including the effects of the initial water level and astronomical tide in the numerical integration procedure gives a more accurate estimate of the water-level rise at the shore. This is due to more correctly specifying the total water depth for all steps in time and space, and the errors introduced by directly adding these effects to the wind surge are generally very small. Thus, in most cases it is usually satisfactory to include these effects after making the storm wind surge calculations. Another method frequently employed is to include the assumed astronomical tide level and the initial water level as constants in numerical integration procedure and correcting the final water level hydrograph for the time-dependent tide. Taking the tide as a constant for the entire computational time reduces the work involved in ensuring correct phrasing. This scheme also involves errors in the computations due to incorrect depths, but for evaluation of the peak surge the solution would be more satisfactory. In the examples we will use the latter technique.

Section VI. APPLICATION

1. General

Because the numerical model described here is quasi-two-dimensional, calculations can be carried out manually, although for most problems there is a considerable amount of work involved. Use of high-speed electronic computers for performing the storm-surge calculations not only reduces the work, but reduces the chances for error. Thus, when electronic computers are available, machine computations are generally preferred, particularly when several storm-surge estimates are to be made. In the case of either the SPH or PMH, several separate computations are generally needed to ensure proper selection of the storm characteristics for a specific location on the coast. Consequently, manual computations would be very laborious. However, the method for carrying storm-surge computations manually is shown by an example as well as by machine computations.

The formulas presented have been discussed from the viewpoint of evaluating water elevations associated with hurricanes. However, nothing restricts the formulas from being used for predicting a surge from extra-tropical storms provided the storm moves in a shoreward direction over the Continental Shelf. For some coastal regions where hurricanes are not experienced or where strong onshore winds may produce higher surges than hurricanes, the numerical method presented may be useful in predicting setup at shore arising from high winds. Computations of extratropical wind surge in regions where water levels associated with hurricanes are dominant, may provide insight in calibrating the numerical model for a specific location. Thus, estimates of open-coast surge can be made for wind storms as well as hurricanes.

2. Storm Surge Computer Program

A program listing for estimating the open-coast storm surge is given in the Appendix. This program is written in FORTRAN IV, for the UNIVAC 1108 and EXEC II operating system. The UNIVAC 1108 used has 64,000 words of core memory and additional memory from magnetic drums and tapes. Numerous comment cards have been provided in the program to identify the symbols and to give a running commentary of the procedures employed. This program with its moderate memory capacity requirements and program simplicity can be readily adapted to other machines in most cases.

Input to the program is supplied by cards. Considerably more cards are required for computing storm-surge associated with actual or observed hurricanes than for computing surge associated with hypothetical hurricanes such as the SPH or PMH. Much of the basic information needed for estimating hypo-hurricanes is generated internal to the program. In subsequent discussions of an example problem, the basic input to the computer will be more clearly demonstrated.

3. Example Problem

For illustration purposes, the peak surge will be determined at the mouth of the Chesapeake Bay using characteristics given by Graham and Nunn (1959) for a storm with a large radius and a moderate forward speed. It is not implied here that this storm is a Standard Project Hurricane (SPH), since a study would be needed to determine if it produced the highest possible peak surge at this location. The parameters taken are as follows:

CPI = 27.57 inches of mercury

P_n = 29.92 inches of mercury

R = 35 nautical miles

V_F = 22 knots (25.3 miles per hour)

V_x = 102 miles per hour

The isovel pattern considered appropriate for the above parameters is given by Graham and Nunn (1959) on their Figure 33.

Figure 3 shows the Chesapeake Bay Entrance and the offshore hydrography over the Continental Shelf. The line along which computations are carried - the traverse line - corresponds to a latitude of 37°00'. This traverse line represents a line which, on the average, is about perpendicular to the bed contours. The path of the storm is taken parallel to and about 35 nautical miles south of the traverse line. Since computations of the surge would be invalid within the Bay, the last raw data position is at the mouth at a longitude of 76°00'. Figure 4 shows the approximate bed profile along the traverse line from the mouth of Chesapeake Bay seaward to the 600-foot depth contour. Experience has shown that a point where the depth is 300 feet is usually sufficient for commencing the computation from the seaward position to the most landward point. Setup in regions deeper than this depth are generally negligible. This will become evident by the example. The discrete points in space in which raw data is supplied and the corresponding depths below mean sea leval are taken as shown on page 53 in the Appendix.

By positioning the isovel so that the maximum wind lies on the traverse line, and winds are about zero at the most landward position, the values of wind (W), radius (r), and theta (θ) can be plotted as a function of distance from the mouth of the Bay seaward. For the example, this is shown on Figure 5 where time in hours indicates the position relative to the mouth after an elapse of time. The method of evaluating W, r and θ along the traverse line is shown on Figure 6.

