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ANALYSIS OF WIND SET-UPS ON LAKE ST CLAIR

by

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Department of Geography
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ABSTRACT

The principal objectives of this study were to investigate the applicability of six different wind set-up theories and the effect of wind, fetch and depth in predicting wind set-ups on Lake St. Clair. A wind set-up is defined as the rise of water level from the "normal" at the leeward shore and a lowering of the level on the windward shore by horizontal shear stresses exerted by wind. Hypotheses were formulated relating wind set-up to wind speed, fetch distance and water depth. Water level data were analyzed, for the period 1963-1972, for St. Clair Shores, Michigan and Belle River, Ontario. Wind speed and direction data were obtained from the Windsor Airport for the calculations of wind stress and fetch. The hypotheses were tested by using regression-correlation analysis.

Wind speed, fetch distance, and water depth explained a significant proportion of the observed wind set-up magnitudes. Although empirical in approach, the regression models developed in this study (using wind, fetch and depth) were just as adequate in predicting wind set-ups as standard theories, which require much more additional information - such as atmospheric stability, air pressure oscillations, vegetation (marsh) effects, and shape factors of the lake.

Even though the regression models and standard theories adequately predicted wind set-ups, there is still a need to considerably improve the prediction. This study concludes with recommendations for further analysis.

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CHAPTER ONE

INTRODUCTION

In shallow lakes the neglect of wind set-up in engineering studies may prove disastrous. Such changes in lake levels may sometimes affect human safety, design and operation of dams, existence of jetties and breakwalls, water intakes, navigation, and cause extensive flooding as observed in 1972-1973. To overcome these problems it is necessary to forecast wind set-up. The magnitude of these changes and the height of waves which can be expected along the shores will govern the degree of protection required for a particular structure or project. This study will investigate the wind set-ups on Lake St. Clair.

The five Great Lakes - Superior, Michigan, Huron, Erie and Ontario with their connecting rivers and Lake St. Clair, have a water surface area of about 95,000 square miles.[1] The total land and water area of the Great Lakes Basin is approximately 295,000 square miles. The average depth of the entire area of the Great Lakes is 302 feet. If the Great Lakes were at their low water datum levels and then rose to their highest stages, the increase of water volume in the lakes would be about 1.3 percent of the total. The Great Lakes system comprises a chain of lakes connecting channels, the excess waters from one lake being discharged through its connecting channel into the lake downstream. The uppermost lake in the chain, Lake Superior, is connected to Lake Huron by the St. Marys River. The Straits of Mackinac connect Lake Michigan and Lake Huron. The outlet of Lake Huron is the St. Clair River

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[1] All figures relating to the Great Lakes have been taken from, United States Corps of Engineers, Water Levels of the Great Lakes, Report on Lake Regulation, Hydraulic and Hydrology, May, 1965.

which extends from the southern end of Lake Huron to Lake St. Clair, which in turn discharges into Lake Erie through the Detroit River. From Lake Huron to Lake St. Clair the difference in elevation is about five feet and from Lake St. Clair to Lake Erie it is about three feet. Lake Erie discharges through its eastern end into Lake Ontario which then discharges into the St. Lawrence River. The level of each of the Great Lakes depends upon the balance between the quantities of water being received by the lake and the quantities of water being removed from the lake. These changes in levels are taking place continually with the natural variations in hydrologic factors, such as precipitation, runoff, evaporation, inflow and outflow.

The factors affecting lake level variations can be classified as, (1) long-period variations, those with general trends upwards or downwards extending over several years; (2) seasonal variations, representing an annually recurring cycle and; (3) short-period variations, lasting from several minutes to a day or two.

Long-period variations are associated with accumulative depatures from normal in the natural hydrologic factors. Seasonal variations of high and low levels in summer and winter are also associated with the natural hydrologic factors. Short period variations such as daily and hourly level fluctations may vary from a few inches to several feet depending on the lake and the weather conditions. These fluctuations are considered to be independent of the volume of water in the lake.

The term wind set-up has been applied to patterns of water level fluctuations when they are caused by winds blowing over the lak or by abrupt deviations in barometric pressure. During such a wind set-up, the level of one area of the lake is raised while the level of another area is lowered. For example, the effect of wind in causing such a disturbance is to drive the surface water forward in greater volume than that carried by the lower return currents, thus raising the water level at the shore toward which the wind is blowing and lowering it at the opposite shore. Such effects are most pronounced in shallow lakes such as Lake St. Clair and in elongated lakes like Lake Erie.

The determination of the wind set-up which can be expected to occur under various climatic conditions is dependent on an accurate evaluation of the characteristics of the water body and the forces exerted by the wind.

The theories for computing the wind set-up stem from the basic differential equation of a change in water surface slope with distance. Recent advances in these theories[1] have proved that functional relationships exist between the wind set-up and the wind, fetch and depth. Wind set-up models and their computational techniques as discussed by various authors have been found to yield results quite close to those observed in nature.

Since prediction methods are becoming more complicated in their formulation and more restrictive in their areas of application the principal objectives of this study are to examine, (1) the

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[1] P. F. Hamblin and W. P. Budgell, Wind Induced Water Level Changes on the South-Eastern Shore of Lake St. Clair, CCIW, Canada, June, 1973.

extent to which six different theories pertaining to wind set-up, are applicable to Lake St. Clair and (2) the effect of wind, fetch and depth in predicting the set-up. The effect of the presence of ice on the lake is also considered in this study.

CHAPTER TWO

REVIEW OF LITERATURE

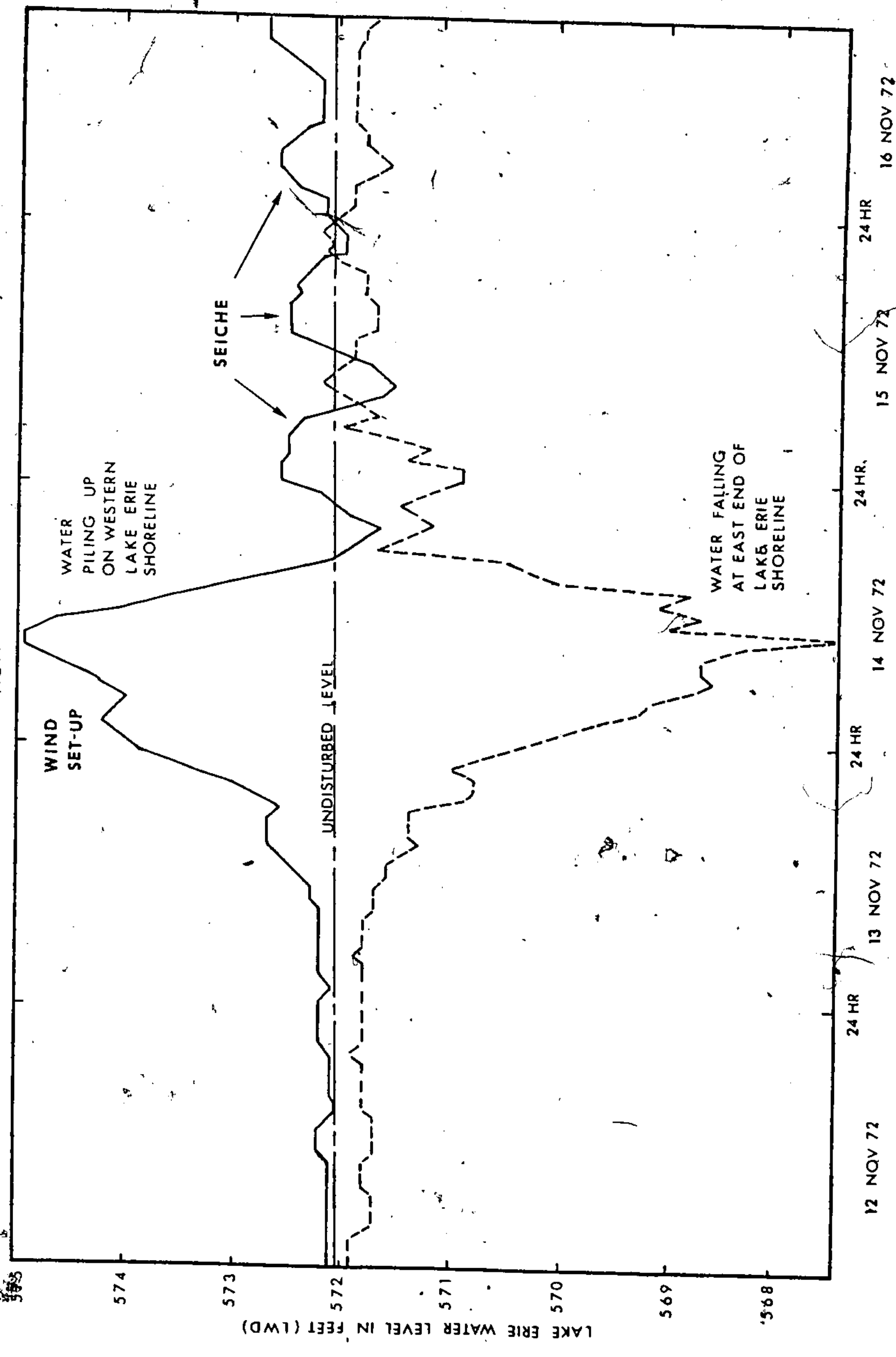
The phenomena of seiches and wind set-up have been extensively investigated, and certain theories regarding their prediction have been developed. Before these theories are discussed, definitions are needed. If the wind, which causes a set-up, dies down quickly or changes direction an oscillatory motion takes place with alternate high and low levels being observed at both ends of the lake, with a periodicity characteristic of the dimensions of the water body. This oscillation is called a seiche. Figure 1 shows the seiche pattern during the November, 1972 storm on Lake Erie. The occurence of a seiche appears to be a function not only of depth and length of fetch, but also, of the bottom characteristics of the lake. The wave length of the fundamental seiche, which has the greatest amplitude, is usually twice the length of the water body. The seiche period can be calculated from the following expression, which is derived by solution of fundamental differential equations for water movements in a lake in which vertical acceleration, frictional forces and geostrophic forces are not taken into account (Hutchinson, 1957):

$$T = 2l/\sqrt{(gd)} \qquad \text{(eq. 1)}$$

Where,

T = period in hours.

FIG. 1



Source: BRAZEL & PHILLIPS, Weatherwise, April, 1974

ℓ = length of lake in feet.
g = acceleration of gravity - 32.2 ft./sec.
d = mean depth along a given length.

The wind exerts a normal horizontal stress on the water, raising the level from 'normal' at the leeward shore and lowering the level on the windward shore. This is called a wind set-up effect, which lasts as long as the force continues to be applied by the wind. Figure 2 is a schematic representation of a wind set-up.

The first accurately recorded observations that lake levels are subject to rhythmic variations, similar in some respects to ocean tides, where made at Geneva. This was mentioned in the scientific literature, in 1730, by Fatio de Duiller, a well known Swiss Engineer.[1] Owing to the peculiar configuration of the Geneva end of Lake Leman, these variations occassionally reached a magnitude of five or six feet, and de Duiller states that at his time, they were known by the local name of 'seiches.' Although Urban Hjarne (1641-1724) observed the periodic changes of Lake Vetter, it is generally accepted that Torbern Bergmen (1735-1784) was the first Swedish scientist who examined the nature of the phenomenon.[2]

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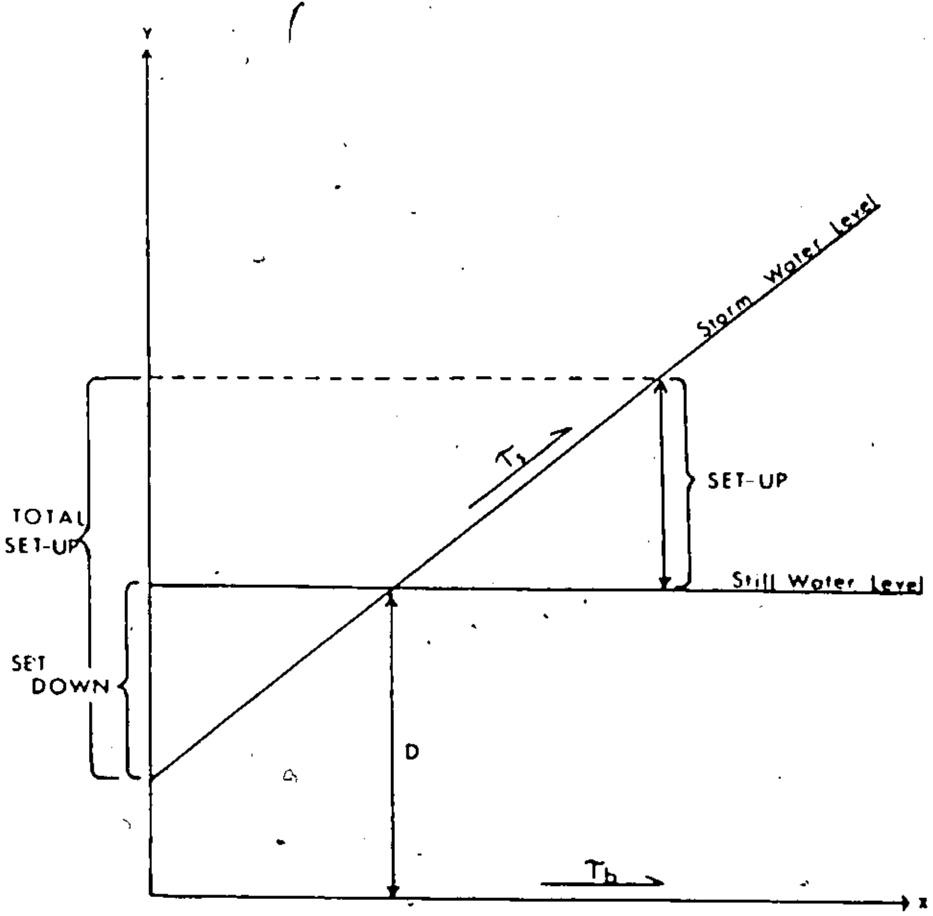
[1] F. Bergsten, The Seiches of Lake Vetter, Geografiska Annaler, Vol.8, 1926, pp.1-73.

[2] Ibid.

FIG. 2

SCHEMATIC REPRESENTATION OF WIND SET-UP



Source HUNT. Winds, Wind Set-Ups & Seiches On Lake Erie, Jan. 1959

Scots Magazine reported the lake level disturbances of several lakes in Scotland caused by the great earthquakes at Lisbon on November 1st, 1755.[1]

H. B. Saussure (1779) related the phenomenon to the sharp and local variations in the pressure of the atmosphere.[2]

The modern mathematics of wave motion is said to date back from works done by Laplace (1776) who arrived at an expression for the velocity of wave propagation. Lagrange (1781), Poisson (1815) and Merian (1828) also dealt effectively with the problem of stationary waves.[3]

The first extensive studies are those of J. P. E. Vaucher and Forel (who was known as the Faraday of seiches). Vaucher (1833) mentions that seiches were of atmospheric origin and could occur at all seasons of the year or at any hour of the day, and that the maximum amplitude does not exceed five feet and the maximum period twenty minutes. Forel, who worked with a self registering limnograph installed at the harbour of Morges on the Lake of Geneva in 1869, concluded that seiches were uninodal (one node), stationary vibrations of lake water. They

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[1] G. Crystal, On the Hydrodynamical Theory of Seiches, Transc. Royal Soc. Edin., Vol.41, Part III, No.25, 1905, pp.599-649.

