CHAPTER 7

WIND TIDES ON LAKE OKEECHOBEE

Lawrence A. Farrer
Chief, Meteorology and Regulation Section, Engineering Division
U. S. Army Engineer District, Jacksonville
Corps of Engineers, Jacksonville, Florida

INTRODUCTION

Determination of wind tides and wave action is an essential step i the design of flood-control and navigation projects and of structures near large bodies of water which may be subjected to hurricane winds.] 1948, the Corps of Engineers initiated a program to collect wind-tide ε wave data on Lake Okeechobee. Basic data collected and investigations made under that program have been published as a series of project bull tins, "Waves and Wind Tides in Inland Waters, Lake Okeechobee, Florida, and in a summary report, "Civil Works Investigation CW-167, Waves and Wind Tides in Shallow Lakes and Reservoirs." Data on wind velocities, wind tides, and waves have been collected under that program during six hurricanes and many minor storms. In this paper an attempt is made to summarize the results of the wind-tide studies and outline the procedur developed for computing wind tides on Lake Okeechobee.

DESCRIPTION OF AREA

Lake Okeechobee is a large, shallow body of fresh water in souther Florida. The lake is nearly circular in shape and has an area of about 730 square miles. The lake bottom is saucer-shaped, with the deepest part at about mean sea level. Bottom composition is chiefly sand, shel. muck, and rock. Aquatic grasses and marsh vegetation cover the western portion of the lake. The entire southern half of the lake and a small section at the north end are inclosed by levees. The crown elevation o existing levees ranges from 32.5 to 37 feet. The lake has a drainage area of 5,500 square miles. The lake is now regulated between the limi of 12.5 and 15.5 feet above mean sea level insofar as hydrologic conditions permit; during flood periods, lake levels often rise several feet above the scheduled stage.

The network of gages from which records have been collected is show on figure 1 along with the topography of the lake bottom. The network c gages includes 14 recording water-level gages, 5 wave staffs, 12 statior where wind speed and direction are measured about 32 feet above the wate surface, and 7 stations where barometric pressures are recorded. Two of the lake stations have additional anemometers near the water surface so that the wind gradient can be measured. Data collected from this networ of gages have been used to evaluate unknowns in the wind-tide formula an develop procedures for computing wind tides.

WIND-TIDE FORMULA

The term "wind tide" is used to describe the changes in water surface caused by action of the wind on the water. Wind tides may be composed of both static and dynamic tides. Dynamic tides, or seiches, occu