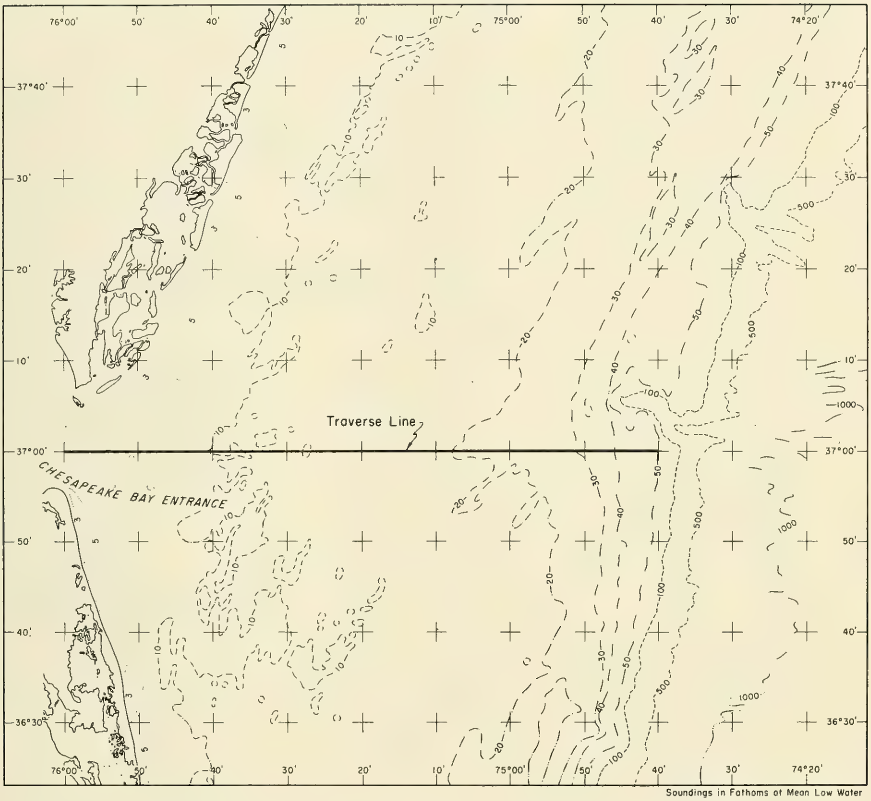

Figure 3. Offshore Bed Contours and Traverse Line for Chesapeake Bay Entrance

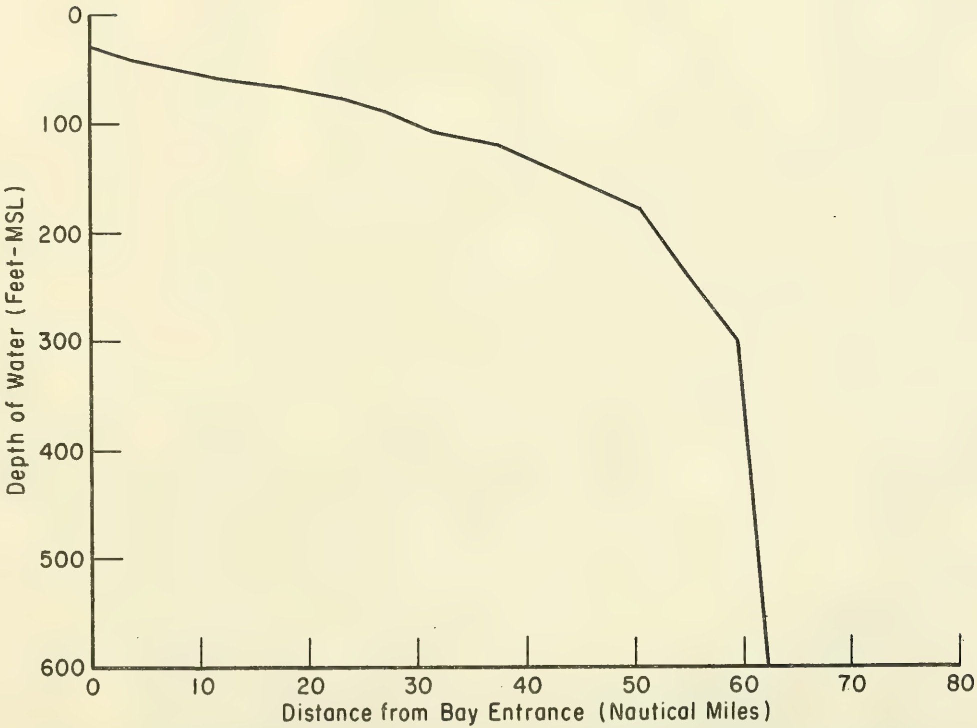

Figure 4. Seabed Profile Offshore of Chesapeake Bay Entrance

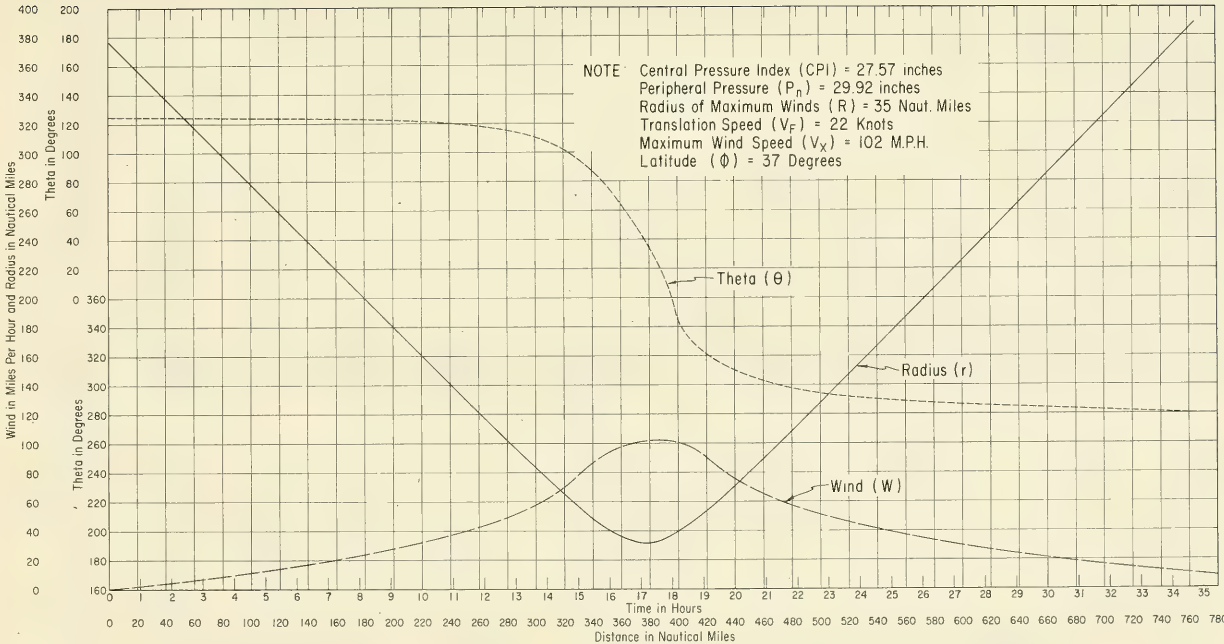

Figure 5. Hypo-Hurricane Characteristics Off Chesapeake Bay Entrance

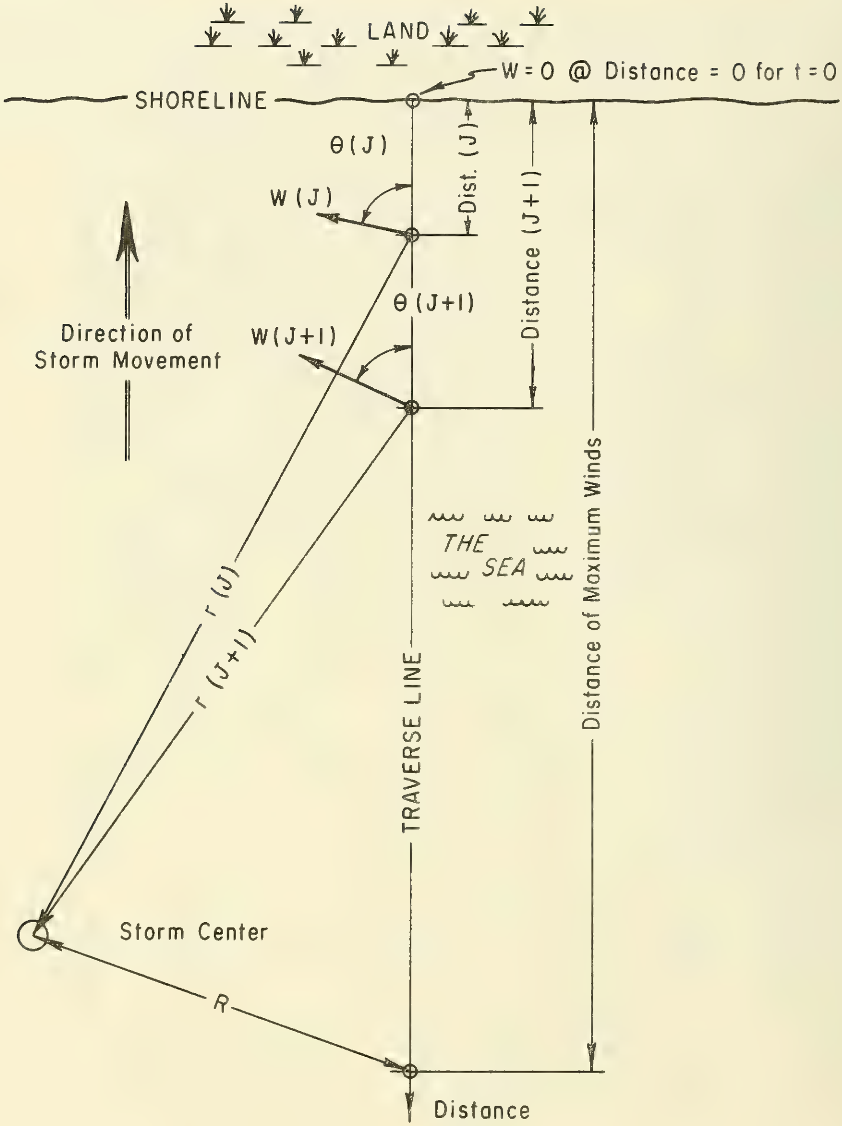

Figure 6. Radial Distances and angles of the Wind Along Traverse Line

From Figure 5, the parameters shown can be read for all selected spatial points and at every time step used. In actual practice, Figure 5 should be plotted on large rectangular graph paper so that the specific values can be read more precisely. The one shown here is for illustration purposes only.

Resolution of the problem will be first considered from the standpoint of computer applications, and then from the standpoint of manual calculations.

The input data in connection with computer program for the example problem is shown in the Appendix on page 52. Every line of data represents an input card, and each card or set of cards is numbered at the right for reference to the following explanation:

CARD 1: This is a title card which is to be used for identification of the problem, such as location, date, etc.

CARD 2: The first number indicated as 62 on the card is the total number of time steps used in computing the storm surge, or symbolically, this is denoted as NM = 62. With reference to Figure 5, it is seen that if 35 hours of computational time are taken, then based on the forward speed of the storm of 22 knots, the distance required on the graph for computational purposes is $V_F t = 770$ nautical miles. However, the parameters must be known 62 nautical miles beyond this distance due to the width of the shelf or a total distance of 832 nautical miles. If 31 hours are selected as computing time, it is seen that the parameters are always defined, thus this time will be used in the computations. Furthermore, if computations are carried out in time steps of one-half hours, then the required number of time increments is 62.

The second value is the number of shelf reaches (LM). There are 18 positions on the traverse line for supplying raw data (see page 53 of the Appendix), thus there are 17 increments along the line.

The third value is an option of the manner in which data is to be supplied. If IDATA = 1, all wind-stress, pressure, and astronomical-tide data are supplied by card externally, otherwise the data are generated internally.

The fourth and fifth values, IOMIT and IOMITD, if equal to 1, omits a detailed printout of output and input data, respectively; otherwise a detailed printout is made.

CARD 3. The set of cards shown here contains the values of the time increments (DELT). Here, they are taken identical for all NM. However, the program is written so that any time increment can be taken for a given time level.

CARD 4: The cards in this set give the distances in nautical miles

(DIST) from shore for all discrete points along the traverse line beginning with the most seaward point.

CARD 5: All cards in this set give the depths (D) below the still-water level for all points corresponding to DIST above.

CARD 6: This set represents the latitudes (PHI) at the discrete points along the traverse line. Since the traverse line corresponds to a latitude 37 degrees, all values are the same.

CARD 7: The first five values on this card, R, P_o, P_n, V_F and S_e, were defined previously. The next three values are the constants C_1, C_2, and C_3, which correspond to the constants given in Equations (25), (26), and (27), respectively. The last value of 1.1 is a wind-stress correction factor (WKCOR). This increases Van Dorn's (1953) wind-stress factor by 10 percent to account for the additional stress caused by energy imparted to the sea due to precipitation.