[2] E. A. Perkins, The Seiche in America, American Met. Journal, Vol.10, No.6, October, 1893, pp.251-263.

[3] G. Crystal, On the Hydrodynamical Theory of Seiches, Transc. Roy. Soc. Edin., Vol.41, Part III, No.25, 1905, pp.599-649.

appear in the form of waves, which alternatively raise and depress the water of the lake on each side of the nodal line of oscillation. There is no change in the nodal line. It reaches its maximum at the two extremities of the longitudinal diameter. They oscillate along the principal direction of the lake, i.e. longitudinal and traverse.[1]

Crystal (1905) mentions that during the next twenty years a large number of enthusiastic observers followed the lead given by Forel and that fifteen-hour seiches were observed by Henry (1900) on Lake Erie (396 km. long) and others as small as fourteen seconds were observed by Endros (1903) in a small pond whose length was only 111 metres. Crystal (1905) stated that a seiche differs from an ocean tide. He termed the enormous oscillations on Lake Erie as forced seiches.

The hydrodynamics of wind set-ups have been investigated theoretically by numerous authors and the theories are based on a fundamental wind set-up equation which can be written as the differential of the change in water surface slope with distance (see equation 2). Considering the problem as a two-dimensional motion based on the assumptions laid down by Ekman (1905) and Lamb (1945) that the extraneous forces be neglected, the equations of motion of a viscous fluid, as derived by Hunt (1959), is of the type,

$$\frac{du}{dt} + u\frac{du}{dx} + w\frac{du}{dz} = \frac{1}{\rho}\frac{dp}{dx} + \frac{1}{\rho}\frac{d\tau}{dz} \qquad \text{(eq. 2)}$$

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[1] G. Crystal, On the Hydrodynamical Theory of Seiches, Transac. Roy. Soc. Edin., Vol.41, Part III, No.25, 1905, pp.599-649.

Where, the differential changes are over time, distance and height and ρ = specific weight of water and τ = shear stress. Several theories are discussed in Appendix A which are used in this study for the prediction of wind set-up.

Hunt (1959) integrated equation (2) with respect to the depth of the lake and deduced a much simpler equation. He neglected the horizontal variation of momentum and the atmospheric pressure gradient. The equation for the surface displacement of water from an initially undisturbed level is expressed as:

$$\frac{dh}{dx} = \frac{\tau_b + \tau_s}{\rho g (D+h)} \quad \text{or} \quad \frac{dh}{dx} = \frac{\alpha \tau_s}{\rho g (D+h)} \qquad \text{(eq. 3)}$$

where,

h = the surface displacement above or below the undisturbed level.[1]

D = depth.

τ_b = frictional stress at the bottom caused by the gradient current due to the inclination of the water surface.

τ_s = surface shear stress that the wind exerts upon the water.

ρg = specific weight of water.

$\alpha = \frac{\tau_s + \tau_b}{\tau_s}$, an average value of 1.04 cm. is used wherever the depth of water is greater than 10 feet.

All equations include wind, fetch and depth but are different due to the site and water body analyzed.

The depth of a lake is defined as the distance from the surface of the water to the lake bed. In lakes of varying depth an integration procedure is used in which the lake is

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[1] Undisturbed or 'calm' level of the lake is defined as the elevation of the lake if no external forces are acting on it. This is obtained by graphing the daily mean elevation.

divided into a number of segments and the mean depth is calculated.

Fetch is the horizontal distance along the wind streamlines across the lake for which the set-up is being determined.

Surface shear is a function of the velocity, temperature, density, stability and turbulence of the air. Bottom shear is affected by the temperature, viscosity, depth and turbulence of the water as well as bottom roughness.[1] A number of investigators, Wust, Boussinesq, Montgomery, Hellstrom, Kuelegan, Sibul and Hunt, have computed the surface shear by analyzing the wind profile above the water surface. The shear stress can be computed by using the Prandtl theory[2] if the vertical velocity profile is logarithmic and the wind velocities are known at two or more elevations above the water surface.

Other Factors Affecting Set-Up:

Other minor factors which have been included in other studies are vegetation, atmospheric pressure changes and shape.

Vegetation:

If the set-up occurs over a marshy area there may be a dampening effect on the set-up, reducing the total set-up due to increased friction losses occuring as the water moves through grasses, and due to the reduction in surface shear between the water and the wind for those times when the grasses protrude above

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[1] U. S. Corps of Engineers, Waves and Wind Tides on Shallow Lakes and Reservoirs, Lake Okeechobee, Florida, June, 1955.

[2] I. A. Hunt, Jr., Winds, Wind Set-Ups and Seiches on Lake Erie, U. S. Corps of Engineers, January, 1959.

the water surface.

Atmospheric Pressure:

When a storm passes over a body of water the reduction in atmospheric pressure near the center of the storm causes the water levels to rise. This factor is considered in computing set-up when the average pressure over the lake varies considerably.

Shape:

The shape can be described by using a few basic parameters - area, perimeter, length of longest axis and the radius of the smallest circumscribing circle and the largest inscribing circle. When the two-dimensional geometric center of gravity of a lake is not the midpoint of the fetch, a planform factor[1] is used. For triangular lakes, the factor varies from 0.67 when the set-up is occuring along a side of a triangle to 1.33 when the set-up occurs at an apex.

Hypothesis:

It is obvious from the literature review and presentation of the theory of wind set-ups that three major factors which control the set-up on any water body are (1) wind speed, (2) fetch and (3) depth. In this study these three factors are analyzed and considered to be the most significant factors for Lake St. Clair. Furthermore, a simple multiple regression

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[1] U. S. Corps of Engineers (1955) study on Lake Okeechobee suggest that if the shorelines form an approximate trapezoid, the planform factor can be obtained from $p = \frac{2}{3}\,\frac{2b_o + b}{b_o + b}$ Where b_o is the width of the windward shore and b is the width of the leeward shore.

equation, although empirical, may be just as significant in predicting set-ups as wind set-up theories developed in other areas. This hypothesis will be tested in this study. Essentially, the use of multiple regression analysis eliminates the air stability, vegetation, shape, and air pressure factors. Therefore, if the multiple regression of just wind, fetch, and depth is found to be as significant as the theories used, the hypothesis that the other factors are important would be rejected.

CHAPTER THREE

METHODOLOGY

Lake St. Clair and Its Environs:

Lake St. Clair is nearly circular in form[1] with a length of 26 miles and a breadth of 24 miles. It has an area of about 450 square miles[2] and an average depth of 11.5 feet. Figure 3 shows an outline of the lake. The length of the coastline is about 169 miles, a major portion of which, on the eastern side, is lined with marsh, which remains under water for a major part of the year. The inlet to the lake is the St. Clair River to the northeast and the outlet is the Detroit River to the southwest. A narrow strip of the lake bed from the Detroit River to the St. Clair River has been dredged for navigation and is much deeper. The area on the northeast forming the St. Clair River delta and covering Dickinson Island, Harsens Island, Walpole Island, Squirrel Island, Ste. Anne Island, and Goose Lake, remains inundated with water.

Site Selection and Instrumentation:

The selection of sites was confined to the western and southern shores of the lake because of the absence of water level gauge stations elsewhere around the lake. On the

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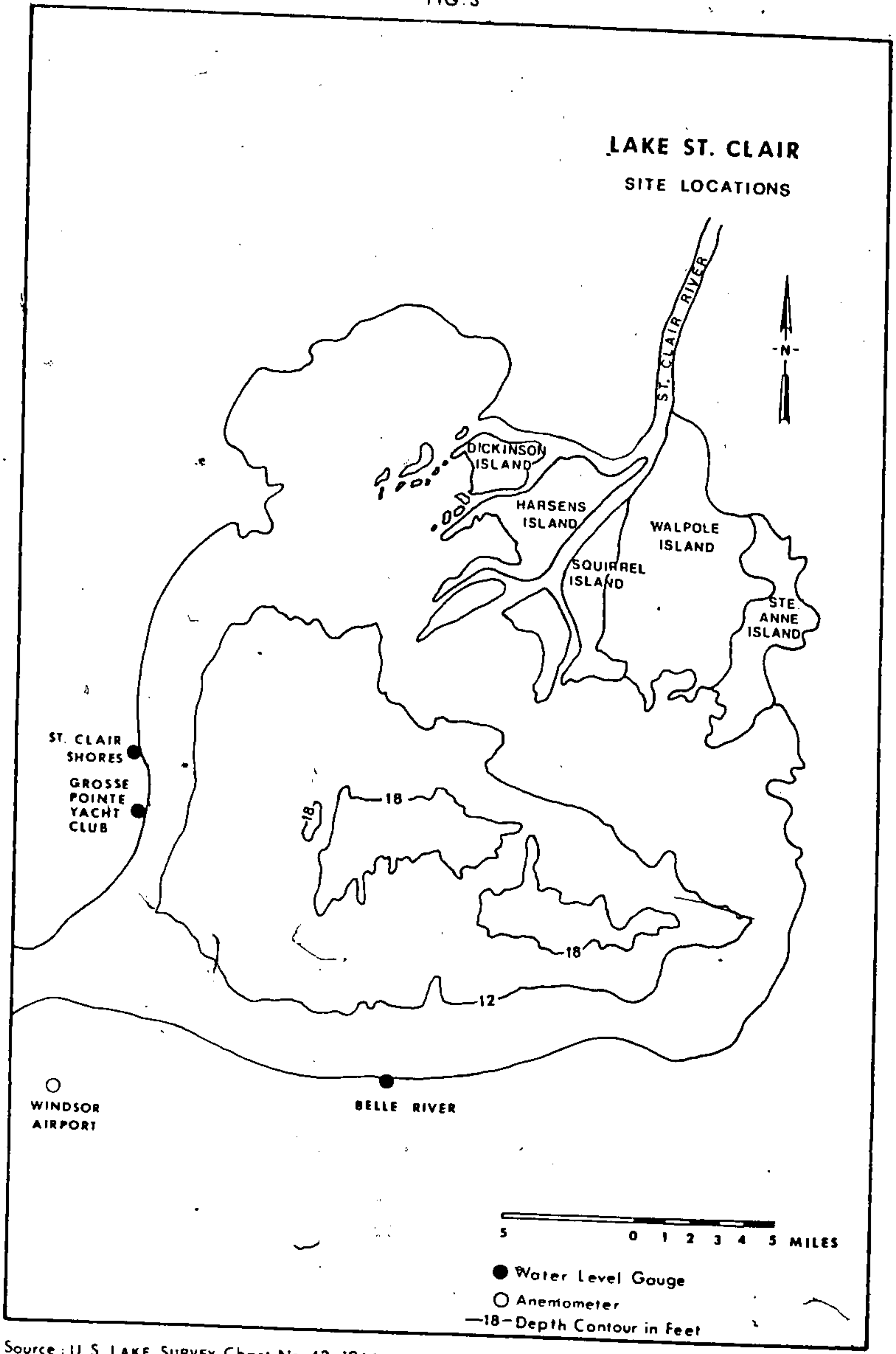
[1] Shape explained on p.22.

[2] Excludes St. Clair River and Detroit River.

FIG. 3



Source: U. S. LAKE SURVEY, Chart No. 42 -1966

Canadian side there is a station at Belle River, Ontario. The gauge is well exposed and is a paper tape continuous water level gauge recorder (see Appendix B). On the western shore, St. Clair Shores was selected for this study (see Figure 3). This station, which also is fairly well exposed, was located at Grosse Pointe Yacht Club prior to 1969.

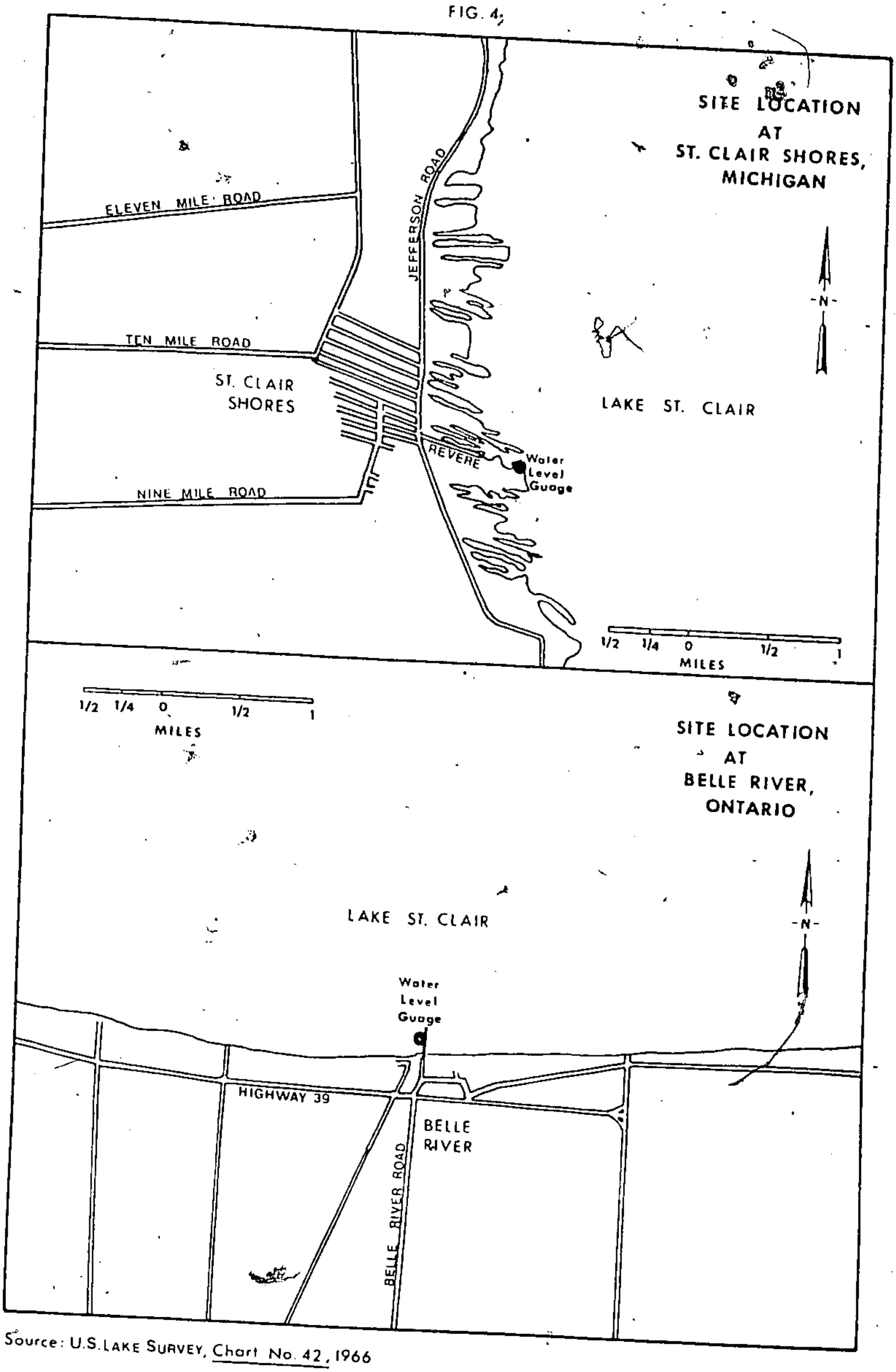
It should be pointed out that the water level gauge at St. Clair Shores was located at Grosse Pointe Yacht Club (Grosse Pointe Shores, Michigan) prior to 1969 and all measurements had been made from that point until the end of 1968. From 1969 to 1972 measurements were taken from St. Clair Shores, Michigan. Site location maps and photographs of the site are shown in Figures 4 and 5.