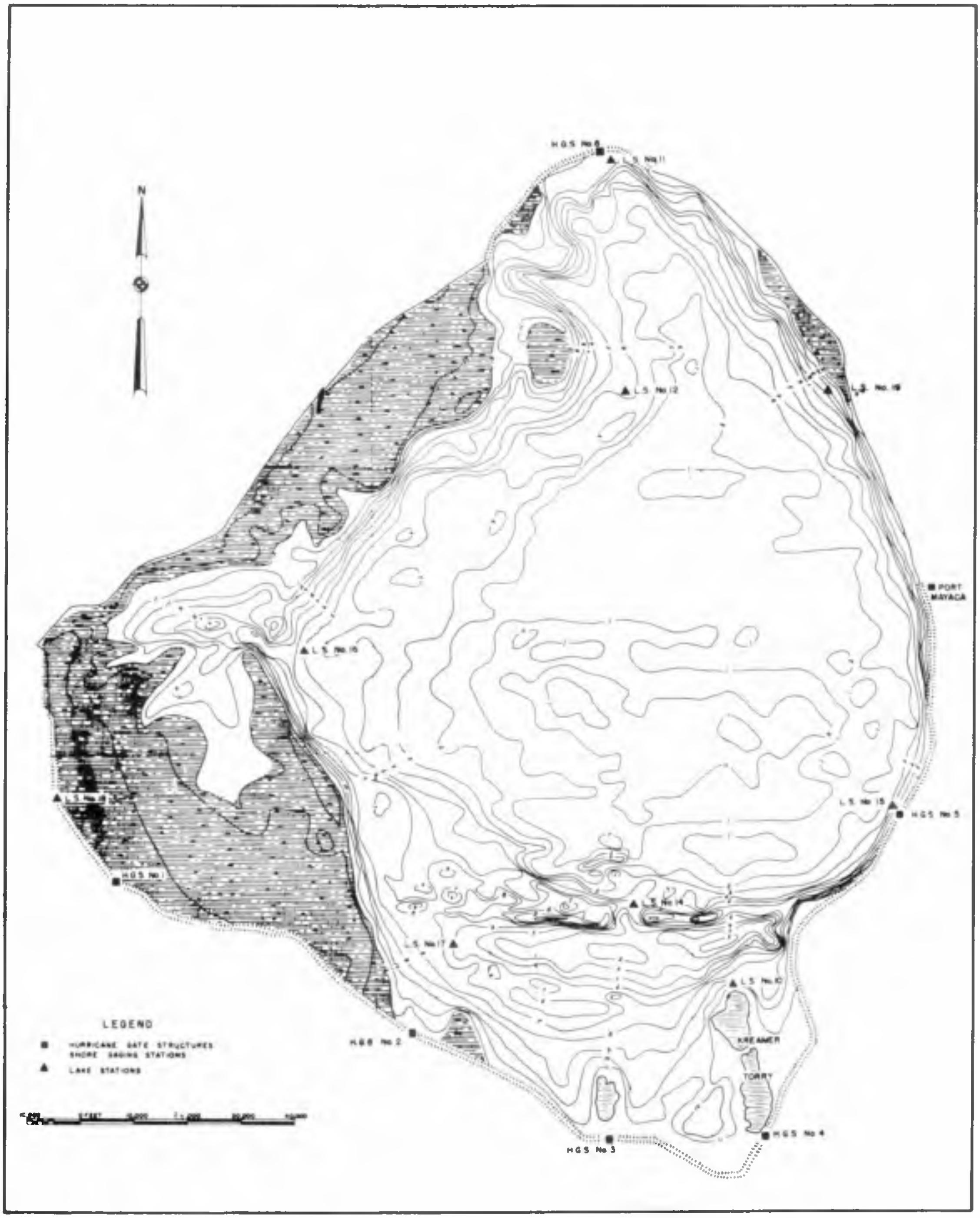


Fig. 1. Topography and gage locations, Lake Okeechobee, Florida

when the momentum of the water carries it beyond the position of stat equilibrium, and oscillations result. The magnitude of the seiches a] pears to be a function of depth, fetch, and bottom characteristics. Seiches of about 1 foot have been recorded on Lake Okeechobee, but the do not appear to have a significant effect on major wind tides on this lake. Analyses of wind tides in this paper pertain solely to static tides.

The basic wind-tide equation used by Hellstrom and others can be written as the differential of the change in water-surface slope with distance:

$$\frac{dh}{dx} = \frac{\lambda T_s}{\gamma (D+h_s)}$$

Terms and symbols used in the wind-tide equations in this paper are de fined as follows:

h_s	Setup above mean water level (ft.)
F	Fetch distance (ft.)
D	Water depth (ft.)
γ	Specific weight of water (62.4 lb./ft.^{3})
V	Wind speed (ft./sec.)
T_s	Tangential stress on water surface (lb./ft.^{2})
T_b	Tangential stress on the bottom (lb./ft.^{2})
λ	A dimensionless parameter, defined as $\lambda = T_s/T_b+1$
N	A dimensionless factor, related to the ratio h_s/D
P	A planform factor used to evaluate the effects of converging and diverging shorelines

The basic equation integrates to

$$h_s = \frac{\lambda T_s F}{2 \gamma (D+h_s)}$$

for a rectangular channel of uniform depth. With the introduction of a planform factor P to account for the effect of converging and diverging shorelines and of Keulegan's N factor to replace h_s on the right of the equation, the basic wind-tide formula becomes

$$h_s = \frac{N \lambda T_s F P}{2 \gamma D}$$

FACTORS AFFECTING WIND TIDES

The principal variables in the basic equation for computing static wind tides are fetch, depth, and shear stress. In some cases, planform and barometric pressure should be considered.

Depth and fetch are physical features of a body of water and can be determined from hydrographic maps. In irregularly shaped lakes of varying depth, the lake should be divided into increments and the average depth determined in each increment so that variations in depth can be taken into consideration. In most cases, the fetch is measured as the straight-line distance across the water surface. However, when there is an appreciable curve in the wind streamlines, the fetch should be measured along the curved line.