CARD 8: The first value is maximum gradient wind speed (WX) and the second value is the energy dissipation factor. Since calibration of the numerical model has not been carried out for this location, a value of 0.0025 is taken.

CARD 9: The cards in this set give the height of the astronomical tide above the mean sea level datum. Here the astronomical tide is taken as a constant for the entire computational period with anticipation of correcting the final hydrograph. However, the program is written in such a way that an actual tidal hydrograph can be provided in the input.

The remaining cards are provided only if IDATA is not equal to 1, which is the case for this example. These cards, with the exception of the first one, give the distances indicated on the horizontal axis on Figure 5 and the corresponding values of the parameters shown. The discrete values of r, W and θ are chosen in such a way that the intermediate values can be interpolated by the program linearly. Thus, when the curves change rapidly, values must be prescribed frequently with distance; when curves change slowly, values can be prescribed less frequently for relatively straight curves. The program by an interpolation procedure reconstructs the curves in tabular form for each unit of distance for possible use in generation of the basic storm surge information.

CARD 10: The values 21, 28 and 26 are the number of points selected for adequate representation of r, W and θ curves, respectively.

CARDS 11, 12, and 13: These cards give the distances along the horizontal axis in which r, W, and θ are specified, respectively.

CARDS 14, 15 and 16: These cards give the values of r, W, and θ at the specified points along the traverse line, respectively.

The output of the program is shown on pages 54 and 55 in the Appendix. Page 53 shows a printout of the basic information of the open-coast storm-surge problem. For example purposes, the values indicated below the series of stars on page 53 are the wind stress, astronomical tide, and pressure setup data generated internally in the program for all reaches along the traverse line for two time levels. These data provide the basic information for the storm-surge problem, and is input by card when IDATA = 1. In case that IOMITD = 1, this information is not printed.

Page 54 in the Appendix shows an example of a detailed printout of the storm-surge results for a single time level. If IOMIT = 1, this information will not be printed.

Page 55 in the Appendix gives a summary of the problem, together with the various components contributing to the total setup at the mouth. Thus, it is seen that the peak surge for this storm for the Chesapeake Bay Entrance is 13.4 feet. The estimate of the peak surge, tabulated in the column of total water level, is assumed to be correct, but other values for the total water level would require correction for the tidal oscillation. Such an adjustment will not be shown here since it is only a matter of trigonometry and arithmetic.

Because the surge is not being evaluated at the shore for this particular problem, wave setup is not a factor in the total setup. Other factors such as effects of the inlet, local bed configurations, may affect the total water level at the mouth, but since we don't know how to estimate them, we will consider these effects negligible. Thus, the peak design water level would be taken 13.4 feet for the given storm at the mouth of Chesapeake Bay.

Bretschneider (1959) used a one-dimensional numerical scheme for computing the open-coast storm surge for the Chesapeake Bay Entrance. Although he used slightly different hurricane characteristics than the ones used here, it appears that for this particular case that both schemes would, for all practical purposes, give a wind surge on the same order of magnitude.

We will now consider determining the storm surge in the Chesapeake Bay Entrance by manual calculation. For such problems, a bookkeeping system is needed, so that all the values to be calculated can be carried out in a systematic manner. One method is to construct tables similar to the one shown on Table 1 for each time level. Such tables allow stepping through all discrete points in space as well as time. For example purposes only, Table 1 shows the necessary computations at a time level centered between t = 16.5 hours and t + t = 17.0 hours. This corresponds to the time of peak surge found previously from the results of the computer program. The table not only shows the basic data for the present time level, but the necessary values evaluated at the previous time level. Many of the columns give a breakdown of the pertinent equations presented in the text so that the final equations can be resolved systematically in steps.

Finally, we see that the peak surge estimated manually is the same as that estimated by high-speed digital computations. However, there is usually a difference in the two values because of truncation and round-off errors.

TABLE 1

MANUAL COMPUTATIONS AT A TIME LEVEL CENTERED BETWEEN

$t = 16.5$ hours and $t + \Delta t = 17.0$ hours

Table 1 - Manual Computations at a Time Level Centered between t = 16.5 hours and $t + \Delta t$ = 17.0 hours

1 Distance Offshore and Δx (N.M.)	2 Water Depth d, $\bar{d}$ (ft. MSL)	3 $\sin\theta$	4 Initial Water Level S_e (ft.)	5 Astro. Tide S_A (ft.)	6 Previous Wind Setup $S_x + S_y$ (ft.)	7 Previous Pressure Setup $S^n_{\Delta p}$ (ft.)	8 Previous Flux V^n (Mi^2/Hr)	9 Previous Wind Stress B^n (Mi/Hr)^2	10 Radial Distance r, $\bar{r}$ (N.M.)	11 Wind Angle θ, $\bar{\theta}$ (Degrees)	12 Wind Speed W, $\bar{W}$ (Mi/Hr)	13 $R/\bar{r}$	14 $e^{-R/\bar{r}}$	15 $S^{n+1}_{\Delta p}$ Eq. (34) (ft.)	16 $\bar{W}\cos\bar{\theta}$ (Mi/Hr)^2	17 $\bar{W}\sin\bar{\theta}$ (Mi/Hr)^2	18 Wind Stress Coef. k Eq. (9a)	19 A^{n+1} = 1.10 · k · Col. 16 (Mi/Hr)^2
62.0	600.0								57.5	318	86.0							
Δx=2	$\bar{d}$=475.0	0.60182	0.5	2.5	0.810	1.39	0.0797	-0.0160	56.7	319	87.0	0.617	0.540	1.23	5712	-4966	2.77×10^{-6}	0.0174
60.0	350								56.0	319	88.0							
5.0	295.0	0.60182	0.5	2.5	0.405	1.43	0.0747	-0.0158	54.0	321	90.0	0.648	0.523	1.28	6295	-05097	2.79×10^{-6}	0.0193
55.0	240								52.0	323	92.0							
5.0	209.0	0.60182	0.5	2.5	0.762	1.50	0.0389	-0.0144	50.0	325	93.7	0.700	0.497	1.35	7192	-5038	2.82×10^{-6}	0.0233
50.0	178.0								48.0	327	95.5							
5.0	166.0	0.60182	0.5	2.5	1.339	1.57	0.0603	-0.0091	46.5	330	97.3	0.753	0.471	1.42	8199	-4734	2.85×10^{-6}	0.0257
45.0	154.0								45.0	332	98.0							
5.0	142.0	0.60182	0.5	2.5	1.799	1.63	0.0056	0.0001	43.5	336	99.0	0.805	0.447	1.48	8954	-3986	2.86×10^{-6}	0.0282
40.0	130.0								42.0	339	100.0							
5.0	122.5	0.60182	0.5	2.5	2.511	1.70	0.0453	0.0085	40.2	344	100.5	0.870	0.419	1.56	9709	-2784	2.87×10^{-6}	0.0307
35.0	115.0								38.5	350	101.0							
5.0	108.5	0.60182	0.5	2.5	3.311	1.76	0.0531	0.0144	37.2	359	101.5	0.940	0.391	1.63	10301	-180	2.87×10^{-6}	0.0325
30.0	102.0								36.0	8	102.0							
5.0	93.0	0.60182	0.5	2.5	4.168	1.78	0.0525	0.0189	34.5	14	102.0	1.014	0.363	1.71	10095	2517	2.88×10^{-6}	0.0320
25.0	84.0								33.0	20	102.0							
5.0	77.5	0.60182	0.5	2.5	5.052	1.78	0.0466	0.0220	32.5	25	101.0	1.077	0.341	1.77	9429	4397	2.88×10^{-6}	0.0299
20.0	71.0								32.0	29	102.0							
5.0	67.5	0.60182	0.5	2.5	5.917	1.76	0.0422	0.0243	32.0	34	102.0	1.094	0.335	1.78	8625	5818	2.88×10^{-6}	0.0273
15.0	64.0								32.0	38	102.0							
5.0	60.0	0.60182	0.5	2.5	6.730	1.71	0.0384	0.0257	32.0	42	101.5	1.094	0.335	1.78	7656	6894	2.87×10^{-6}	0.0242
10.0	56.0								32.0	46	101.0							
5.0	50.0	0.60182	0.5	2.5	7.495	1.65	0.0332	0.0263	32.5	50	100.5	1.077	0.341	1.77	6492	7737	2.87×10^{-6}	0.0205
5.0	44 0								33.0	53	100.0							
1.5	42.0	0.60182	0.5	2.5	7.714	1.60	0.0290	0.0263	33.2	52	99.8	1.053	0.349	1.74	6132	7849	2.86×10^{-6}	0.0193
3.5	40.0								33.5	56	99.5							
1.5	38.0	0.60182	0.5	2.5	7.929	1.58	0.0269	0.0262	33.7	57	99.2	1.037	0.355	1.73	5360	8253	2.86×10^{-6}	0.0169
2.0	36.0								34.0	58	99.0							
1.0	34.5	0.60182	0.5	2.5	8.065	1.56	0.0243	0.0247	34.4	58	96.1	1.017	0.362	1.71	4894	7832	2.84×10^{-6}	0.0153
1.0	33.0								34.8	59	93.1*							
0.5	31.5	0.60182	0.5	2.5	8.189	1.55	0.0123	0.0219	34.9	60	90.2	1.003	0.367	1.70	4068	7046	2.79×10^{-6}	0.0125
0.0	30.0								35.0	60	87.2**							

Time (t) = 16.5 hours; Time ($t+\Delta t$) = 17.0 hours.
Δt = 0.5 hours.