The instrumentation at this station consists of a float operated Fisher Porter Digital recorder which punches the water level data on a paper tape. Two more water level gauging stations, one at Algomac in the north and the other at Tecumseh in the southwest are not used in this study. The former is located along the St. Clair River and the latter is slightly inland and less representative then Belle River. The Windsor Airport was selected as the site for wind data collection because of its proximity to the lake and because it is approximately equidistant to the stations analyzed in this study.

Data Used In This Study:

Water level data for ten years (1963-1973) were obtained

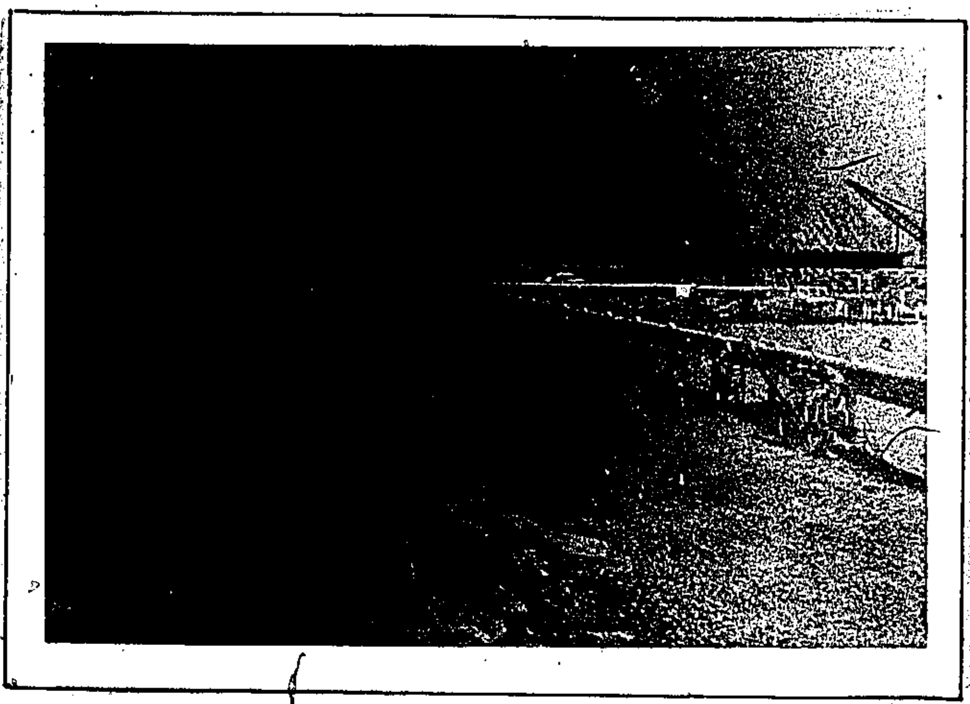
FIG. 4



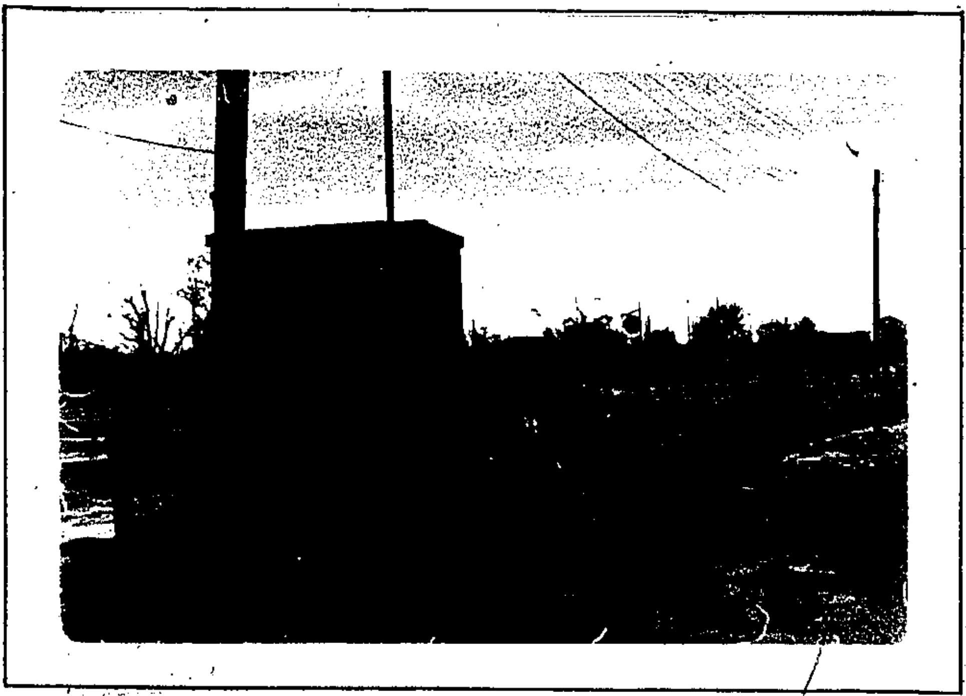
Source: U.S. LAKE SURVEY, Chart No. 42, 1966

Figure 5

Water Level Gauge At St. Clair Shores, Michigan



Water Level Gauge at Belle River, Ontario



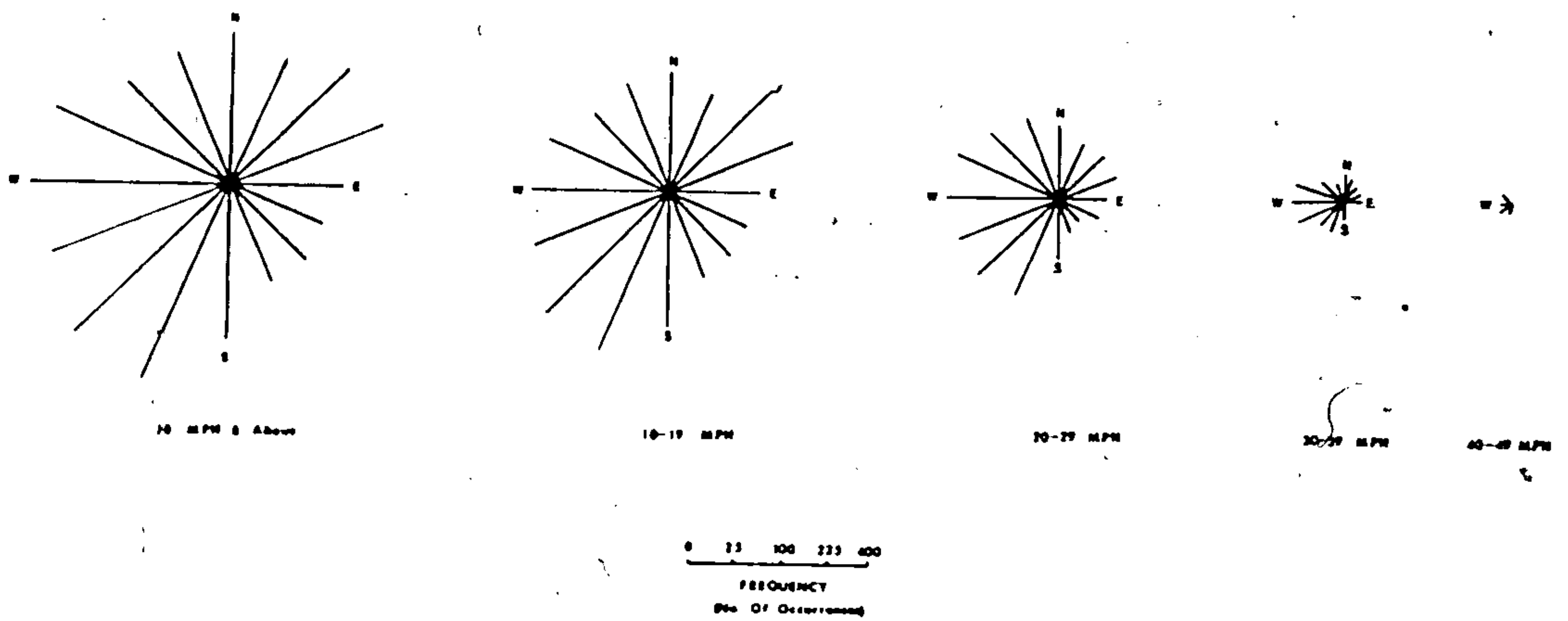
for the Belle River Station from the Marine Sciences Directorate in Ottawa. The data for the St. Clair Shores Station were secured from the Lake Survey Center in Detroit. The Windsor Airport data for the same period were obtained from the Atmospheric Environment Service at Toronto. All data were procured on an hourly basis.

As a first step, wind frequency patterns for the airport data were calculated. This was done by using a Fortran complier which sorted the daily maximum wind speeds into different classes and directions. Daily maximum wind speeds were plotted on graphs (Appendix C) and wind roses were diagramed. Figure 6 shows wind roses stratified according to speed for the total ten year period. Since an analysis for a three year period for all wind speeds has already been done (Hamblin and Budgell, 1973), it was decided that all cases where daily maximum wind speed was equal to or greater than 30 miles per hour be taken for this study because the data sample of Hamblin and Budgell for the higher wind speeds was very small. This was also done on the assumption that a significant amount of set-up does occur above this wind speed level, and to avoid the very small oscillations which may be related more to instrument error than natural influences. The data were further stratified by examining the prevailing wind directions, northwest and southwest. After omitting the southeast quadrant due to its insignificance, 158 cases were obtained for St. Clair Shores and 135 cases for the station at Belle River. Days on which the daily maximum wind

FIG.6

FREQUENCY OF WINDS BY CLASSES

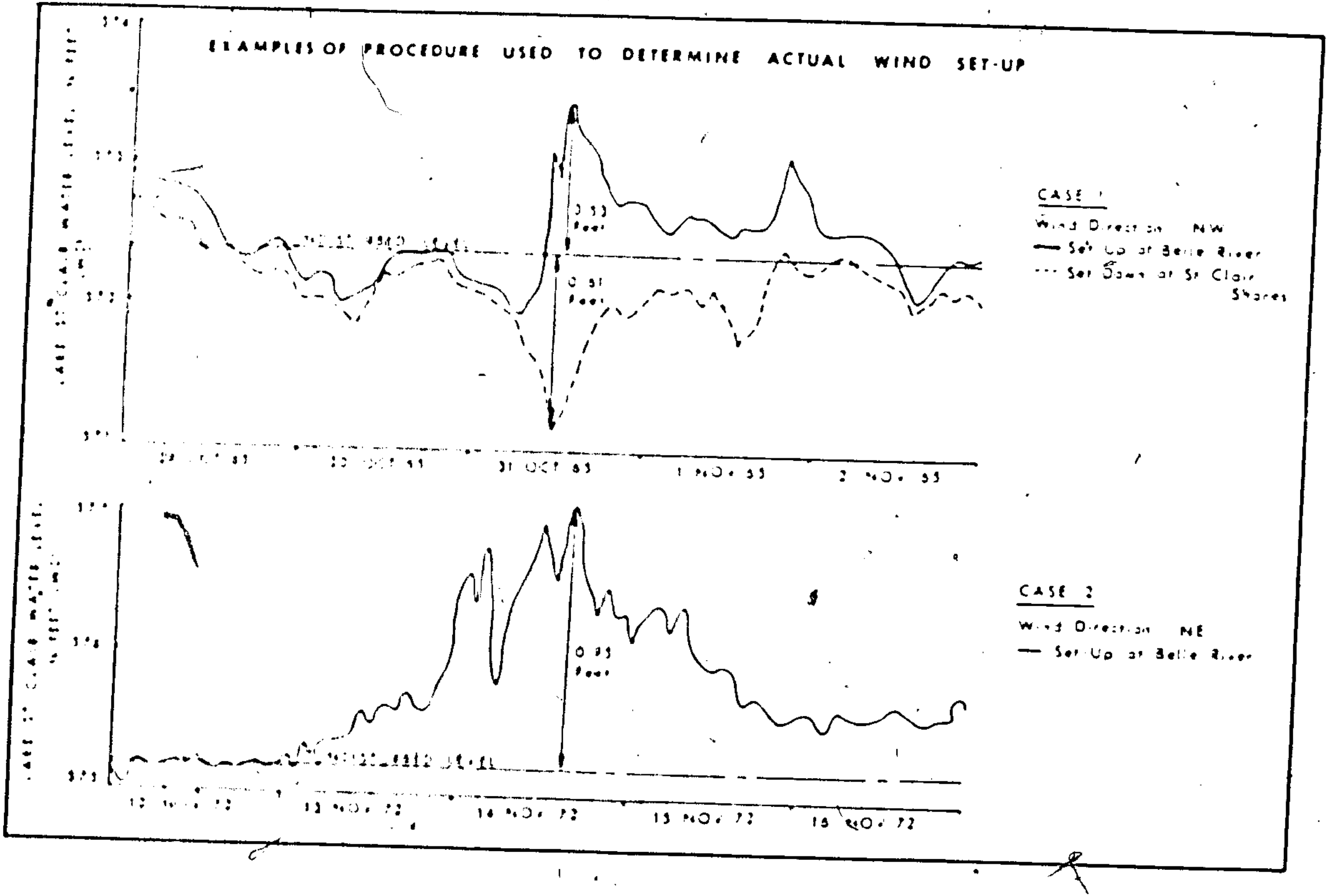
WINDSOR AIRPORT 1963-1973



speed peaked more than once were considered as one case. The next step was to plot the water level and wind data for each individual case over a period of five days. If the day in question was n, the period n-2 to n+2 was analyzed to calculate the actual set-up. Figure 7 shows the method in which they were actually measured from the graph. The peak wind speed was matched with the occurence of peak set-up and the change in level from the previous two day undisturbed level of water was measured. In certain cases it was found that there was a lag period of one hour. This is due to the fact that the set-up produced is the result of the wind forces acting over a certain period of time and that it takes the lake a definite time interval to fully react to the forces applied. A study of the differences in times of definite changes in the wind and the corresponding lake level patterns show the lake to have approximately a one-hour lag behind the maximum wind peak in accordance with the findings of Saville, 1953.

Evaluation of Parameters In The Theoretic Equations:

After the data sample had been selected, the parameters for the theoretical equations were evaluated. Shape is one of the most important properties of a geographic pattern. Chorley and Hagett (1967) mention that subjective categories - 'circular,' 'shoestring,' 'star-shaped' - are commonly used in descriptions of shape, but they each are limited in geometrical range and show strong operator-variance in assignment. Bunge (1962) suggested a method based on two theories: (1) that any simply



EXAMPLES OF PROCEDURE USED TO DETERMINE ACTUAL WIND SET-UP connected shape can be matched by a polygon of any number of sides, whose sides are of equal but variable length; (2) that if the distances between all vertices of the polygon are summed in a standard manner there exists just one set of sums that uniquely describe the polygon shape. Gibbs (1961) used a shape index in describing American cities. The index relates the area of the circle that would be generated by the longest axis, to the actual area, so that values of 1.00 indicate a circular shape. Based on the above deductions the shape of Lake St. Clair was calculated as shown below:

(1) Water area of lake including Detroit River and St. Clair River = 490 square miles.[1]

(2) Length of Detroit River = 32 miles.