Surface shear, T_s, is the tangential stress exerted by the wind on the water surface. Since it is very difficult to obtain a direct measurement of this force over rough water, the surface shear is usually computed from measurements of the wind gradient above the water surface. Von Karman and Prandtl found that the wind profile is logarithmic and that the surface shear can be computed from the equation

$$T_s = \rho_a V^2$$

$$\text{where } V = \frac{k_o V}{2.3 (\log z - \log z_o)},$$

and k_o is a coefficient which Von Karman found to have a value of 0.4, ρ_a the density of air, V the wind velocity, z the distance above the water surface at which the wind velocity was measured, and z_o a roughness parameter obtained by projecting the wind velocity to the boundary layer. Unfortunately, very few reliable measurements have been obtained to establish the velocity gradient above a water surface during unusual storms or hurricanes. Multiple anemometer stations were not established on Lake Okeechobee until 1953 and the highest velocity recorded since that time was 60 feet per second. Anemometers on lake station 14 are now operated about 5.5, 13.5, and 32 feet above the normal water surface. Direct computation of T_s using data collected at that station showed considerable scatter, which made it difficult to extrapolate the data to high wind velocities. Plotting data observed at the 32-foot level against that at the 5.5-foot level indicated the linear relationship shown on figure 2. The points plotted as (.) on figure 2 are data recorded on October 9, 1953, when air and lake temperatures were about equal and rain was falling. The data plotted as (x) were obtained in February and March 1954 after cold air masses had moved across the lake. The air temperature was from 1° to 17° F. colder than the water temperatures and the air was relatively stable. This relationship was used to compute values of T_s for wind velocities measured at the 32-foot level. The resulting shear curve, which has the equation $T_s = 4.39 \times 10^{-6} V^2$, is shown on figure 3. For comparison, figure 3 also shows a shear curve computed by Sibul from wind-velocity measurements in a wind-actuated model at the University of California with winds extrapolated to the 30-foot level by using a logarithmic relation. The close agreement between the curves obtained from