Storm Characteristics and other Basic Information:

P_o = 27.57 inches of mercury ϕ = 37.0° → $\sin\phi$ = .60182 (constant in this case)

P_n = 29.92 inches of mercury   K = 0.0025

V_F = 22.0 knots   Wind Stress Correction factor = 1.10

R_r = 35.0 nautical miles $\Delta p = (p_n - p_o)$ = 2.35 inches of mercury

NOTE:

Columns 6 through 9 are values evaluated at previous time level.

Columns 10, 11 and 12 are values taken from curves given on Figure 5.

* Wind reduced by a factor of 0.945 due to interference with land mass.

** Wind reduced by a factor of 0.890 due to interference with land mass.

*** This is a test.

Table 1 (Continued)

20 $B^{n+1} = 1.10 \cdot k \cdot$ Col. 17 $(Mi/Hr)^2$	21 $\frac{S^n_{\Delta p} + S^{n+1}_{\Delta p}}{2}$ (ft.)	22 $D^{n+\frac{1}{2}}$ Eq. (19) $\sum$Cols. 2, 4,5,6,21 (ft.)	23 D^{n+1} Eq. (20) $\sum$Cols. 2, 4,5,6,15 (ft.)	24 $\left(\frac{B^n + B^{n+1}}{2}\right)\Delta t$ (Mi/Hr)	25 $\left(\frac{5280}{D^{n+\frac{1}{2}}}\right)$	26 1+ Col.25 $\cdot K \cdot \Delta t \cdot \lvert V^n \rvert$	27 $V^{n+1} = \frac{\text{Col.24}+V^n}{\text{Col.26}}$ Eq. (27) (Mi^2/Hr)	28 $K \cdot (5280)^2$	29 $\lvert B^{n+1} \rvert \cdot (D^{n+1})^2$	30 $V_c^{n+1} = \sqrt{\frac{\text{Col.29}}{\text{Col.28}}}$ Eq. (28) (Mi^2/Hr)***	31 V^{n+1} (Value used) (Mi^2/Hr)	32 $\frac{106 \cdot \Delta x}{D^{n+1}}$	33 $\Delta S_y = 2 \cdot \sin\phi \cdot$ Col.32 $\cdot V^{n+1}$ Eq. (25) (ft.)	34 $S_y = \sum \Delta S_y$ Eq. (21) (ft.)	35 $\Delta S_x = 406 \cdot \frac{\Delta x \cdot A^{n+1}}{D^{n+1}}$ Eq. (25) (ft.)	36 $S_x = \sum \Delta S_x$ Eq. (22) (ft.)	37 Total Setup S_T Eq. (23) (ft.)
-0.0151	1.31	480.12	480.04	-0.0078	120.94	1.0120	0.0710	69,696	3479.62	0.2234	0.0710	0.442	0.038	0.038	0.029	0.029	4.30
-0.0156	1.35	299.76	299.69	-0.0077	310.26	1.0290	0.0651	69,696	1401.10	0.1418	0.0651	1.768	0.139	0.177	0.131	0.160	4.62
-0.0156	1.42	212.97	212.90	-0.0075	614.65	1.0299	0.0305	69,696	707.09	0.1007	0.0305	2.489	0.091	0.268	0.222	0.382	5.00
-0.0148	1.49	171.83	171.76	-0.0060	944.21	1,0712	0.0507	69,696	436.62	0.0791	0.0507	3.086	0.188	0.456	0,304	0.686	5.56
-0.0125	1.55	148.35	148.28	-0.0031	1266.76	1.0089	0.0025	69,696	274.84	0.0628	0.0025	3.574	0.011	0.467	0.386	1.072	6.02
-0.0088	1.63	129.64	129.57	-0.0001	1658.78	1.0939	0.0413	69,696	147.74	0.0460	0.0413	4.090	0.203	0.670	0.481	1.553	6.78
-0.0006	1.69	116.50	116.44	0.0035	2054.07	1.1363	0.0498	69,696	8.13	0.0108	0.0108	4.552	0.059	0.729	0.567	2.120	7.48
0.0080	1.71	101.88	101.88	0.0067	2685.90	1.1763	0.0503	69,696	83.04	0.0345	0.0345	5.202	0.216	0.945	0.638	2.758	8.41
0.0139	1.77	87.32	87.32	0.0090	3656.29	1.2130	0.0458	69,696	105.98	0.0390	0.0390	6.070	0.285	1.230	0.695	3.452	9.45
0.0184	1.77	78.19	78.20	0.0168	4560.01	1.2405	0,0476	69,696	112.52	0.0402	0.0402	6.777	0.328	1.558	0.709	4.162	10.50
0.0218	1.75	71.48	71.51	0.0119	5456.31	1.2619	0.0399	69,696	111.48	0.0400	0.0399	7.412	0.356	1.914	0.687	4.849	11.54
0.0244	1.71	62.21	62.27	0.0127	7203.56	1.2989	0.0353	69,696	94.61	0.0368	0.0353	8.511	0.362	2.276	0.668	5.517	12.56
0.0260	1.67	54.38	54.45	0.0131	9427.35	1.3417	0.0314	69,696	77.08	0.0333	0.0314	2.920	0.110	2.386	0.216	5.733	12.86
0.0260	1.65	50.58	50.66	0.0131	10897.08	1.4364	0.0278	69,696	66.73	0.0309	0.0279	3.139	0.105	2.491	0.203	5.936	13.16
0.0245	1.63	47.20	47.28	0.0123	12513.65	1.3801	0.0265	69,696	54.77	0.0280	0.0265	2.242	0.072	2.563	0.131	6.067	13.34
0.0216	1.62	44.31	44.39	0.0109	14199.22	1.2183	0.0190	69,696	42.56	0.0247	0.0190	1.194	0.027	2.590	0.057	6.124	13.41

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APPENDIX

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C                 QUASI-TWO-DIMENSIONAL OPEN COAST STORM SURGE PROGRAM
C
C  NOTATION USED:
C      XR = REFERENCE HORIZONTAL DISTANCE FOR RADII IN N.M.
C      XW = REFERENCE HORIZONTAL DISTANCE FOR WIND IN N.M.
C      XT = REFERENCE HORIZONTAL DISTANCE FOR THETA IN N.M.
C      IR = TOTAL NO. OF RADII VALUES READ FROM CURVE.
C      IW = TOTAL NO. OF WIND VALUES READ FROM CURVE.
C      IT = TOTAL NO. OF THETA VALUES READ FROM CURVE.
C      VR = RADII READ FROM CURVE IN N.M.
C      VW = WIND SPEED READ FROM CURVE IN MPH.
C      VT = THETA READ FROM CURVE IN DEGREES.
C       T = ANGLE MEASURED FROM THE POSTIVE X-AXIS COUNTER CLOCKWISE TO
C             THE WIND VECTOR,(THETA).
C    DIST = DISTANCE FROM COAST IN N.M.
C      DT = TOTAL WATER DEPTH IN FEET.
C      SA = SETUP DUE TO ASTRONOMICAL FORCES IN FEET.
C      SE = INITIAL SETUP IN FEET.
C      SP = SETUP DUE TO PRESSURE IN FEET.
C       D = DEPTH BELOW MEAN WATER LEVEL IN FEET.
C       W = WIND SPEED IN MPH.
C     WWX = W * W * COS(THETA) IN MPH SQ.
C     WWY = W * W * SIN(THETA) IN MPH SQ.
C      NM = MAX. NO. OF TIME INCREMENTS.
C      LM = MAX. NO. OF SHELF REACHES.
C      PO = CENTRAL PRESSURE INCHES OF HG.
C      PN = PERIPHERAL PRESSUE IN INCHES OF HG.
C       R = RADIUS OF MAX. WINDS IN N.M.
C      RS = RADII MEASURES FROM STORM CENTER TO POINT ON TRAVERSE TN NM.
C    DELT = TIME INCREMENTS IN HOURS.
C       V = Y-COMPONENT OF VOLUME TRANSPORT.
C     PHI = GEOGRAPHICAL LATITUDE IN DEGREES.
C      PI = 3.14159
C      VF = FORWARD SPEED OF STORM IN KNOTS.
C   WKCOR = CORRECTION FACTOR FOR WIND STRESS COEFFICIENT.
CC1,C2,C3 = DIMENSION CORRECTION FACTORS.
C      WX = MAXIMUM GRADIENT WIND SPEED (MPH).
C     WK = VAN DORNS WIND STRESS FACTOR.
C     BFF = BOTTOM FRICTION FACTOR.
C DELSXN = INCREMENTAL X-COMP SETUP IN FEET.
C DELSYN = INCREMENTAL Y-COMP SETUP IN FEET.
C     SX = TOTAL X-COMP SETUP AT SHORE IN FEET.
C     SY = TOTAL Y-COMP SETUP AT SHORE IN FEET.
C    SPP = PRESSURE SETUP AT PREVIOUS TIME LEVEL.
C    SPN = PRESSURE SETUP AT NEW TIME LEVEL.
      DIMENSION SP(50),WWX(50),WWY(50),WK(50),D(50),DIST(50),XR(100),XW(
     1100),XT(100),RS(1500),W(1500),VR(100),VW(100),VT(100),A(20),SA(99)
     2,DELT(200),PHI(50),T(1500),DAVG(50),DELX(50),SX(100),SY(100),SWW(1
     300),SPRES(100),STOT(100),SINPHI(50),SXP(100),SYP(100),SPP(100),VP(
     4100),EP(100)
C  READ STORM IDENTIFICATION TITLE.
      READ (5,1) (A(I),I=1,20)
    1 FORMAT (20A4)
      READ (5,10) NM,LM,IDATA,IOMIT,IOMITD
   10 FORMAT (5I5)
      READ (5,15) (DELT(I),I=1,NM)
      READ (5,15) (DIST(L),L=1,LM)
      READ (5,15) (D(L),L=1,LM)
      READ (5,15) (PHI(L),L=1,LM)
   15 FORMAT (8F10.2)
```