(3) Average width of Detroit River = 3/4 miles.[2]

(4) Water area of Detroit River = 32 x 3/4 = 24 square miles approximately.

(5) Length of St. Clair River = 39 miles.[3]

(6) Average width of St. Clair River = ½ mile.[4]

(7) Water area of St. Clair River = 39 x ½ = 19.5 or 20 square miles approximately.

(8) Total water area of both rivers = 24 + 20 = 44 square miles.

(9) Water area of Lake St. Clair = 490 - 44 = 446 square miles approximately.

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[1] All statistics used for calculation of shape have been taken from, Canadian Hydrographic Service, Great Lakes Pilot, Vol.1, 1967.

[2] Width of Detroit River varies from 1/8 to 3 3/4 miles.

[3] The distance from the lower end of St. Clair Cut-Off Channel, along the South Channel to Chenal Encarte is about 11 miles. The upper channel from Chenal Encarté to Lake Huron is about 28 miles.

[4] Measured from map, U. S. Lake Survey, Chart No.42.

(10) Length of longest axis of Lake (Figure 8) = 28.5 miles.

(11) Radius = 14.25 miles.

(12) Area of lake $= r^2$
$= 3.142\ (14.25)^2$
$= 3.142 \times 203$
= 638 square miles approximately.

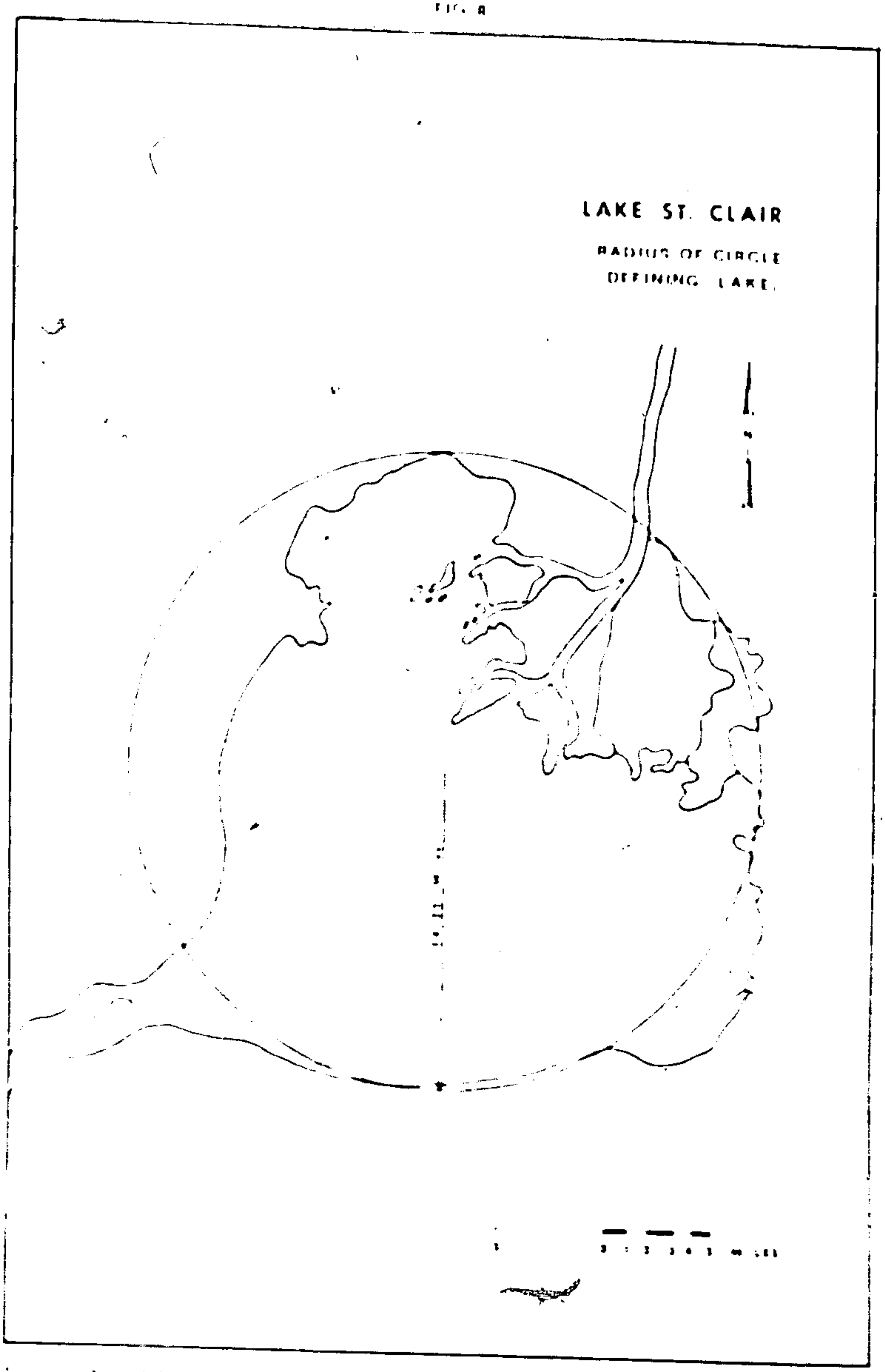
(13) Ratio of actual area to calculated area,
$\frac{446}{638} = .70$

A ratio of .70 suggests that the shape of the lake is fairly circular.

The average depth from each station was determined in terms of different directions by constructing bed profiles. The average depth from each station was then calculated from the different directions. These are presented in Table 1 and Figures 9, 10, 11. The average depth of the lake from profiles drawn in all directions from the two stations at three locations is $\frac{11.93 + 12.20 + 11.10}{3} = 11.74$ feet. The depth shown above was calculated at LWD 571.7 feet. In order to compute the depth for each particular day, the difference from the mean daily level was added to the average depth.

Fetch is the straight line distance over open water in the direction of the wind. Saville (1962), McClendon (1962) and Cochran (1962) noted that according to existing relationships,

FIG. 8



Source: U.S. Lake Survey [illegible]

Table 1

Average Depths

(1) Belle River
(2) St. Clair Shores at Grosse Pte. Yacht Club
(3) St. Clair Shores at St. Clair Shores

Direction	Average Depth In Feet (1)	(2)	(3)
WNW/ESE	8.80	14.3	15.4
NW/SE	11.70	13.5	13.6
NNW/SSE	13.90	10.9	11.4
NE/SW	12.10	9.1	6.7
ENE/WSW	11.75	12.5	11.6
NNE/SSW	12.30	10.7	9.9
N/S	13.00		
E/W		14.3	9.6
For all Directions	11.93	12.2	11.1

FIG 9

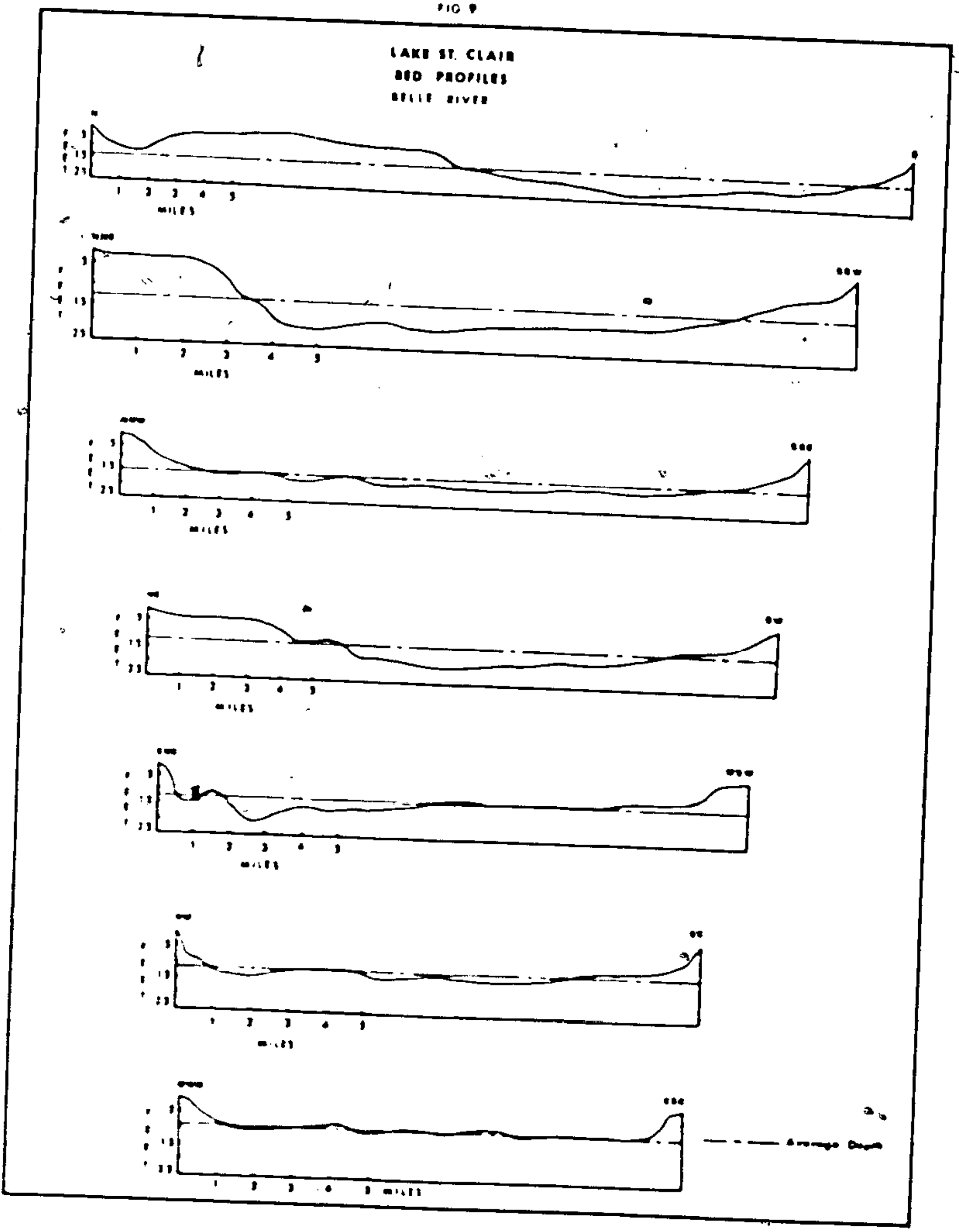
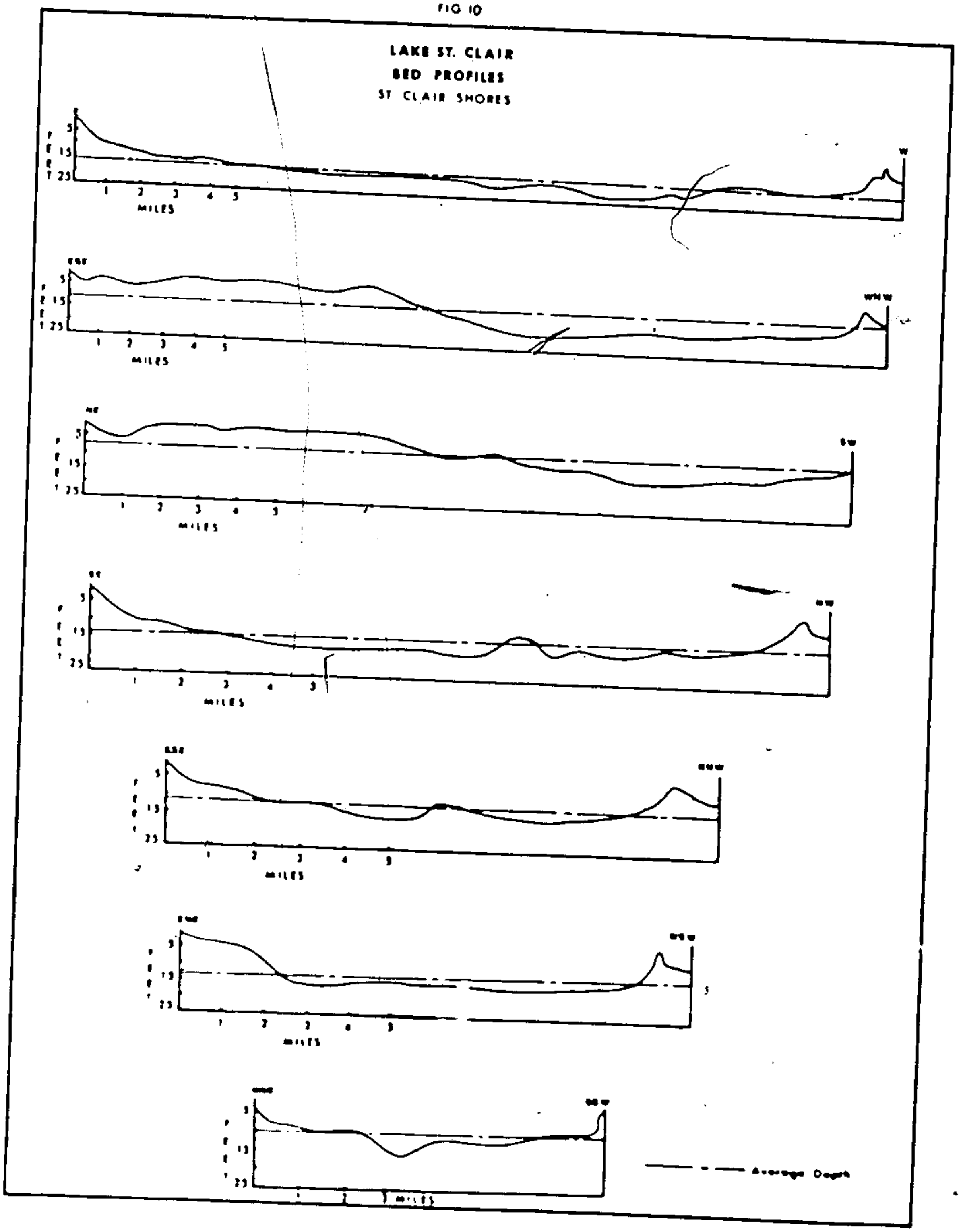
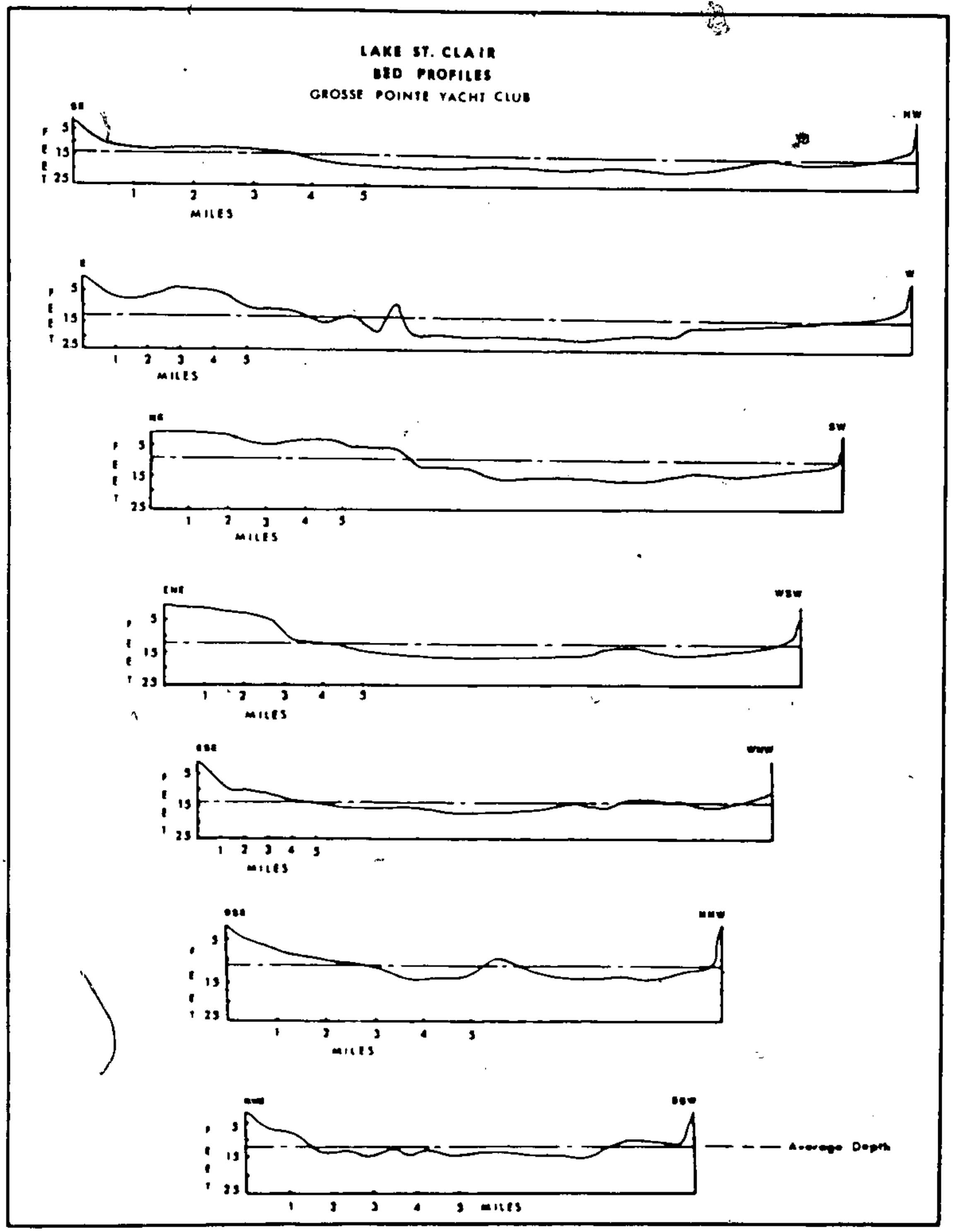