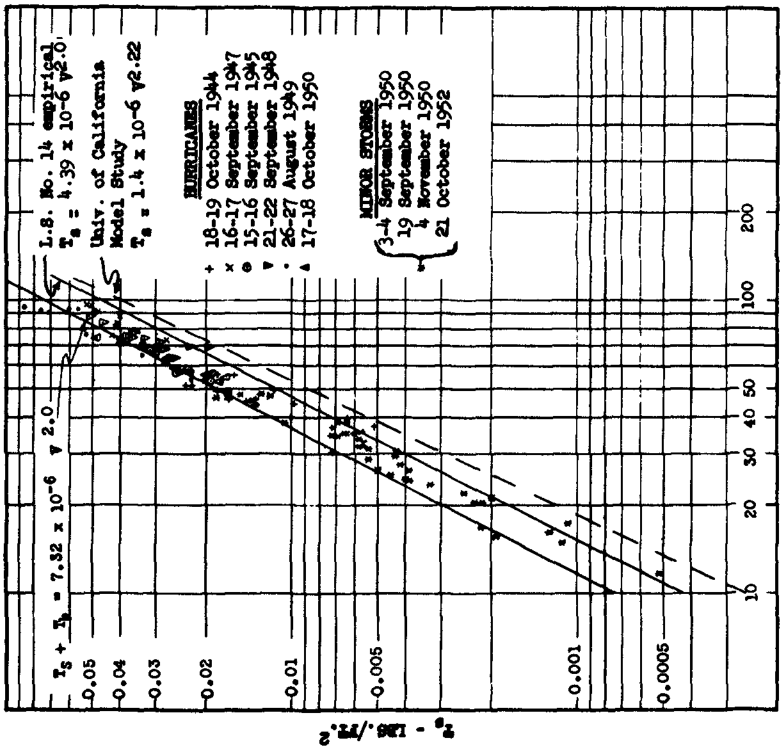


Fig. 3. Shear-stress curves

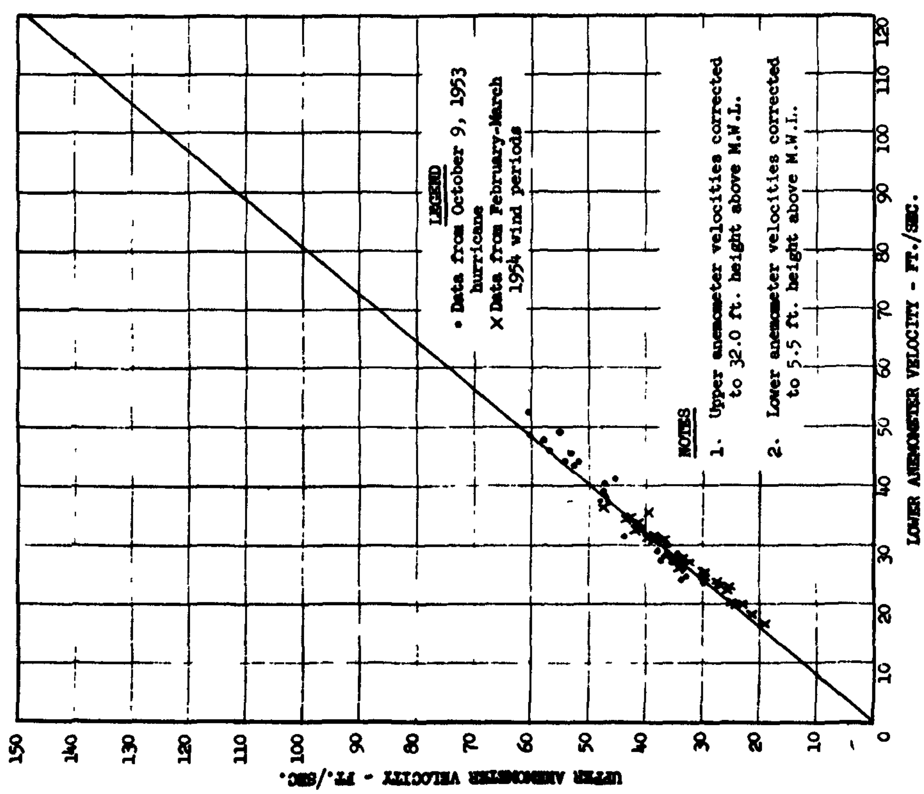


Fig. 2. Relation between wind velocity and elevation of anemometers

model and field measurements indicates that data from wind-actuated models can be used in analyzing wind-tide problems.

Total shear stress, λT_s or $T_s + T_b$, has been determined from laboratory studies by Hellstrom, Keulegan, and Sibul. The model data indicated that T_b varies from zero to a value greater than T_s. However, definite relationships between T_b and bottom roughness, depth, and other factors have not been determined for conditions similar to those found in Lake Okeechobee. Therefore, values of λT_s were obtained by solving the wind-tide equation for λT_s using the basic data collected at Lake Okeechobee during six hurricanes and many minor storms. Basic data are contained in the project bulletins referred to above. The shear stresses needed to reproduce observed wind tides, which ranged from 1 to 10 feet, are plotted on figure 3 against lakewide average wind velocities at the 32-foot level. The values shown were obtained from the wind-tide equation using average depths and velocities over the whole lake without a correction for planform. The scatter of data indicates the value of λ may vary from 1 to 2, and the average value is about 1.66. Some of the scatter in the data could be eliminated by computing the wind tides by a step-integration procedure in which the effect of variations in depth and wind velocity is considered. Computations using step-integration procedures indicated λ may have values of about 1.2 near the center of the lake and about 2 near the edges where the bottom is sloping and considerably rougher. Additional studies are needed to determine how bottom shear varies with depth, bottom roughness, water turbulence, and other factors. Until such studies are completed, the shear-stress curve shown on figure 3--which has the equation $\lambda T_s = 7.32 \times 10^{-6} V^2$--will be used to compute wind tides in Lake Okeechobee. Tickner has found that the wind tides in the model at the University of California can be doubled when window screen is stapled to the bottom to simulate bottom roughness.

Planform.--A planform factor P is used when the center of gravity of a body of water is not at the midpoint of the fetch. For a triangular lake, the factor varies from 0.67 when the wind tide is occurring along a side of the triangle to 1.33 when the tide occurs at an apex. If the shoreline forms an approximate trapezoid, the planform can be obtained from the formula

$$P = \frac{2}{3}\left(\frac{2\, b_o + b}{b_o + b}\right)$$

where b_o is the width of the windward shore and b is the width of the leeward shore.

N is a variable, derived by Keulegan, based on the ratio of setup to depth. With its use, wind tides with either exposed or nonexposed bottom may be computed. Variations in the values of N with h_s/D are obtained from a curve through the following points:

h_s/D	N	h_s/D	N
0.01	1.00	1.00	0.75
0.10	0.97	1.50	0.58
0.30	0.92	2.00	0.44
0.50	0.89	4.00	0.19
0.70	0.85	10.00	0.04

Atmospheric pressure.--When a hurricane passes over a large body c water, the reduction in atmospheric pressure near the center of the storm causes the water level to rise. When there is a difference in th pressure at the point where the wind tide occurs and the average pressu over the lake, a correction of 1.14 feet of water for each inch of mercury is applied.