```
      LMM = LM - 1
      PI = 3.14159
      READ (5,20) R,PO,PN,VF,SE,C1,C2,C3,WKCOR
      READ (5,20) WX,BFF
   20 FORMAT (10F7.2)
      READ (5,15) (SA(N),N=1,NM)
C     IF IDATA = 1 ,WIND STRESS,ASTRONOMICAL SETUP,PRESSURE SETUP AND WIND
C       STRESS COEFFICIENT DATA SUPPLIED BY AN EXTERNAL SOURCE, OTHERWISE
C       DATA GENERATED INTERNALLY FROM WIND,RADII,AND THETA CURVES.
      IF (IDATA .EQ. 1) GO TO 220
      READ (5,10) IR,IW,IT
      READ (5,30) (XR(I),I=1,IR)
      READ (5,30) (XW(I),I=1,IW)
      READ (5,30) (XT(I),I=1,IT)
      READ (5,30) (VR(I),I=1,IR)
      READ (5,30) (VW(I),I=1,IW)
      READ (5,30) (VT(I),I=1,IT)
   30 FORMAT (10F8.2)
      XRE = XR(IR) + 1.0
      IND = XRE
      DO 35 I=1,IT
   35 VT(I) = (VT(I) * PI)/180.0
      IK = 1
C     IN THE FOLLOWING THREE LOOPS ALL ORDINATE VALUES ON THE CURVES ARE
C       INTERPOLATED FOR EACH UNIT OF DISTANCE.
      DO 60 I=1,IR
      RS(IK) = VR(I)
      II = XR(I)
      IKN = XR(I+1)+1
      III = IKN - 1
      IF (II .EQ. III) GO TO 50
      IK = IK + 1
      RATIO = (VR(I+1) - VR(I))/(XR(I+1) - XR(I))
   40 RS(IK) = RS(IK-1) + RATIO
      IK = IK + 1
      IF (IK .GE. IKN) GO TO 60
      GO TO 40
   50 IK = IK + 1
   60 CONTINUE
      IK = 1
      DO 90 I=1,IW
      W(IK) = VW(I)
      II = XW(I)
      IKN = XW(I+1) + 1
      III = IKN - 1
      IF (II .EQ. III) GO TO 80
      IK = IK + 1
      RATIO = (VW(I+1) - VW(I))/(XW(I+1) - XW(I))
   70 W(IK) = W(IK-1) + RATIO
      IK = IK + 1
      IF (IK .GE. IKN) GO TO 90
      GO TO 70
   80 IK = IK + 1
   90 CONTINUE
      IK = 1
      KII = 0
      DO 120 I=1,IT
      IF (KII .EQ. 1) GO TO 93
      T(IK) = VT(I)
      IF (VT(I+1) .GT. 0.0) GO TO 95
      KII = 1
```