LAKE ST. CLAIR
BED PROFILES
BELLE RIVER
N
S
SSW
FEET
5
15
25
1
2
3
4
5
MILES
Average Depth

FIG 10



LAKE ST. CLAIR
BED PROFILES
ST CLAIR SHORES

FIG 11

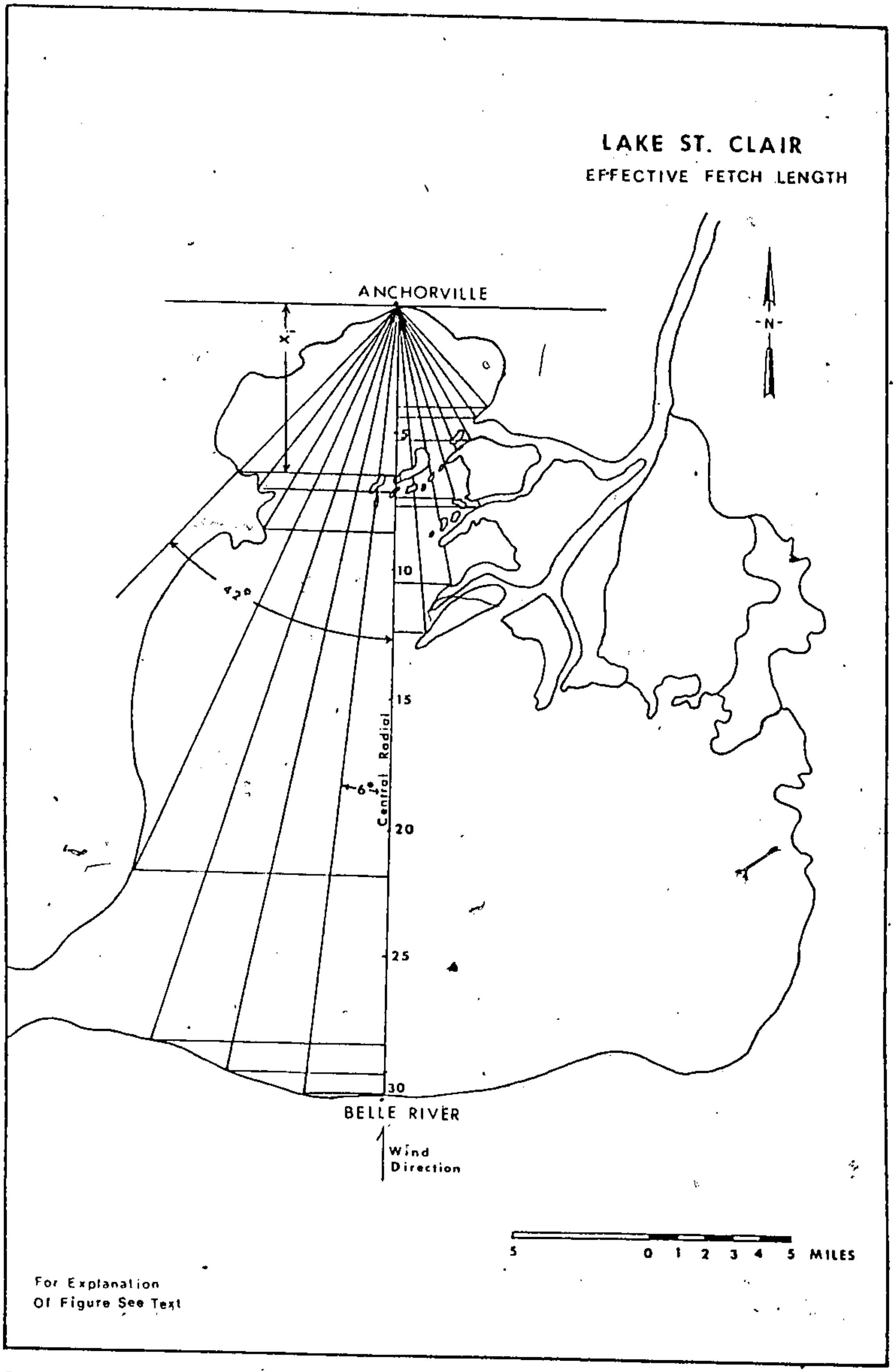


LAKE ST. CLAIR
BED PROFILES
GROSSE POINTE YACHT CLUB

wind velocities over short fetches, at angles from 30° to 45° to the longer fetches, produced higher waves than could be expected over the short fetch. These considerations led them to the development of a method for computing effective fetch lengths. Their method was based on the concept that the width of a fetch in reservoirs normally places a definite restriction on the length of the effective fetch; the less the width-to-length ratio, the shorter the effective fetch. This procedure assumes that the effectiveness of any segment in the fetch is indicated by the ratio of the actual length of the segment to the expected length in a fetch of unrestricted width. This ratio is the same as that of the projection of these lengths on the central radial. It also assumed that the effectiveness of the wind in generating waves is proportional to the cosine of the angle from the average wind direction. The total effectiveness of each fetch segment is proportional to the product of these two values. Total effectiveness of the entire fetch is considered as the sum of these products divided by the sum of the cosines.

Fifteen radials were drawn at intervals of 6° from Anchorville, as shown in Figure 12. The radials were oriented so that the vertex of all radials was located at the above station with the central raidal in the direction of the wind. These fifteen radials cover a sector of 42° on each side of the central radial. Each radial is extended so that it runs

FIG. 12



Source: U.S. LAKE SURVEY, Chart No. 42, 1966 the full length of the water body. For Lake St. Clair, effective fetch length was considered for Belle River only when the winds were from the south. In accordance with the foregoing assumptions, the method for computing the effective fetch is developed as shown by Saville (1962), McClendon (1962) and Cochran (1962). The following steps describe the measurement of the effective fetch, as shown in Figure 12.

(1) The effective length of each of the fifteen radials was tabulated. Effective length is represented for each radial by the component of its length measured in direction parallel to the central radial (x_i).

(2) The effective length of each radial was multiplied by the cosine of the angle between the central radial and the radial under consideration ($x_i \cos \alpha$).

(3) The fifteen products were totaled (209.01 units).

(4) This sum was divided by the sum of the cosines (14.88 units).

(5) The resulting quotient was then converted to obtain the effective fetch length (14.13 miles, see Table 2).

Fetch distances were measured from the map in all generating directions for both the stations. These are shown in Table 2.

Another important factor which influences the set-up is the water surface shear stress exerted by the wind on the water surface, and the bottom shear stress which is caused by flowing water with wind blowing over its surface.

Table 2

Effective Fetch Length For Belle River*

α	$\cos\alpha$	x_i	$x_i \cos\alpha$
42	0.743	6.25	4.64
36	0.809	7.25	5.86
30	0.866	7.60	6.58
24	0.914	21.60	19.72
18	0.951	21.70	26.35
12	0.978	28.70	28.10
6	0.995	29.60	29.42
0	1.000	30.00	30.00
6	0.995	12.75	12.68
12	0.978	10.80	10.57
18	0.951	10.20	9.70
24	0.914	7.80	7.12
30	0.866	5.40	4.67
36	0.809	4.20	3.40
42	0.743	3.75	2.28
Total	13.512		201.09

$\frac{201.09}{13.512} = 14.88$ units

30 units = 28.5 miles

1 unit = $\frac{28.5}{30} = .95$ miles

14.88 units = $\frac{28.5 \times 14.88}{30} = 14.13$ miles

* Only when winds are from the south.

Fetch Distances

(1) St. Clair Shores At Grosse Point Yacht Club
(2) St. Clair Shores At St. Clair Shores
(3) Belle River

Direction	Distance In Miles (1)	(2)	(3)
NNE/SSW	10.5	8.0	17.0
NE/SW	17.75	20.0	19.0
ENE/WSW	15.50	12.0	17.0
ESE/WNW	23.5	25.25	12.6
SE/NW	14.5	17.0	13.5
SSE/NNW	10.25	12.75	20.5
N			28.5
S			14.13
E/W	23.5	25.0	

Saville (1952) expressed surface shear as a function of the wind velocity:

$$\tau_s = K\rho_a V^2 \qquad \text{(eq. 4)}$$

where,

K = a numerical constant .003
ρ_a = air density
V = wind velocity.

He then substituted the surface shear stress term in his equation:

$$\tau_s = \frac{Kn\rho_a V^2 F}{pgD} \qquad \text{(eq. 5)}$$

where n = a coefficient defined as $n = \frac{\tau_s}{\tau_o} + 1$, where τ_o is the shear stress along the bottom. This coefficient was considered to have a value of 1.5 for laminar flow.

Wind velocity used in this equation is wind over the lake. The problem of defining over-lake wind from land sites has been investigated by various authors. Richards, Dragert, and McIntyre (1966) used five years of wind observations over Lake Erie and Lake Ontario to obtain an empirical relationship which could be used to evaulate the ratio between over-water and over-land winds. They confirmed that wind speeds increase over water during unstable conditions and decrease during stable conditions. They also showed that these changes are greatest in low winds and least in high winds.

The determination of the coefficient of wind stress may be made with reference to the wind velocity at a standard height above the water surface of the lake. This, as shown by Hunt (1959), could be done by using the Prandtl-Karman (1935) rule of velocity distribution:

$$\frac{U}{U_*} = \frac{1}{K} \ln \frac{Z}{Z_o} \qquad \text{(eq. 6)}$$

where,

U = the horizontal velocity at elevation Z.
U_* = the friction velocity and is equal to $\sqrt{\tau_s/\rho}$ where τ_s is the surface shear stress and ρ the density of the fluid.
K = the Von Karman universal constant and is equal to 0.40.
Z_o = the effective roughness, a constant of integration obtained from the condition $U = 0$ where $Z = Z_o$.

Since the majority of the work confirming the theories of Prandtl and Von Karman has been done in closed conduits, Hunt (1959) suggests a general equation of velocity distribution over a wave-covered water surface, taking into consideration atmospheric equilibrium conditions. This is expressed as:

$$\frac{U_w - C + M}{U_*} = \frac{1}{K} \ln \frac{Z}{Z_w} \qquad \text{(eq. 7)}$$

where,

U_w = the wind velocity over water measured at elevation Z.
C = the ripple velocity corresponding to the peak frequency of the wave steepness spectrum. The value is approximately 65 cm./sec.
M = a stability parameter and is a function of the difference between the air temperature (T_A) and the surface water temperature (T_w).
U_* = the friction velocity.
Z_w = the effective roughness of the water surface. It appears to be a function of ripple height and is constant at 1.5 cm.

This expression can be rewritten as:

$$\tau_s = \rho a \left(\frac{K}{\ln \frac{Z}{Z_w}}\right)^2 (U_w - C + M)^2 \qquad \text{(eq. 8)}$$

where,

ρa = .0023 slugs/foot^3
K = 0.4
Z = 33.3 feet, which is the average height of the anemometer at Windsor Airport.

Z_w = 1.5/30.5 feet
C = 65/30.5 feet
H = .35(T_A-T_w) where T_A-T_w is in °F.

The shear stress in the foot-pound-second system of units becomes:

$$\tau_s = .0023 \left(\frac{0.4}{\ln \frac{33.3}{1.5/30.5}}\right)^2 (U_w - 65/30.5 + .35\ (T_A-T_w))^2 \qquad \text{(eq. 9)}$$

or $$\tau_s = .0023 \times .00376\ (U_w - 2 + .35\ (T_A-T_w))^2$$

or $$\tau_s = 8.6 \times 10^{-6}\ (U_w - 2 + .35\ (T_A-T_w))^2 \qquad \text{(eq. 10)}$$

A stability parameter has been used to account for the atmospheric stability. Since very little is known about the temperature conditions over Lake St. Clair and the effects of thermal stratification, three stability classes have been arbitrarily set up following Hamblin and Budgell (1973), in terms of an average (wind-water) temperature relationship, to work out the shear stresses. The stability classes are shown in Table 3. The resulting shear stress calculated [illegible] different wind velocities are presented in Appendix D, E and F. These values were used in the equations to compute the set-up.

Plate and Goodwin (1965) expressed the momentum equation for standing water, as applied to a body of fluid contained between two vertical sections a distance dx apart, as:

$$\tau_s - \tau_b = \gamma y \left(S_o + \frac{1}{\rho g}\frac{dp}{dx}\right) \qquad \text{(eq. 11)}$$

where,

y = the depth at the point considered, which was assumed to be essentially constant along the channel.
S_o = water surface slope.