PROCEDURES FOR COMPUTING WIND TIDES

Wind tides can be computed on lakes or reservoirs where variations in bottom, shorelines, and wind velocity are small, using lakewide aver ages and the basic wind-tide equation. However, where there are large variations in any of these factors, more accurate results can be obtain by breaking the lake up into sections. Two integration methods have be used on Lake Okeechobee. In the cross-sectional method, the lake is di vided into cross sections perpendicular to the wind streamlines. Then, the average bottom elevation, fetch, and wind velocity over each cross section are determined and the water-surface profile across the lake coı puted. The integration procedure is started at the approximate center ‹ gravity of the lake. A setup or setdown across the section to be computed is assumed and values of P and N obtained and substituted in the wind-tide equation along with values of F and λT_s. The setup is computed and compared with that originally estimated. If the assumed setuı does not agree with the computed, new assumptions are made and the proc· ess repeated until satisfactory agreement is obtained. Then, similar computations are made for the next cross section. When the wind-tide profile has been completed, the volume of water above the normal level ı the setup portion of the lake is determined and compared with the volume removed in the setdown end. If the volumes do not balance, an adjustmer must be made in the location of the node line and the entire integration process repeated until a volume check is obtained.

Another method, suggested by Hunt, divides the lake into a number c segments. The number of segments required depends on variations in size of lake, depth, and wind speed. The wind-tide profile is computed for each zone in the same manner as described for cross sections, beginning at an assumed node line. However, with a cross section divided into a number of segments, variation in the water-surface profile in different