```
      GO TO 95
   93 VT(I) = 6.2832
      T(IK) = VT(I)
      KII = 0
   95 II = XT(I)
      IKN = XT(I+1) + 1
      III = IKN - 1
      IF (II .EQ. III) GO TO 110
      IK = IK + 1
      RATIO = (VT(I+1) - VT(I))/(XT(I+1) - XT(I))
  100 T(IK) = T(IK-1) + RATIO
      IK = IK + 1
      IF (IK .GE. IKN) GO TO 120
      GO TO 100
  110 IK = IK + 1
  120 CONTINUE
      HOUR = 0.0
C  IN THE FOLLOWING LOOP THE PERTINENT INTERPOLATED VALUES ARE USED TO
C     GENERATE THE BASIC INPUT DATA FOR THE STORM SURGE PROBLEM.
      DO 210 N=1,NM
C  THE STORMS POSITION RELATIVE TO THE SHORELINE IS DETERMINED.
      DISTC = HOUR * VF
      DO 170 L=1,LM
      DI = DIST(L) + DISTC + 1.0
      LD = DI
C  SETUP DUE TO THE ATMOSPHERIC PRESSURE DIFFERENTIAL IS EVALUATED.
      SP(L) = 1.14 * (PN - PO) * (1.0 - EXP(-R/RS(LD)))
      IF (DIST(L) -1.0) 130,140,145
C  THE WIND SPEED NEAR SHORE DUE TO THE STORMS INTERFERENCE WITH THE
C     LAND MASS.
  130 WIND = W(LD) * 0.89
      GO TO 150
  140 WIND = W(LD) * 0.945
      GO TO 150
  145 WIND = W(LD)
  150 WSQ = WIND * WIND
      WWX(L) = WSQ * COS(T(LD))
      WWY(L) = WSQ * SIN(T(LD))
      IF (W(LD) .LE. 16.0) GO TO 160
C  VAN DORNS WIND STRESS COEFFICIENT IS DETERMINED.
      WK(L) = 0.0000011 + 0.0000025 * (1.0 - 16.0/W(LD))**2
      GO TO 170
  160 WK(L) = 0.0000011
  170 CONTINUE
      WRITE (39) DELT(N)
      DO 200 LL=1,LMM
      WRITE (39) WWX(LL+1),WWX(LL),WWY(LL+1),WWY(LL),SA(N),SP(LL+1),SP(L
     1L),WK(LL)
  200 CONTINUE
      HOUR = HOUR + DELT(N)
  210 CONTINUE
  220 CONTINUE
      WRITE  (6,230)
C  THE BASIC INFORMATION OF THE STORM PROBLEM IS WRITTEN OUT.
  230 FORMAT (1H1,30X,52HQUASI-TWO-DIMENSIONAL OPEN COAST STORM SURGE PR
     1OGRAM///)
      WRITE (6,1) (A(I),I=1,20)
      WRITE (6,250)
  250 FORMAT (54X,10HINPUT DATA,/,54X,10H----- ----,///)
      WRITE (6,260) PO,PN,R,WX,VF,SE,RFF,WKCOR,C1,C2,C3
  260 FORMAT (11X,19HCENTRAL PRESSURE = ,F5.2,8H IN. HG.,22X,22HPERIPHER
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```
     1AL PRESSURE = ,F5.2,8H IN. HG.//,5X,25HRADIUS TO MAXIMUM WIND = ,F
     24.1,5H N.M.,24X,24HMAXIMUM GRADIENT WIND = ,F5.1,7H MI/HR.,//,10X,
     320HTRANSLATION SPEED = ,F4.1,6H KNOTS,32X,15HINITIAL RISE = ,F4.2,
     45H FEET,//,5X,25HBOTTOM FRICTION FACTOR = ,F6.4,19X,32HWIND STRESS
     5 CORRECTION FACTOR = F4.2,//,17X,5HC1 = ,F6.1,21X,5HC2 = ,F6.1,21X
     6,5HC3 = ,F7.1,///)
      WRITE (6,270)
  270 FORMAT (40X,41HSEABED PROFILE OVER THE CONTINENTAL SHELF,//,46X,13
     1HDISTANCE FROM,8X,5HDEPTH,/,47X,12HSHORE (N.M.),8X,6H(FEET))
      DO 280 L=1,LM
      WRITE (6,290) DIST(L),D(L)
  280 CONTINUE
  290 FORMAT (49X,F5.2,9X,F5.1)
      IF (IDATA .NE. 1) GO TO 340
      DO 330 N=1,NM
C  STORM DATA IS READ FROM CARDS. THIS OPTION IS USED FOR SUPPLYING RAW
C     DATA ASSOCIATED WITH ACTUAL STORMS.
      READ (5,300) DELT(N)
  300 FORMAT (6XF6.2)
      WRITE (39) DELT(N)
      DO 320 LL=1,LMM
      READ (5,310) WWX(LL+1),WWX(LL),WWY(LL+1),WWY(LL),SA(N),SP(LL+1),SP
     1(LL),WK(LL)
      WRITE (39) WWX(LL+1),WWX(LL),WWY(LL+1),WWY(LL),SA(N),SP(LL+1),SP(L
     1L),WK(LL)
  310 FORMAT (4F10.0,6X,3F6.2,5X,F10.9)
  320 CONTINUE
  330 CONTINUE
  340 CONTINUE
      REWIND 39
      TII = 0.0
      IF (IOMITD .EQ. 1) GO TO 405
C  IF IOMITD NOT EQUAL 1, INPUT COMPUTATIONAL DATA PRINTED OUT.
      DO 400 N=1,NM
      WRITE (6,350)
  350 FORMAT (///,1X,119H**************************************************
     1**********************************************************************
     2******)
      READ (39) DELT(N)
      TI = TII
      TII =TI + DELT(N)
      WRITE (6,360) TI,TII
  360 FORMAT (1X,/1X11HTIME (T) = ,F6.2,6X,16HTIME (T+DELT) = ,F6.2,//)
      WRITE (6,370)
  370 FORMAT (10X,8HWWX(I+1),7X,6HWWX(I),7X,8HWWY(I+1),8X,6HWWY(I),5X,11
     1HASTRO. TIDE,4X,7HSP(I+1),8X,5HSP(I),5X11HWIND STRESS,/,67X,6H(FEE
     2T),9X,4H(FT),10X,4H(FT),6X,9HPARAMETER,//)
      DO 390 LL=1,LMM
      READ (39) WWX(LL+1),WWX(LL),WWY(LL+1),WWY(LL),SA(N),SP(LL+1),SP(LL
     1),WK(LL)
      WRITE (6,380) WWX(LL+1),WWX(LL),WWY(LL+1),WWY(LL),SA(N),SP(LL+1),S
     1P(LL),WK(LL)
  380 FORMAT (10X,F7.1,8X,F7.1,7X,F7.1,8X,F7.1,7X,F4.2,10X,F4.2,10X,F4.2
     1,5X,F10.8)
  390 CONTINUE
  400 CONTINUE
  405 CONTINUE
      REWIND 39
      WRITE (6,410)
      IF (IOMIT .EQ. 1) GO TO 422
  410 FORMAT (1H1)
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```
      WRITE (6,420)
  420 FORMAT (54X,11HOUTPUT DATA,/,54X,11H------ ----,///)
      WRITE (6,260) PO,PN,R,WX,VF,SE,BFF,WKCOR,C1,C2,C3
  422 CONTINUE
      DO 425 L=1,LMM
C  INCREMENTAL X-VALUES AND AVG. DEPTHS ARE COMPUTED.
      DELX(L) = DIST(L) - DIST(L+1)
      DAVG(L) =(D(L) + D(L+1))/2.0
  425 CONTINUE
      DO 430 L=1,LM
      PHI(L) = (PHI(L) * PI)/180.0
C  THE SINE OF THE LATITUDE IS EVALUATED.
      SINPHI(L) = SIN(PHI(L))
  430 CONTINUE
      TII = 0.0
      DO 500 N=1,NM
      IF (IOMIT .EQ. 1) GO TO 435
      WRITE (6,410)
  435 CONTINUE
      READ (39) DELT(N)
      SUMSX = 0.0
      SUMSY = 0.0
      IF (IOMIT .EQ. 1) GO TO 445
      TI = TII
      TII = TI + DELT(N)
      WRITE (6,360) TI,TII
      WRITE (6,440)
  440 FORMAT (1X,5HDIST.,3X,5HDEPTH,5X,6HD AVG.,3X,9HPRES.RISE,2X,10HAST
     1RO.TIDE,3X,7HINITIAL,5X,6HY-FLUX,5X,7HONSHORE,4X,10HALONGSHORE,2X,
     210HTOTAL WIND,3X,5HTOTAL,/,1X,4H(NM),3X,8H(FT.MLW),2X,8H(FT.MLW),4
     3X,4H(FT),7X,4H(FT),6X,10HLEVEL(FT),1X,11H(FT*FT/SEC),1X,10HSETUP (
     4FT),2X,10HSETUP (FT),2X,10HSETUP (FT),2X,10HSURGE (FT),//)
  445 CONTINUE
      DO 490 L=1,LMM
C  STORM SURGE COMPUTATIONS BEGIN.
      READ (39) WWX(L+1),WWX(L),WWY(L+1),WWY(L),SA(N),SP(L+1),SP(L),WK(L
     1)
      AN = WK(L) * (WWX(L) + WWX(L+1)) * WKCOR
      BN = WK(L) * (WWY(L) + WWY(L+1)) * 0.5 * WKCOR
      SPN = (SP(L) + SP(L+1))/2.0
      IF (N .NE. 1) GO TO 450
C  PROBLEM IS INIALIZED FOR FIRST TIME LEVEL.
      SXP(L) = 0.0
      SYP(L) = 0.0
      SPP(L) = SPN
      VP(L) = 0.0
      BP(L) = BN
      SAP = SA(N)
  450 DTS = DAVG(L) + SE + SXP(L) + SYP(L)
      DTN = DTS + SA(N) + SPN
      DTH = DTS + ((SA(N) + SAP)/2.0) + ((SPP(L) + SPN)/2.0)
      DA = C3/(DTH)
      DEN = DA *DA *BFF * ABS(VP(L)) *DELT(N)
      VN = ((BN + BP(L))* DELT(N) * 0.5 + VP(L))/(1.0 + DEN)
      BY = ABS(BN)
      VNTEST = SQRT(BY/( BFF*DA*DA))
      VNN = ABS(VN)
C  A CHECK IS MADE TO INSURE THAT THE ALONGSHORE DOSE NOT EXCEED THE
C    LIMITING VALUE.
      IF (VNTEST .GT. VNN) GO TO 460
      IF (VN) 456,457,457
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 456 VN = - VNTEST
     GO TO 460
 457 VN = VNTEST
 460 DELSYN = (C2 * DELX(L) * (SINPHI(L) + SINPHI(L+1)) * VN)/DTN
     DELSXN = (C1 * DELX(L) * AN)/DTN
     SUMSX = SUMSX + DELSXN
     SUMSY = SUMSY + DELSYN
     VS = 7744.0 * VN
     ST = SA(N) + SE + SUMSX + SUMSY + SPN
     SW = SUMSX + SUMSY
     IF (IOMIT .EQ. 1) GO TO 485
C  IF IOMIT NOT EQUAL 1, OUTPUT RESULTS ARE PRINTED OUT IN DETAIL FOR
C    EACH TIME LEVEL.
     WRITE (6,470) DIST(L),D(L)
 470 FORMAT (1X,F5.1,5X,F5.1)
     WRITE (6,480) DAVG(L),SPN,SA(N),SE,VS,SUMSX,SUMSY,SW,ST
 480 FORMAT (21X,F5.1,5X,F4.2,8X,F4.2,7X,F4.2,8X,F7.1,5X,F6.3,7X,F6.3,6
    1X,F6.3,5X,F5.2)
 485 SXP(L) = SUMSX
     SYP(L) = SUMSY
     SPP(L) = SPN
     VP(L) = VN
     BP(L) = BN
 490 CONTINUE
     IF (IOMIT .EQ. 1) GO TO 495
     WRITE (6,470) DIST(LM),D(LM)
C  NEW VALUES ARE SET EQUAL TO PREVIOUS VALUES.
 495 SX(N) = SUMSX
     SY(N) = SUMSY
     SWW(N) = SW
     SPRES(N) = SPN
     STOT(N) = ST
 500 CONTINUE
     K = 1
 505 CONTINUE
     WRITE (6,410)
     WRITE (6,510)
C  THE RESULTS ARE SUMMARIZED FOR ALL TIME LEVELS.
 510 FORMAT (38X,41HSUMMARY OF OPEN COAST STORM SURGE PROBLEM,///)
     WRITE (6,1) (A(I),I=1,20)
     WRITE (6,260) PO,PN,R,WX,VF,SE,HFF,WKCOR,C1,C2,C3
     WRITE (6,520)
 520 FORMAT (,///,2X,4HTIME,6X,5HSETUP,5X,5HSETUP,4X,9HTOT. WIND,3X,9HA
    1ST. TIDE,3X,13HINITIAL WATER,4X,8HPRESSURE,3X,11HTOTAL WATER,/,1X,
    27H(HOURS),3X,7HX-COMP.,3X,7HY-COMP.,4X,5HSETUP,7X,5HLEVEL,9X,5HLEV
    3EL,10X,5HSETUP,7X,5HLEVEL,/,10X,9H(FT. MLW),1X,9H(FT. MLW),2X,9H(F
    4T. MLW),3X,9H(FT. MLW),4X,9H(FT. MLW),7X,9H(FT. MLW),3X,9H(FT. MLW
    5),//)
     AHOUR = 0.0
     DO 540 N=1,NM
     AHOUR = AHOUR + DELT(N)
     WRITE (6,530) AHOUR,SX(N),SY(N),SWW(N),SA(N),SE,SPRES(N),STOT(N)
 530 FORMAT (2X,F6.2,,6X,F5.2,5X,F5.2,5X,F5.2,7X,F5.2,9X,F5.2,10X,F5.2,
    18X,F5.2)
 540 CONTINUE
     IF (K .EQ. 2) GO TO 550
     K = K+1
     GO TO 505
 550 CONTINUE
     END
```