Table 3

Stability Classes*

Stability Class	Period	Average Temperature in °F (T_a-T_w)	Equation
Stable	Jan. 1st - June 31st	+4°	8.6×10^{-6} $((U_w \times 1.466) - .60)^2$
Neutral	July 1st - Aug. 31st	0°	8.6×10^{-6} $((U_w \times 1.466) - 2)^2$
Unstable	Sept. 1st - Dec. 31st	-4°	8.6×10^{-6} $((U_w \times 1.466) - 3.40)$

* Procedure similar to Hamblin and Budgell

τ_s = water surface shear stress.
τ_b = calculated bottom shear stress.
y = depth at point of consideration.
γ = specific weight of water.
$\frac{dp}{dx}$ = pressure gradient above the fluid.
g = acceleration of gravity.

The difference $\tau_s - \tau_b$ can be calculated from measured values of the depth, the water surface slope and the pressure gradient, but the problem arises of separating τ_b and τ_s. Kuelegan (1951) found for laminar flow that $\tau_b = 0.5\ \tau_s$, but it has been argued by Francis (1951) that for turbulent flow the bottom shear stress is considerably smaller. Kuelegan (1951) assumed $\tau_b = 0.25\ \tau_s$, Francis (1951) $\tau_b \approx 0$, and later Baines and Knapp (1965) produced evidence that $\tau_b = 0.1\ \tau_s$. Plate and Goodwin (1965) consider that the true ratio of τ_b to τ_s is not constant, but depends on the depth of flow and on the roughness of the bottom of the channel. The latter effect can be quite pronounced as shown by Sibul and Johnson (1959). Calculations of the bottom shear stress in this study were performed on the assumption that $\tau_b = 0.1\ \tau_s$, or in other words, bottom shear was considered to be one-tenth as effective as the surface shear. This assumption follows the more recent evidence on the relationship.

Other factors such as atmospheric pressure changes and vegetation may have an effect on the set-up. The former is expected to have a very slight effect. A study by the United States Corps of Engineers on Lake Okeechobee (1953) states that when a storm passes over a large[1] body of water, the reduction in atmospheric pressure near the center of the storm causes the water levels to rise.

Hunt (1959) in deriving his equation for set-up concluded that the atmospheric pressure gradient for storms over Lake Erie was small. He verified this assumption with the help of synoptic weather maps. Under these considerations it was deduced that this factor might be applied to Lake St. Clair as a correction factor. Sea level pressure changes were computed from observed data for each particular case and are shown in Table 4. There were only five cases when the change in pressure seemed significant, but the correction was not applied as the observed set-ups compared fairly well with the computed set-ups.[2] The magnitude of the correction is computed from the assumption that a pressure difference of one-inch of mercury approximately corresponds to 1.14 feet of water.

Another correction factor can be applied if the reduction in set-up is due to vegetation. It can be evaluated by applying a correction factor C_m to the predicted set-up to obtain the observed set-up S_o, so that $S_o = S(1-C_m)$. Saville (1952) shows that C_m decreases with some function of the depth over the marshy area and is expressed dimensionlessly as a ratio

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[1] Lake Okeechobee has an area of about 730 square miles as compared to 446 square miles for Lake St. Clair.

[2] The pressure change on 17th January, 1967 tends to have a slight effect on the set-up.

Table 4

Sea Level Pressure[1]
(in Millibars)

Date	Minimum	Maximum	Difference
03-05-1964	984.0	1017.2	33.2
01-17-1967	1007.8	1033.0	25.2
12-10-1971	989.2	1014.4	25.2
12-30-1971	991.7	1016.0	24.3
01-25-1972	1014.7	1035.0	20.3

[1] Data obtained from Windsor Airport and differences are considered over a period of 24 hours.

of the depth, or the set-up and a friction length parameter of the marsh vegetation. This correction factor is also dependent on a term embodying the ratio of that portion of the marsh area included in the fetch to the entire fetch length. When the fetch lies outside the marsh area, full set-up is reached after some appropriate lag in time. It is expected that the presence of vegetation does not affect the set-up on Lake St. Clair. This assumption is made since a sufficient depth of water exists over the vegetation, causing a bottom return flow over the top of the vegetation.

After reviewing data collection procedures and employing standard procedures for estimating all parameters in the theoretic equations, there is reason to believe that the hypothesis outlined in the previous chapter can be adequately analyzed. The next chapter describes the findings of the analysis.

CHAPTER FOUR

ANALYSIS

The first step in the analysis was to generate values of theoretical set-ups with the seven theoretic equations (Appendix G). A fortran program, as shown in Appendix H, was used to accomplish this purpose. After this procedure was completed the observed and theoretic data were categorized into five different classes (Table 5). The primary aim in this study is not only to achieve a workable set of prediction equations, but also to examine the nature, the direction and the strength of relationships. Hamblin and Budgell (1973) used regression coefficients and correlation coefficients to determine the relationships between wind set-up and wind speed. The analysis in this study is more detailed than Hamblin and Budgell's and allows a more comprehensive test of their preliminary findings. A simple regression and correlation test was used to determine the relationships between observed set-ups and wind, fetch and depth. A multiple regression procedure was employed to test the importance of each of these three variables and all of them combined.

Results of Regression-Correlation Analysis:

The results of the analyses have established the relationships between wind speed, fetch and depth and the observed wind set-up.

TABLE 5

Data Classification and Notations Used For Analysis.

		Number of Days Studied	
		St. Clair Shores	Belle River
TOTSAM	= All days in study which represent the sample	158	135
TOTSAM<1	= Days when set-up was < 1 foot	156	130
ICE*	= Days with ice on lake	38	41
WOICE	= Days without ice on lake	120	94
WOICE<1	= Days without ice on lake and set-ups < 1 foot during the day	118	89

STS = St. Clair Shores
BR = Belle River

* Ice covered lake conditions are defined as those days when the lake around the station under consideration was either completely or partly frozen. These particular days were selected by checking 'Great Lakes Ice Atlas, Maps,' 1969 (see bibliography).

The extent to which wind, fetch and depth have an effect is shown in Table 6.

It can be noted from Table 6 that when the observed set-up is regressed against the mean wind speed,[1] fetch and depth independently, the best results are achieved with the mean wind speed for the case when there is no ice cover on the lake. During winter, when the lake is ice covered (Figure 13), fetch is significant (r = 0.469) only at St. Clair Shores. Fetch is as significant (r = 0.303) as wind speed (r = 0.297) for Belle River during the summer (note WOICE column). In each case in the table the correlations of the observed set-up and the mean wind speed is comparitively higher for St. Clair Shores than for Belle River. However, there is very little difference among the r values when mean wind speed or the square of the mean wind speed is considered.. The linear equations between the observed set-up and the square of the mean wind speed is shown in Appendix I. The depth variable is not significant for St. Clair Shores. However, this variable is significant at Belle River during conditions when the lake is ice covered (r = 0.374).

The reason the depth variable is positively correlated with observed set-ups at Belle River might be related to small oscillations caused by wave attack on the fringes of fast ice.

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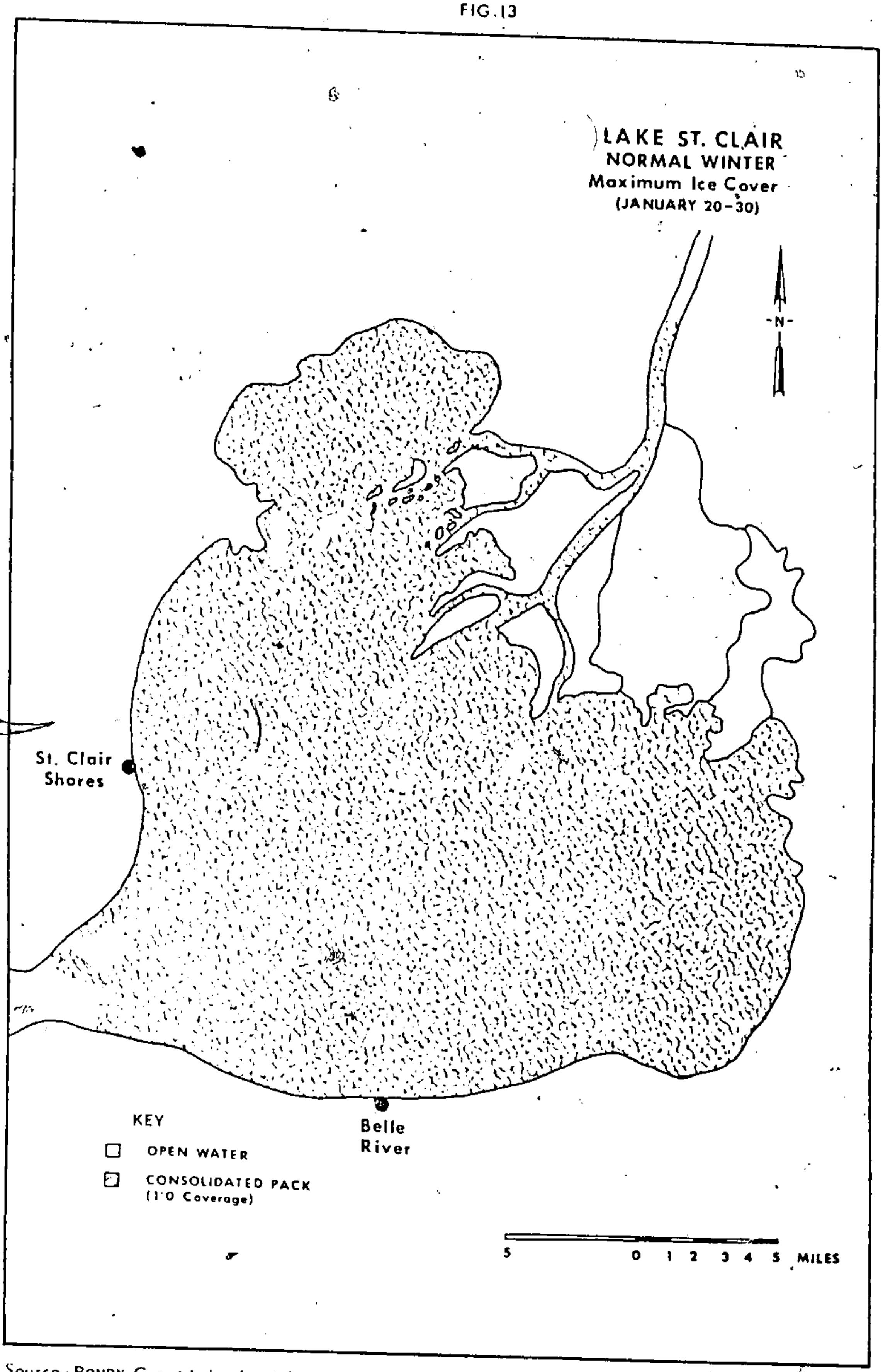
[1] Mean wind speed has been calculated by taking the average of n-5 hours if the wind speed peaked at n hours.

FIG. 13



Source : RONDY, Great Lakes Ice Atlas, 1971

Table 6

Regression-Correlation Analysis

Multiple R Values

$\overline{\text{Wind}}, \overline{\text{Wind}}^2$, Fetch, Depth Against Set-Up

Variables	TOTSAM		TOTSAM<1		ICE		WOICE		WOICE<1	
	STS	BR	STS	BR	STS	BR	STS	BR	STS	BR
$\bar{v}$, F, D	0.291*	0.180⌿	0.298*	0.179⌿	0.576*	0.394⌿	0.487*	0.468*	0.466*	0.397*
$\bar{v}^2$, F, D	0.273*	0.178⌿	0.280*	0.173⌿	0.571*	0.396⌿	0.487*	0.470*	0.461*	0.396*

Observed vs Theory - r values

Variables	TOTSAM STS	TOTSAM BR	TOTSAM<1 STS	TOTSAM<1 BR	ICE STS	ICE BR	WOICE STS	WOICE BR	WOICE<1 STS	WOICE<1 BR
BERB[1]	0.226*	0.156⌿	0.210*	0.037⌿	0.398+	0.110⌿	0.478*	0.441*	0.459*	0.374*
HUNT	0.208*	0.134⌿	0.198+	0.039⌿	0.415*	0.125⌿	0.443*	0.421*	0.429*	0.385*
SAVL	0.191+	0.131⌿	0.176+	0.025⌿	0.385+	0.107⌿	0.447*	0.430*	0.429*	0.383*
KUEL	0.214*	0.136⌿	0.202+	0.048⌿	0.438*	0.139⌿	0.441*	0.410*	0.429*	0.377*
ZEE1	0.226*	0.157⌿	0.210*	0.038⌿	0.399+	0.107⌿	0.478*	0.442*	0.459*	0.377*
ZEE2	0.226*	0.157⌿	0.210*	0.038⌿	0.399+	0.110⌿	0.476*	0.441*	0.459*	0.375*
HELL	0.190+	0.127⌿	0.175+	0.023⌿	0.392+	0.110⌿	0.446*	0.418*	0.429*	0.369*

Correlation of Variables with Set-Up

Variables	TOTSAM STS	TOTSAM BR	TOTSAM<1 STS	TOTSAM<1 BR	ICE STS	ICE BR	WOICE STS	WOICE BR	WOICE<1 STS	WOICE<1 BR
Fetch	0.107⌿	0.145⌿	0.137⌿	0.064⌿	0.469*	0.206⌿	0.099⌿	0.303*	0.133⌿	0.206+
Depth	0.054⌿	-0.034⌿	0.118⌿	0.138⌿	0.258⌿	0.374+	-0.088⌿	-0.259⌿	-0.012⌿	-0.094⌿
Wind	0.255*	0.120⌿	0.288*	0.103⌿	0.284⌿	0.137⌿	0.446*	0.297*	0.419*	0.335*
Wind^2	0.237*	0.114⌿	0.207+	0.094⌿	0.267⌿	0.141⌿	0.446*	0.294*	0.415*	0.329*

* Significant at .01 level ; + Significant at .05 level ; ⌿ Not Significant

[1] Refer to Appendix A for explanation.

The wave force is dampened by the ice more effectively when the waters are shallow than when they are deep. There are several facts that lead to this conclusion. Fast ice is consistently present in winter in the southern and eastern portion of the lake, while the rest of the lake is only partially ice-covered. This would be true particularly in the Early Decay Period (Figure 14). The extent of fast ice offshore is small at Belle River so that the ice probably does not fully eliminate small oscillations in water levels generated in the open lake areas. Fast ice is less persistent at St. Clair Shores, and thus wind and fetch tend to explain more of the observed set-up than the depth variable itself. Studies of the set-up produced by wind action in the Gulf of Bothnia have shown that a continuous cover of fast ice in winter has a fairly strong reducing effect on the set-up.[1] This effect seems to hold true for Lake St. Clair.

The multiple correlation coefficients from the stepwise regression analysis, where wind speed, fetch and depth are analyzed, are significant for St. Clair Shores in every case (Table 6). For Belle River the R values are significant only when there is no ice cover on the lake. This lends support to the arguments given above concerning the dampening effect of fast ice on water oscillations on the southern end of the lake.