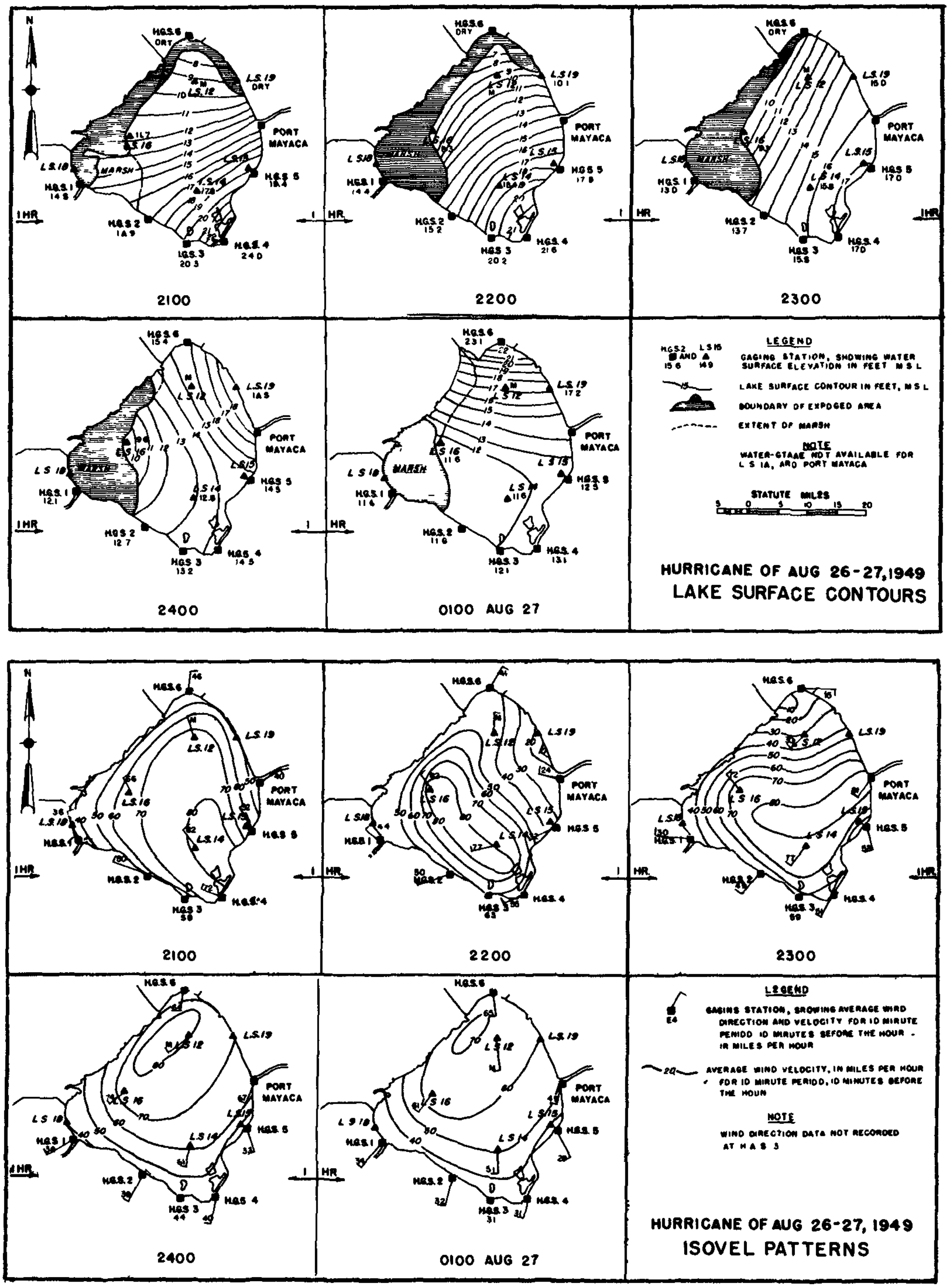


Fig. 4. Water-surface contours and wind velocities during 1949 hurricane

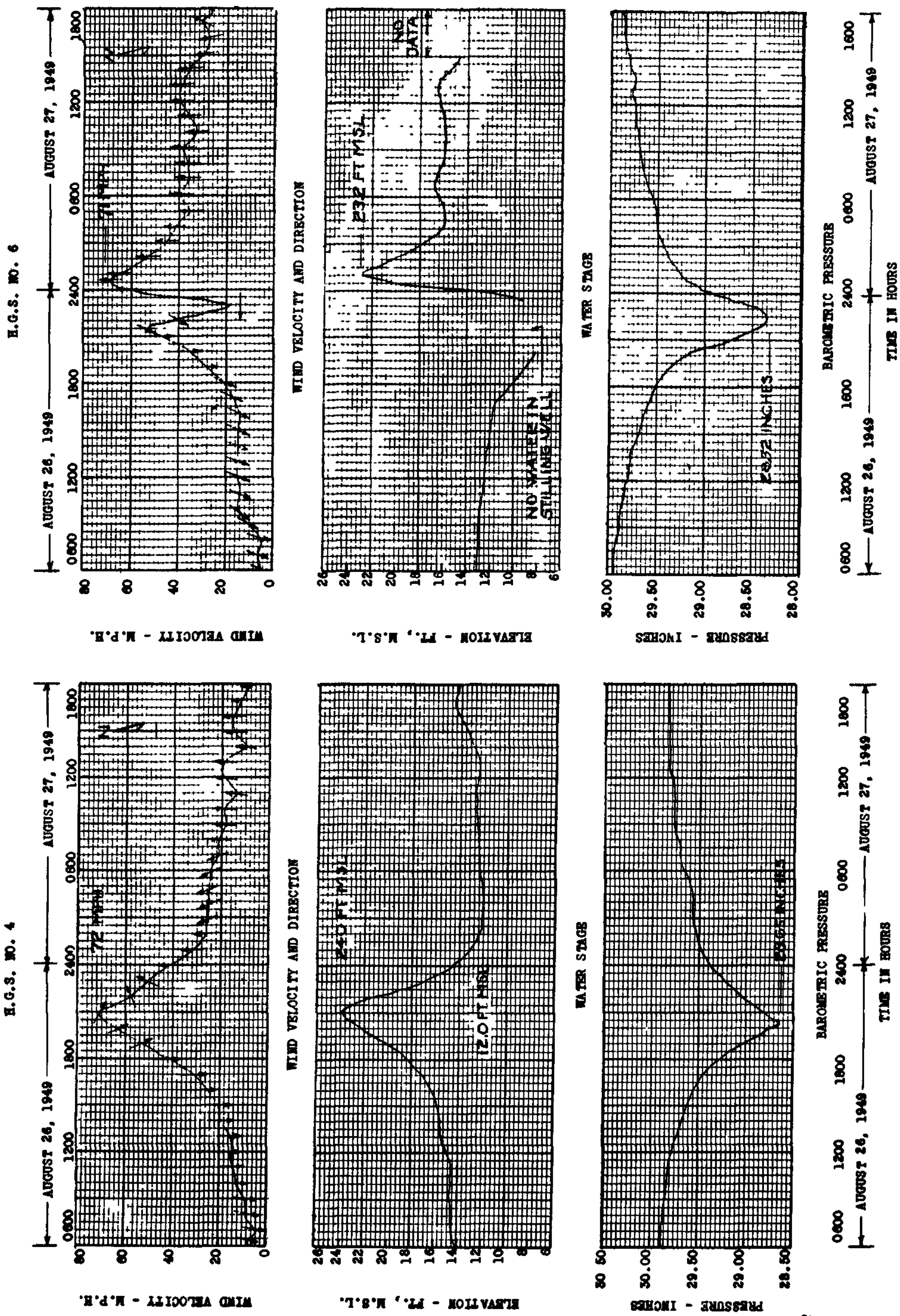