```
CHESAPEAKE BAY ENTRANCE                                                                              1
 62   17     0     0     0                                                                           2
       .5         .5         .5         .5         .5         .5         .5         .5
       .5         .5         .5         .5         .5         .5         .5         .5
       .5         .5         .5         .5         .5         .5         .5         .5
       .5         .5         .5         .5         .5         .5         .5         .5              3
       .5         .5         .5         .5         .5         .5         .5         .5
       .5         .5         .5         .5         .5         .5         .5         .5
       .5         .5         .5         .5         .5         .5         .5         .5
       .5         .5         .5         .5         .5         .5
    62.        60.        55.        50.        45.        40.        35.        30.
    25.        20.        15.        10.        5.         3.5        2.         1.                 4
     0.
     600.       350.       240.       178.       154.       130.       115.       102.
      84.        71.        64.        56.        44.        40.        36.        33.              5
     30.
     37.0       37.0       37.0       37.0       37.0       37.0       37.0       37.0
     37.0       37.0       37.0       37.0       37.0       37.0       37.0       37.0             6
     37.0
 35.00   27.57   29.92   22.00   0.5   203.00  106.00   5280.   1.1                                  7
102.00   .0025                                                                                       8
      2.5        2.5        2.5        2.5        2.5        2.5        2.5        2.5
      2.5        2.5        2.5        2.5        2.5        2.5        2.5        2.5
      2.5        2.5        2.5        2.5        2.5        2.5        2.5        2.5
      2.5        2.5        2.5        2.5        2.5        2.5        2.5        2.5
      2.5        2.5        2.5        2.5        2.5        2.5        2.5        2.5             9
      2.5        2.5        2.5        2.5        2.5        2.5        2.5        2.5
      2.5        2.5        2.5        2.5        2.5        2.5        2.5        2.5
      2.5        2.5        2.5        2.5        2.5        2.5
 21    28    26                                                                                      10
   0.     252.    290.    320.    333.    345.    355.    365.    370.    375.
 378.     380.    385.    390.    400.    410.    420.    433.    450.    510.                       11
 765.
   0.      90.    140.    180.    210.    252.    270.    290.    300.    310.
 320.     340.    345.    360.    369.    380.    390.    402.    410.    420.                       12
 433.     450.    472.    490.    540.    598.    669.    765.
   0.     190.    230.    260.    280.    300.    310.    320.    330.    340.
 350.     370.    380.    390.    395.    400.    405.    410.    430.    450.                       13
 470.     490.    510.    560.    640.    765.
 377.     129.     92.5    65.5    54.     45.     39.     34.     32.5    32.
  31.5     32.     32.5    35.     40.     46.     53.     64.     80.    137.                       14
 389.
   0.      10.     17.     24.     30.     40.     46.     53.     57.5    63.
  70.      86.5    90.     97.    100.    102.    102.    100.     97.     90.                       15
  80.      70.     60.     54.     41.     30.     20.     10.
 125.     123.    121.    118.    115.5   111.    107.    102.     95.5    87.
  77.      50.     35.     15.      0.    338.    330.5   326.5   316.5   308.                       16
 301.     296.    293.    288.8   285.    280.
```

QUASI-TWO-DIMENSIONAL OPEN COAST STORM SURGE PROGRAM

CHESAPEAKE BAY ENTRANCE

INPUT DATA

CENTRAL PRESSURE = 27.57 IN. HG.   PERIPHERAL PRESSURE = 29.92 IN. HG.

RADIUS TO MAXIMUM WIND = 35.0 N.M.   MAXIMUM GRADIENT WIND = 102.0 MI/HR.

TRANSLATION SPEED = 22.0 KNOTS   INITIAL RISE = .50 FEET

BOTTOM FRICTION FACTOR = .0025   WIND STRESS CORRECTION FACTOR = 1.10

C1 = 203.0   C2 = 106.0   C3 = 5280.0

SEABED PROFILE OVER THE CONTINENTAL SHELF

DISTANCE FROM SHORE (N.M.)	DEPTH (FEET)
62.00	600.0
60.00	350.0
55.00	240.0
50.00	178.0
45.00	154.0
40.00	130.0
35.00	115.0
30.00	102.0
25.00	84.0
20.00	71.0
15.00	64.0
10.00	56.0
5.00	44.0
3.50	40.0
2.00	36.0
1.00	33.0
.00	30.0

****

TIME (T) = .00   TIME (T+DELT) = .50

WWX(I+1)	WWX(I)	WWY(I+1)	WWY(I)	ASTRO. TIDE (FEET)	SP(I+1) (FT)	SP(I) (FT)	WIND STRESS PARAMETER
-25.1	-26.8	36.7	39.2	2.50	.28	.28	.00000110
-21.1	-25.1	30.8	36.7	2.50	.28	.28	.00000110
-17.5	-21.1	25.4	30.8	2.50	.27	.28	.00000110
-14.2	-17.5	20.6	25.4	2.50	.27	.27	.00000110
-11.2	-14.2	16.3	20.6	2.50	.26	.27	.00000110
-8.6	-11.2	12.4	16.3	2.50	.26	.26	.00000110
-6.3	-8.6	9.1	12.4	2.50	.26	.26	.00000110
-4.4	-6.3	6.3	9.1	2.50	.25	.26	.00000110
-2.8	-4.4	4.1	6.3	2.50	.25	.25	.00000110
-1.6	-2.8	2.3	4.1	2.50	.25	.25	.00000110
-.7	-1.6	1.0	2.3	2.50	.24	.25	.00000110
-.2	-.7	.3	1.0	2.50	.24	.24	.00000110
-.1	-.2	.1	.3	2.50	.24	.24	.00000110
-.0	-.1	.0	.1	2.50	.24	.24	.00000110
-.0	-.0	.0	.0	2.50	.24	.24	.00000110
.0	-.0	.0	.0	2.50	.24	.24	.00000110

****

TIME (T) = .50   TIME (T+DELT) = 1.00

WWX(I+1)	WWX(I)	WWY(I+1)	WWY(I)	ASTRO. TIDE (FEET)	SP(I+1) (FT)	SP(I) (FT)	WIND STRESS PARAMETER
-35.0	-37.0	51.4	54.4	2.50	.29	.29	.00000110
-30.3	-35.0	44.4	51.4	2.50	.28	.29	.00000110
-25.9	-30.3	37.9	44.4	2.50	.28	.28	.00000110
-21.9	-25.9	31.9	37.9	2.50	.28	.28	.00000110
-18.2	-21.9	26.5	31.9	2.50	.27	.28	.00000110
-14.8	-18.2	21.5	26.5	2.50	.27	.27	.00000110
-11.8	-14.8	17.1	21.5	2.50	.26	.27	.00000110
-9.1	-11.8	13.2	17.1	2.50	.26	.26	.00000110
-6.7	-9.1	9.8	13.2	2.50	.26	.26	.00000110
-4.8	-6.7	6.9	9.8	2.50	.25	.26	.00000110
-3.1	-4.8	4.5	6.9	2.50	.25	.25	.00000110
-1.8	-3.1	2.6	4.5	2.50	.25	.25	.00000110
-1.4	-1.8	2.0	2.6	2.50	.25	.25	.00000110
-1.2	-1.4	1.7	2.0	2.50	.25	.25	.00000110
-.9	-1.2	1.3	1.7	2.50	.24	.25	.00000110
-.7	-.9	1.0	1.3	2.50	.24	.24	.00000110