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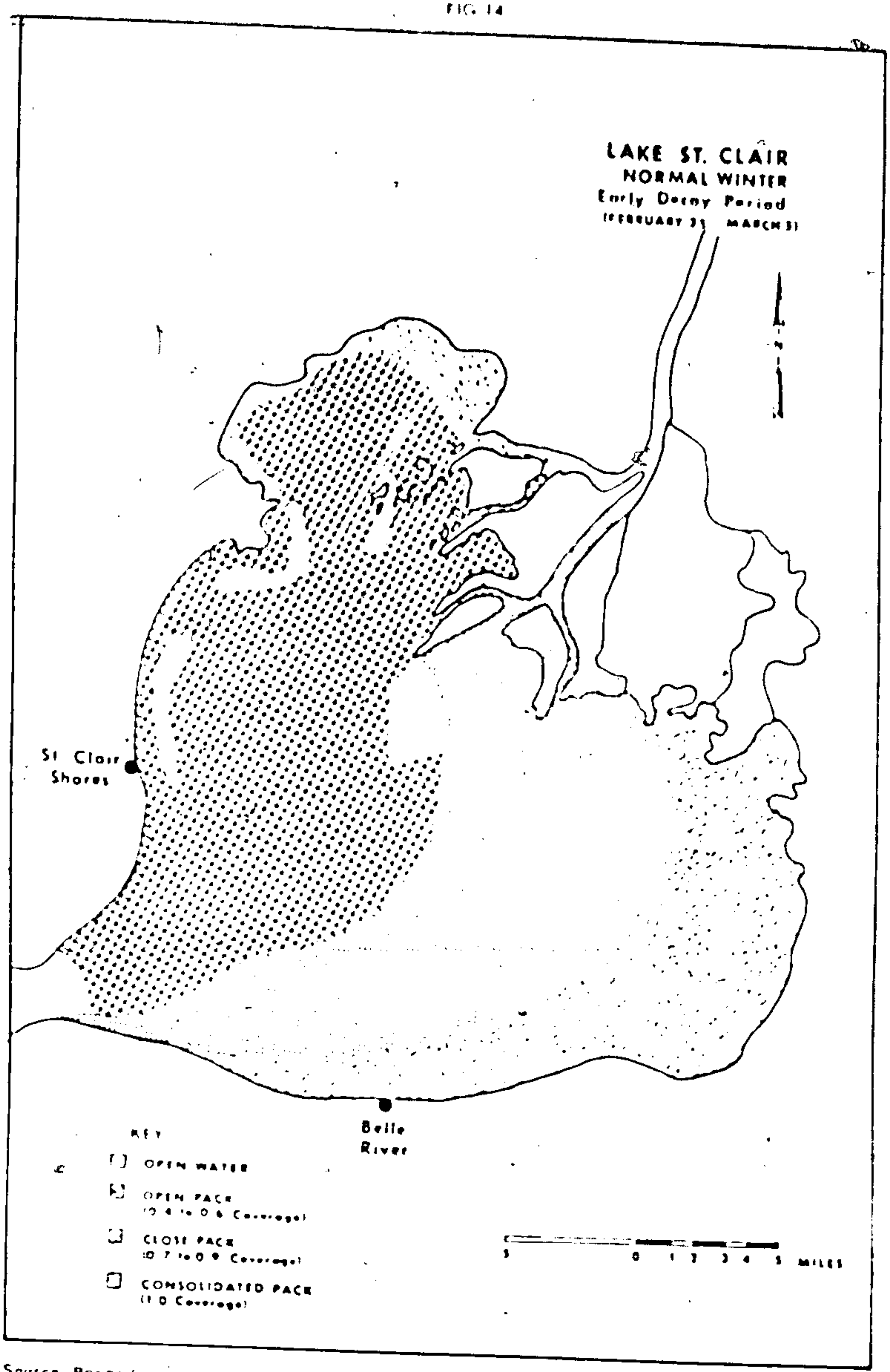
[1] E. Lisitzn, The Effect of Ice Upon Sea Level Records, UNESCO Pub. No. 27, May, 1965.

FIG. 14



Source: Rondy, *Great Lakes Ice Atlas*, 1971

Table 6 summarizes the functional relationships among the observed set-up and the independent variables, wind fetch and depth. Appendix J containn statistics specifying the percentage explanation of observed set-up by the individual variables. From those statistics, Table 7 was constructed to show the most significant relationships. This table provides additional information as to the individual or combination of variable(s) which explain the observed set-ups.

The additional features shown in this table, besides the conclusions just discussed are: (a) for both sites a combination of wind speed and fetch gives the best relationship with observed set-ups, (b) in the case of Belle River, the depth variable should be employed in prediction equation for summertime conditions. The depth variable is unimportant for small oscillations and for St. Clair Shores.

Analysis of Theories:

A linear regression analysis of the six theories with the observed wind set-ups shows that all the equations give very similar results (Table 6, Appendix K). For the cases when the lake was ice-covered correlations become lower as in the regression-correlation analysis of the individual factors of wind, fetch and depth. For Belle River none of the equations proved significant for the case when the lake was ice-covered. This is due to the supression of wind effects by the ice cover as discussed previously.

Table 7

Best Functional Relationships and Equations Derived From Multiple Regression Analysis - Between Observed Set-Ups and Wind Speed, Fetch and Depth*

Data Samples	St. Clair Shores	Belle River**
TOTSAM	$h_s = f(\bar{v})$*** $h_s = 0.120 + 0.012\bar{v}$	----- -----
TOTSAM<1	$h_s = f(\bar{v}, F)$ $h_s = 0.029 + 0.011\bar{v} + 0.006F$	----- -----
ICE	$h_s = f(F)$ $h_s = -0.029 + 0.014F$	$h_s = f(D)$ $h_s = -0.206 + 0.034D$
WOICE	$h_s = f(\bar{v}, F)$ $h_s = -0.241 + 0.024\bar{v} + 0.007F$	$h_s = f(\bar{v}, F, D)$ $h_s = 0.610 + 0.028F + 0.075\bar{v} + 0.017D$
WOICE<1	$h_s = f(\bar{v}, F)$ $h_s = -0.204 + 0.022\bar{v} + 0.008F$	$h_s = f(\bar{v}, F)$ $h_s = -0.119 + 0.014\bar{v} + 0.013F$

h_s = set-up

$\bar{v}$ = mean wind speed

F = fetch

D = depth

* The functional relationships and equations are quite similar when the square of the mean wind speed is used instead of V.

** There is no significant relationship between h_s and $\bar{v}$, F, and/or D for data aggregated on a yearly basis.

*** Only those variables which register a significant increase in R^2 at the .05 level are included in the equation.

CHAPTER FIVE

CONCLUSION

An important result in analyzing the significance of the theories and regression analysis is that wind speed, fetch and depth alone explain just as adequately the observed set-ups. Factors such as atmospheric stability, air pressure changes, vegetation (marsh) effects, planform factor which may be important on other lakes do not contribute any additional significance to predicting the observed set-ups on Lake St. Clair. The theoretical equations contain all the above factors, while the linear and multiple regression equations include only wind, fetch and/or depth. Correlation coefficients (Table 6) for the theories and regression relationships are quite similar.

However, the overall level of r values (in this study) remains quite low, yet significant. This is somewhat similar to the study of Lake St. Clair water levels by Hamblin and Budgell (1973). They found a moderate correlation between wind speed and wind set-ups. They suggested that the problems of measurement of so small a range of wind set-ups (such as those recorded on Lake St. Clair) may have reduced the correlation between wind and observed set-ups. Problems of accurate estimation of set-ups from hourly water level data could partially explain low r values. Another consideration is the accurate estimation of wind speed. In this study, and in that of Hamblin and Budgell, wind speed data (and direction of wind) were obtained from the Windsor Airport and not on the immediate site. How important this factor may be in explaining why r values are quite low between wind and set-ups should be analyzed by a study of wind differences along Lake St. Clair and sites inland from the lake.

Recommendations for Further Study:

This study chose two separate approaches to the problem of wind set-up analysis. The first was empirical. This consisted of evaluating observed set-ups and independent variables such as wind, fetch and depth by a regression-correlation analysis. The second approach considered seven theoretic equations developed from other water bodies. These equations were applied to Lake St. Clair to determine whether oscillations on Lake St. Clair conformed to theoretic expectations.

Both approaches could be enhanced considerably in any future study. For example, McCorquodale (1974) suggests deriving theoretic equations relying on ideas of two dimensional, unsteady, open channel flow (see Appendix L for explanation and diagrams of this approach). In any future empirical approach to the problem of wind set-ups, several factors should be analyzed: (a) wind speed and direction accuracy, (b) proper calculation of observed wind set-ups, (c) influence of waves on the observed set-ups,[1] (d) accuracy in estimating the influence of bottom shear stresses on surface oscillations,[2] (e) representativeness and accuracy of water level gauges around the lake,[3] and (f) ice cover properties and dampening effects on water oscillations.

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[1] Kuelegan (1951) in his experiments found that an additional term was to be used in the equations to account for the additional stress due to the form resistance of the waves. Saville (1954) working with data obtained on the generation of waves (up to 7 feet) from storms on Lake Okeechobee indicated there was no necessity for such an additional term. He concluded that the effect of the form resistance of waves became gradually less important with increased length of fetch, until at some undetermined point it becomes essentially negligible.

[2] One of the methods for calculating the bottom stress as suggested by Plate and Goodwin (1965) is by using momentum balances for both the air and the water. The shear stress is expressed by,

$\tau_b = \frac{\gamma}{C^2} V_{av}$ where, V_{av} = the mean velocity of the channel flow with wind blowing, and C^2 is calculated from a Chezy equation of the form

$$\frac{C}{\sqrt{g}} = 0.06 \log Y_n + B$$

where Y_n is the depth of flow with wind blowing and B is a coefficient which depends only on the slope S_o, but not on wind conditions.

[3] There is no instrumentation on the northern and eastern shores.

One pratical aspect of any wind set-up study is the ability to forecast (given forecasts of wind) the extent of shoreline flooding. From this study, a strong recommendation is given to enhance the relationship between wind and wind set-ups to a level which allows a much more efficient prediction of possible flooding.

It is suggested that a more detailed study might include the entire record of water level data from Lake St. Clair and employ more sophisticated analyses such as time series or power spectral analysis.

APPENDIX A

Wind Set-Up Theories

Zuider Zee:

One of the simpler formulas known as the Zuider Zee equation was used by the Dutch to study the problem in Holland (U. S. Corps of Engineers, 1955). It is stated as,

$$s = \frac{V^2F}{800D} \qquad \text{(eq.12)}$$

where,

s = total set-up in feet
V = wind velocity in miles per hour
F = fetch in miles
D = depth in feet

The equation was later modified to compute the set up (h_s) in feet above the undisturbed level as,

$$h_s = \frac{V^2F}{1400D} \qquad \text{(eq.13)}$$

Beach Erosion Board:

Investigations of wind set-ups on Lake Okeechobee in Florida by the Beach Erosion Board (U. S. Corps of Engineers, 1955) resulted in the development of an equation in which the total set up was represented by,

$$s = \frac{K\lambda P_a V^2F}{\gamma D} \quad \text{or}$$

$$s = 1.165 \times \frac{10^{-3}V^2F}{D} \qquad \text{(eq.14)}$$

The constant K was evaluated as about equal to 0.003 which agreed closely to that obtained by Kuelegan (1953). It should be noted that this coefficient (1.165×10^{-3}) is almost identical with that

(1.125×10^{-3}) of the Zuider Zee formula (Saville, 1953). This close agreement between coefficients applicable to such widely varying conditions as those in Kuelegan's model experiments, the Zuider Zee and Lake Okeechobee indicates that this is a wind set up formula for general application. Since computed shear stresses were used in the other equations the model equation for Lake Okeechobee was used to compute the set ups.

Kuelegan:

Kuelegan's model for wind set ups was separated into set up due to skin friction between wind and water surface (U. S. Corps of Engineers, 1955) and that due to the form resistance of the waves. The total set up was expressed as,

$$s = \left[3.30 \times 10^{-6} \frac{V^2}{gd} + 1.08 \times 10^{-4} \frac{(V-V_c)^2}{gd} F \left(\frac{D}{F}\right)^{\frac{1}{2}}\right] F \qquad \text{(eq.15)}$$

where V_c is the critical wind velocity found by initiating wave action, equal to about 3.0 ft./sec. in model experiments. By relating the set up due to skin friction and that due to form resistance to the wind speed V, observed in the set up model, the relation was expressed dimensionlessly and the constants 3.30×10^{-6} and 2.08×10^{-4} derived, since g (gravity) and L (length) were constant in the model tests. Kuelegan also states that the critical wind velocity for genesis of waves on a large body of water is about one-third as great as the values obtained in laboratory channels and could be omitted without introducing a large error. The equation then becomes,

$$s = \left[3.30 \times 10^{-6}\ \{1 + 63\left(\frac{d}{F}\right)^{\frac{1}{2}}\right] \frac{V^2 F}{gD} \qquad \text{(eq.16)}$$

A complex integration procedure was also developed by Kuelegan for obtaining set ups in lakes of varying planform and depth. The basic equation is,

$$h_s = \frac{\lambda \tau_s F}{2 \gamma (D+h_s)} \qquad \text{(eq.17)}$$

Saville:

Saville (1953) working on the theoretical developments made by Hellstrom (1941), Kuelegan (1953), Thijsse (1952), derived an equation which is expressed as,

$$h_s = \frac{n F \tau_s}{p g D} \qquad \text{(eq.18)}$$

where,

h_s = slope of the water surface
τ_s = surface shear stress
F = fetch
p = density of water
g = gravity
D = depth
n = a coefficient defined as $n = \frac{\tau_s}{\tau_o} + 1$ where τ_o is the shear stress along the bottom

Hellstrom:

Hellstrom in his analysis of wind effects on lakes and rivers, presented a very comprehensive study of the problem of computing set up.[1] His equation for deep lakes was applied in this study to see if such theory is applicable. It is expressed as,

$$h_s = \frac{\lambda \tau_{sF}}{2 \gamma D} \qquad \text{(eq.19)}$$

The theories for computing the set up were confined to regular shaped bodies of water of uniform depth, thus avoiding the determination of the more complex factors existing under natural conditions.

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[1] U.S. Corps of Engineers, Waves and Wind Tides in Shallow Lakes and Reservoirs, Lake Okeechobee, Florida, June, 1955.

APPENDIX B

Instrument Specifications

Plastic Tape

Tape width: 11/16 inch.
Tape thickness: 0.004 inch.
Material: P.V.C.

Code

5 channel CCITT, suitable for direct use in electronic computer or teletyper.

Measuring Range

000 - 99.99 feet.

Reading Accuracy (by means of digital readout)

1/100 of a foot.

Measuring Accuracy

1/200 of a foot.

Recording Length

At 15 minutes readout, the tape supply will last for approximately 6 months.

Power Supply

7.5 volt dry cell battery.

Current Consumption

Starting current, average, 250 mA, Running current, average, mA.

Float Tape

Perforated to prevent slippage. Stainless steel for corrosion resistance.