Fig. 5 Meteorological data at

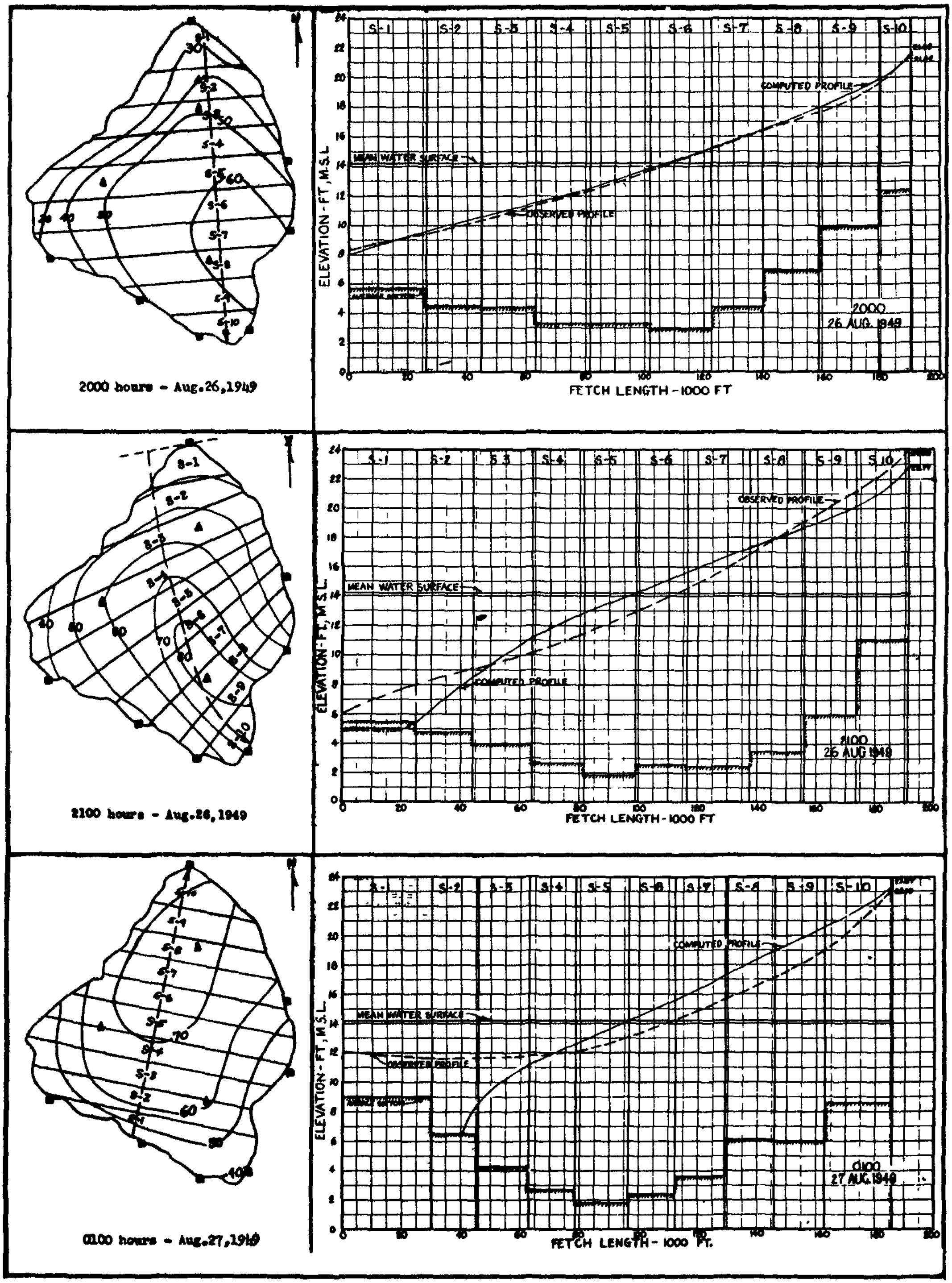
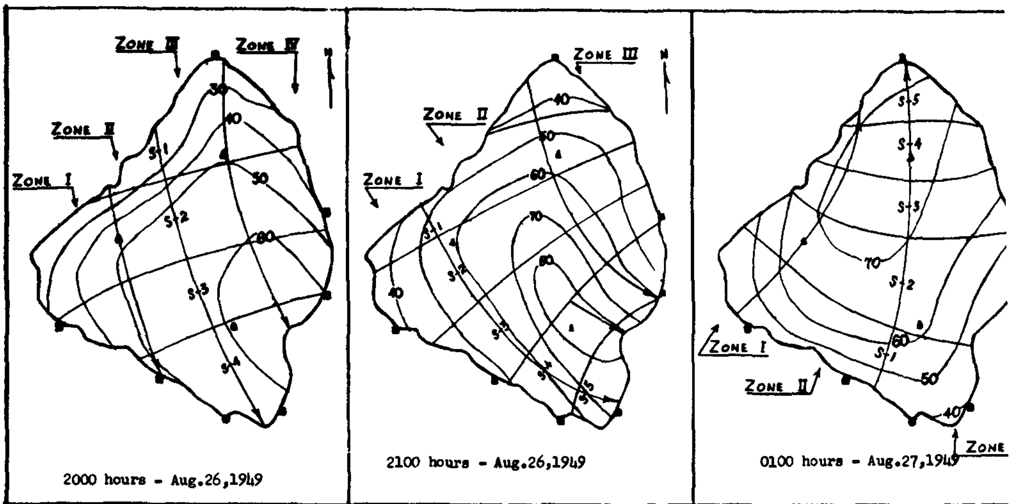
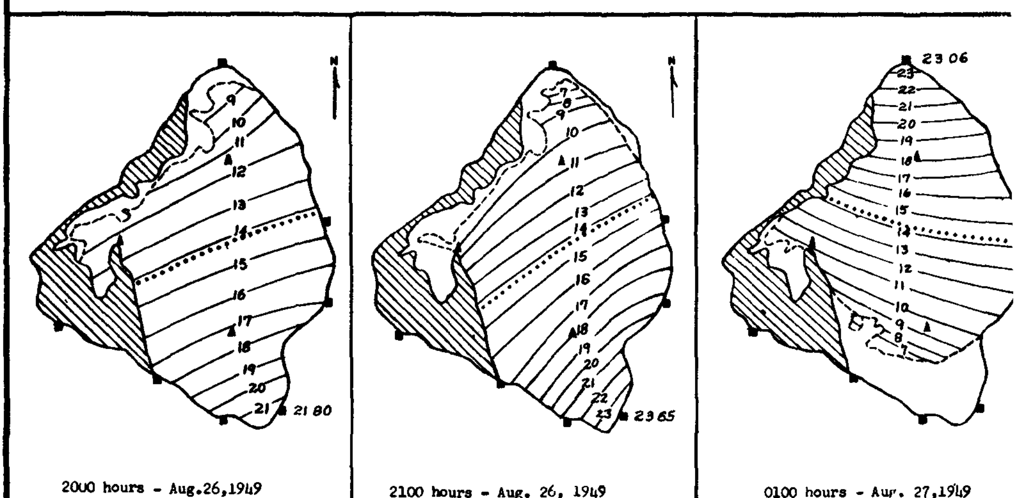