TIME (T) = 30.50 TIME (T+DELT) = 31.00

DIST. (NM)	DEPTH (FT.MLW)	D AVG. (FT.MLW)	PRES.RISE (FT)	ASTRO.TIDE (FT)	INITIAL LEVEL(FT),	Y-FLUX (FT*FT/SEC)	ONSHORE SETUP (FT)	ALONGSHORE SETUP (FT)	TOTAL WIND SETUP (FT)	TOTAL SURGE (FT)
62.0	600.0									
		475.0	.25	2.50	.50	107.8	.000	.007	.007	3.26
60.0	350.0									
		295.0	.25	2.50	.50	29.1	.000	.015	.016	3.27
55.0	240.0									
		209.0	.26	2.50	.50	-97.1	.001	-.022	-.021	3.24
50.0	178.0									
		166.0	.26	2.50	.50	-80.2	.002	-.061	-.059	3.20
45.0	154.0									
		142.0	.26	2.50	.50	-71.2	.002	-.101	-.099	3.16
40.0	130.0									
		122.5	.27	2.50	.50	-63.7	.003	-.142	-.139	3.13
35.0	115.0									
		108.5	.27	2.50	.50	-58.4	.005	-.185	-.181	3.09
30.0	102.0									
		93.0	.27	2.50	.50	-51.9	.006	-.229	-.223	3.05
25.0	84.0									
		77.5	.28	2.50	.50	-45.0	.008	-.275	-.267	3.01
20.0	71.0									
		67.5	.28	2.50	.50	-40.7	.011	-.322	-.311	2.97
15.0	64.0									
		60.0	.29	2.50	.50	-37.7	.014	-.371	-.357	2.93
10.0	56.0									
		50.0	.29	2.50	.50	-32.8	.018	-.422	-.404	2.89
5.0	44.0									
		42.0	.29	2.50	.50	-28.5	.020	-.438	-.418	2.88
3.5	40.0									
		38.0	.30	2.50	.50	-26.3	.022	-.454	-.432	2.86
2.0	36.0									
		34.5	.30	2.50	.50	-23.5	.023	-.464	-.441	2.86
1.0	33.0									
		31.5	.30	2.50	.50	-20.5	.024	-.474	-.450	2.85
.0	30.0									

CHESAPEAKE BAY ENTRANCE

CENTRAL PRESSURE = 27.57 IN. HG. PERIPHERAL PRESSURE = 29.92 IN. HG.

RADIUS TO MAXIMUM WIND = 35.0 N.M. MAXIMUM GRADIENT WIND = 102.0 MI/HR.

TRANSLATION SPEED = 22.0 KNOTS INITIAL RISE = .50 FEET

BOTTOM FRICTION FACTOR = .0025 WIND STRESS CORRECTION FACTOR = 1.10

C1 = 203.0 C2 = 106.0 C3 = 5280.0

TIME (HOURS)	SETUP X-COMP. (FT. MLW)	SETUP Y-COMP. (FT. MLW)	TOT. WIND SETUP (FT. MLW)	AST. TIDE LEVEL (FT. MLW)	INITIAL WATER LEVEL (FT. MLW)	PRESSURE SETUP (FT. MLW)	TOTAL WATER LEVEL (FT. MLW)
.50	-.00	.00	-.00	2.50	.50	.24	3.24
1.00	-.00	.00	-.00	2.50	.50	.24	3.24
1.50	-.00	.00	-.00	2.50	.50	.25	3.25
2.00	-.01	.00	-.00	2.50	.50	.26	3.25
2.50	-.01	.01	-.01	2.50	.50	.27	3.26
3.00	-.01	.01	-.01	2.50	.50	.28	3.27
3.50	-.02	.01	-.01	2.50	.50	.28	3.28
4.00	-.02	.02	-.01	2.50	.50	.29	3.29
4.50	-.03	.02	-.01	2.50	.50	.30	3.30
5.00	-.04	.03	-.01	2.50	.50	.32	3.31
5.50	-.05	.04	-.01	2.50	.50	.33	3.32
6.00	-.06	.05	-.01	2.50	.50	.34	3.33
6.50	-.08	.07	-.01	2.50	.50	.35	3.35
7.00	-.10	.09	-.01	2.50	.50	.37	3.36
7.50	-.13	.12	-.01	2.50	.50	.39	3.38
8.00	-.16	.15	-.01	2.50	.50	.40	3.40
8.50	-.20	.19	-.00	2.50	.50	.42	3.42
9.00	-.24	.24	.00	2.50	.50	.45	3.45
9.50	-.29	.31	.02	2.50	.50	.47	3.49
10.00	-.35	.38	.04	2.5	.50	.50	3.53
10.50	-.41	.48	.06	2.50	.50	.53	3.59
11.00	-.49	.59	.10	2.50	.50	.56	3.66
11.50	-.56	.72	.16	2.50	.50	.60	3.76
12.00	-.64	.88	.24	2.50	.50	.64	3.88
12.50	-.72	1.08	.36	2.50	.50	.69	4.06
13.00	-.74	1.32	.57	2.50	.50	.75	4.32
13.50	-.67	1.61	.94	2.50	.50	.82	4.76
14.00	-.42	1.96	1.54	2.50	.50	.90	5.44
14.50	.11	2.37	2.49	2.50	.50	.99	6.48
15.00	1.00	2.81	3.81	2.50	.50	1.10	7.91
15.50	2.26	3.21	5.47	2.50	.50	1.24	9.71
16.00	3.73	3.34	7.08	2.50	.50	1.39	11.47
16.50	5.11	3.08	8.19	2.50	.50	1.55	12.74
17.00	6.09	2.62	8.71	2.50	.50	1.70	13.41
17.50	6.48	1.99	8.47	2.50	.50	1.78	13.25
18.00	6.19	1.34	7.52	2.50	.50	1.76	12.28
18.50	5.25	.82	6.07	2.50	.50	1.61	10.68
19.00	4.15	.26	4.42	2.50	.50	1.46	8.87
19.50	3.19	-.26	2.94	2.50	.50	1.31	7.25
20.00	2.42	-.72	1.71	2.50	.50	1.17	5.88
20.50	1.85	-1.07	.79	2.50	.50	1.04	4.83
21.00	1.43	-1.30	.13	2.50	.50	.94	4.06
21.50	1.11	-1.44	-.33	2.50	.50	.85	3.52
22.00	.88	-1.51	-.63	2.50	.50	.78	3.15
22.50	.71	-1.52	-.81	2.50	.50	.71	2.90
23.00	.58	-1.48	-.90	2.50	.50	.66	2.76
23.50	.47	-1.42	-.95	2.50	.50	.62	2.67
24.00	.39	-1.35	-.96	2.50	.50	.58	2.62
24.50	.32	-1.27	-.95	2.50	.50	.54	2.59
25.00	.26	-1.21	-.94	2.50	.50	.51	2.57
25.50	.22	-1.14	-.92	2.50	.50	.48	2.56
26.00	.18	-1.06	-.88	2.50	.50	.46	2.58
26.50	.15	-.99	-.84	2.50	.50	.43	2.59
27.00	.12	-.92	-.79	2.50	.50	.41	2.62
27.50	.10	-.85	-.75	2.50	.50	.39	2.64
28.00	.08	-.79	-.70	2.50	.50	.38	2.67
28.50	.07	-.72	-.66	2.50	.50	.36	2.70
29.00	.05	-.66	-.61	2.50	.50	.35	2.74
29.50	.04	-.61	-.56	2.50	.50	.33	2.77
30.00	.04	-.56	-.52	2.50	.50	.32	2.80
30.50	.03	-.51	-.48	2.50	.50	.31	2.83
31.00	.02	-.47	-.45	2.50	.50	.30	2.85

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13. ABSTRACT

A quasi-two-dimensional numerical model for open-coast storm-surge computations is discussed from the standpoint of underlying assumptions, range of validity, calibration, and application. While it is possible to make computations manually, electronic digital calculations are generally preferred. Elementary aspects of hurricanes and the physical factors of storm-generation processes are discussed. The basic hydrodynamic equations are given, together with the assumptions generally made in their development. The equations consistent with the model are reduced forms of the basic equations in which several terms have been neglected. These omissions are indicated, and their effects on the resulting numerical scheme are discussed. The use of design hurricanes for engineering studies is treated. Effects of astronomical tide, initial water level, and atmospheric-pressure setup are considered. A problem is solved for the Chesapeake Bay Entrance by computer and manually. The computer program used is listed.

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I. Title
II. Bodine, B. R.

A quasi-two-dimensional numerical model for open-coast storm-surge computations is discussed from the standpoint of underlying assumptions, range of validity, calibration, and application. Elementary aspects of hurricanes and physical factors of storm-generation are discussed. The basic hydrodynamic equations are given, together with assumptions made in their development. Equations consistent with the model are reduced forms of basic equations in which several terms have been neglected. Use of design hurricanes for engineering studies is treated. Effects of tide, initial water level, and atmospheric-pressure setup are considered. A problem is solved for the Chesapeake Bay Entrance by computer and manually. The program is listed.