Fig. 6. Wind-tide profiles computed by cross-sectional method



a. Wind velocities over each segment



b. Water-surface contours

Fig. 7. Water-surface contours computed by segmental method

parts of the cross section may exist and adjustments between adjacent zones are required. Where variations in water levels occur perpendicular to the wind streamlines, Manning's formula is used to compute the flow to the adjacent segments. The procedure is one of trial and error and computations are continued until reasonable balances are obtained. After satisfactory water-surface profiles are obtained for each segment, water-surface contours are constructed and the total volume in the lake under the water-surface contours determined. If the volume does not check, an adjustment is made in the nodal line and the entire procedure repeated.

WIND TIDES DURING 1949 HURRICANE

On August 26, 1949, a very severe hurricane came off the Atlantic Ocean and entered Florida near West Palm Beach. It continued on a northwesterly path and the center passed over the northern edge of Lake Okeechobee. Isovel patterns over the lake for the period from 9 p.m. on August 26 to 1 a.m. on the 27th are shown on figure 4 along with water-surface contours for the same period. Graphs on figure 5 show variations in wind velocities, water levels, and barometric pressures at stations where maximum wind tides were recorded. Wind tides computed by both the cross-sectional and segmental integration methods are shown on figures 6 and 7, along with maps of the zones used in computing wind-tide profiles.

SUMMARY

Although much remains to be learned about wind tides and tangential shear stresses, the empirical curves and procedures described here can be used to compute wind tides on Lake Okeechobee with considerable accuracy. Additional studies are needed to determine relationships between wind velocities and shear stresses. It is hoped that sufficient data can be collected on Lake Okeechobee or other bodies of water subjected to hurricane winds to permit verification of all factors in the wind-tide equation and development of accurate procedures for determining wind tides on all bodies of water.

ACKNOWLEDGMENTS

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