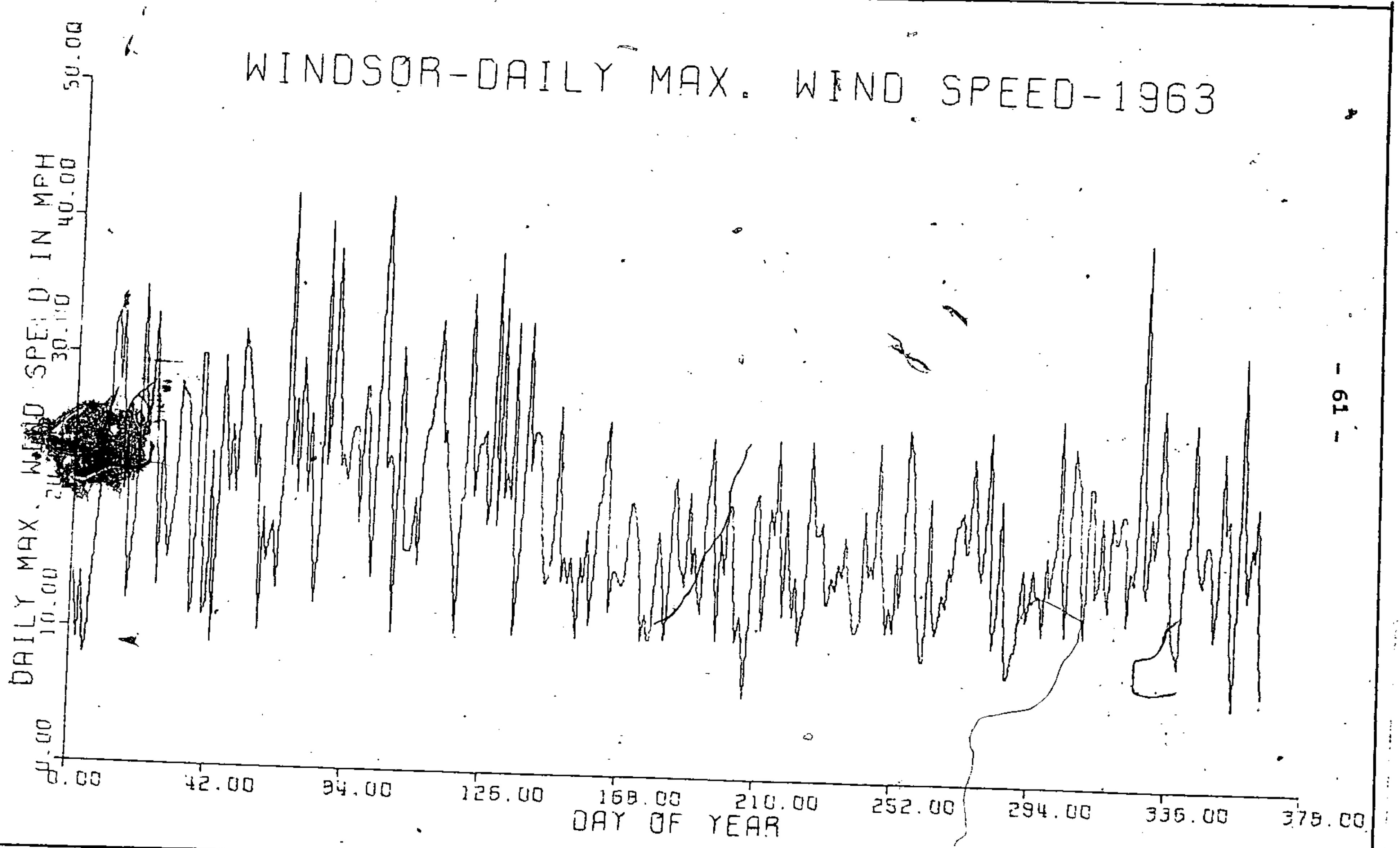
General Description

The Ott Punch Tape Recorder is a battery powered water level recorder using ITT 5 level code to supply a punched tape decimal readout of water levels. The punch cycle can be varied and is controlled by an electrically wound clock driving a cycling cam. The unit supplied by the Tides and Water Levels section normally punch every 15 minutes but are easily converted by removing three pins from the control cam. This gives a 1 hour punch cycle.

The recorder has an indicator, which is a visual readout of the water level in feet, tenths and hundreds of a foot. The range of the instrument is 0-99.99 feet. There is also a battery condition indicator mounted on the front face of the punch unit cover.

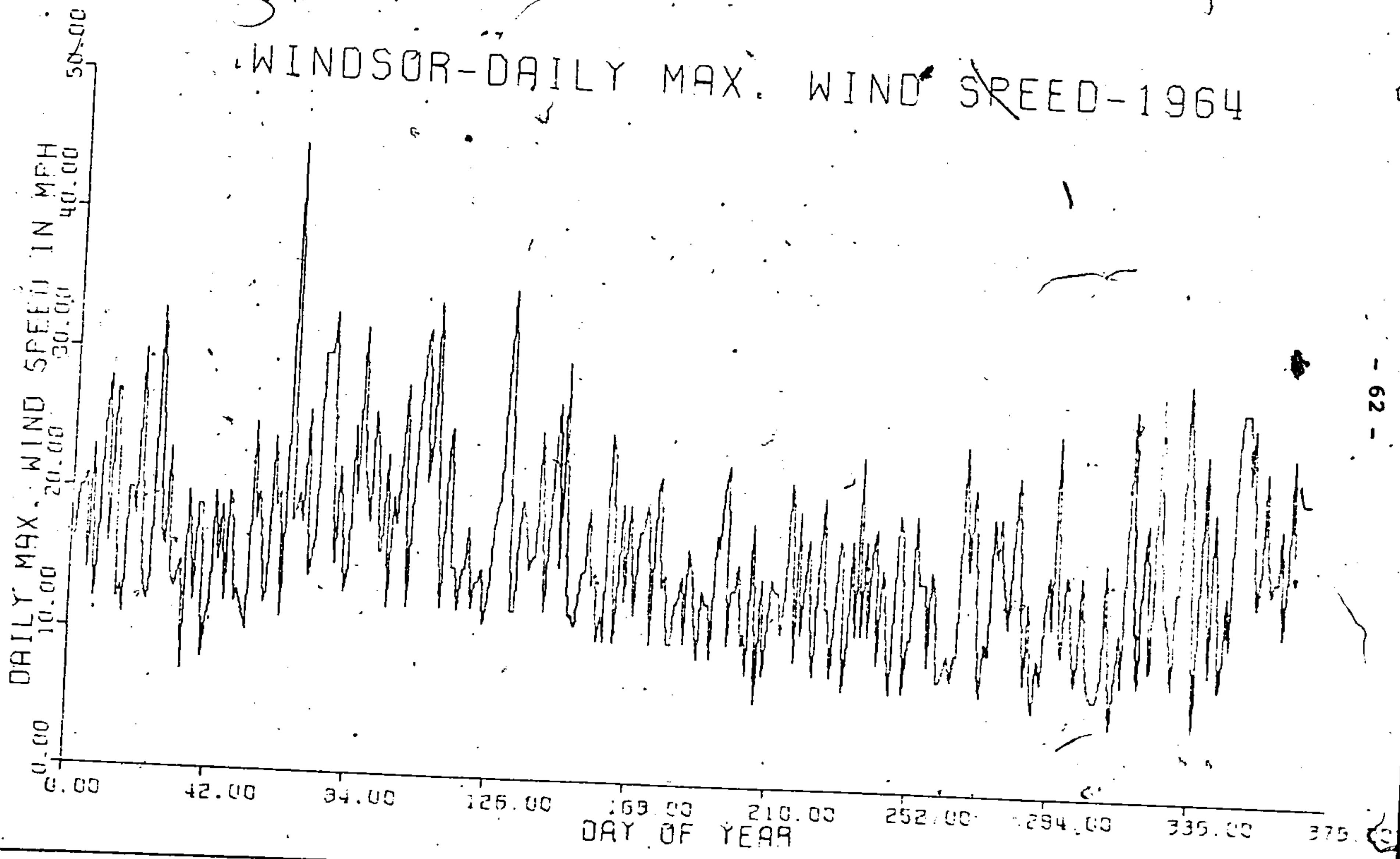
At the back of the recorder are mounted the float sprocket wheel, the timer clock and a punch cycle counter. The cycle counter is used to verify that the recorder has given the correct number of punches for a given time interval.

APPENDIX C



WINDSOR-DAILY MAX. WIND SPEED-1963

APPENDIX C cont'd



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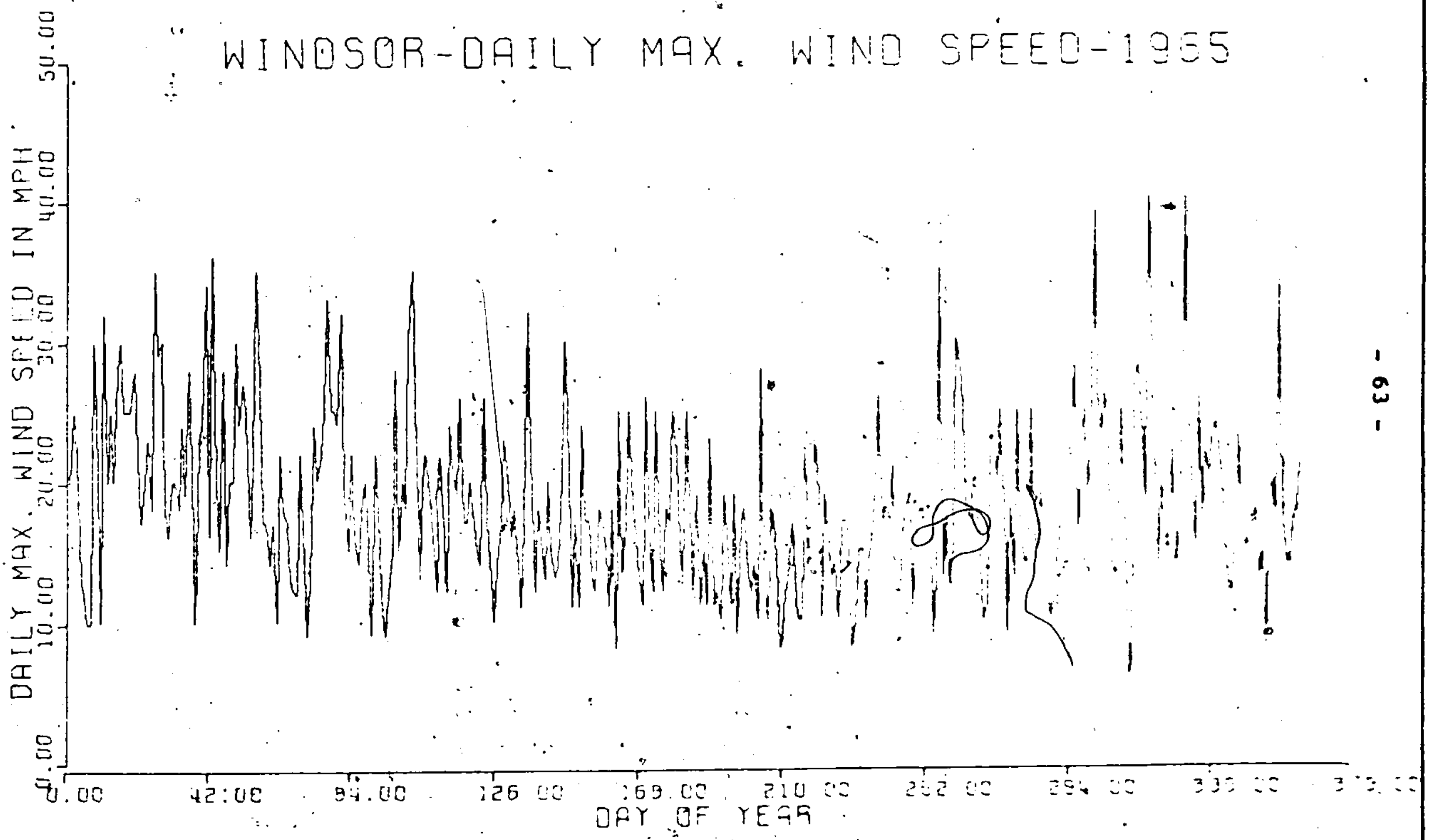

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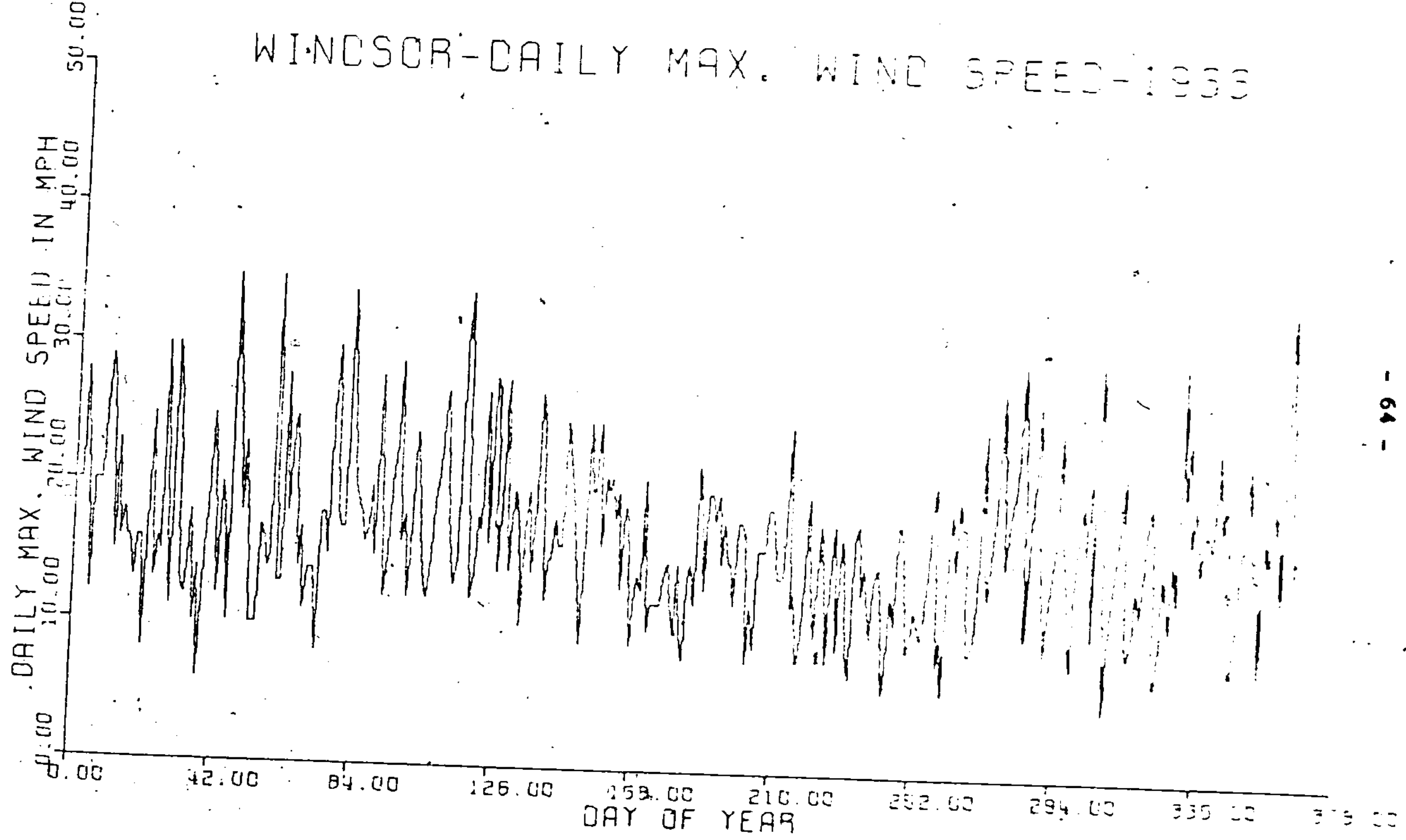

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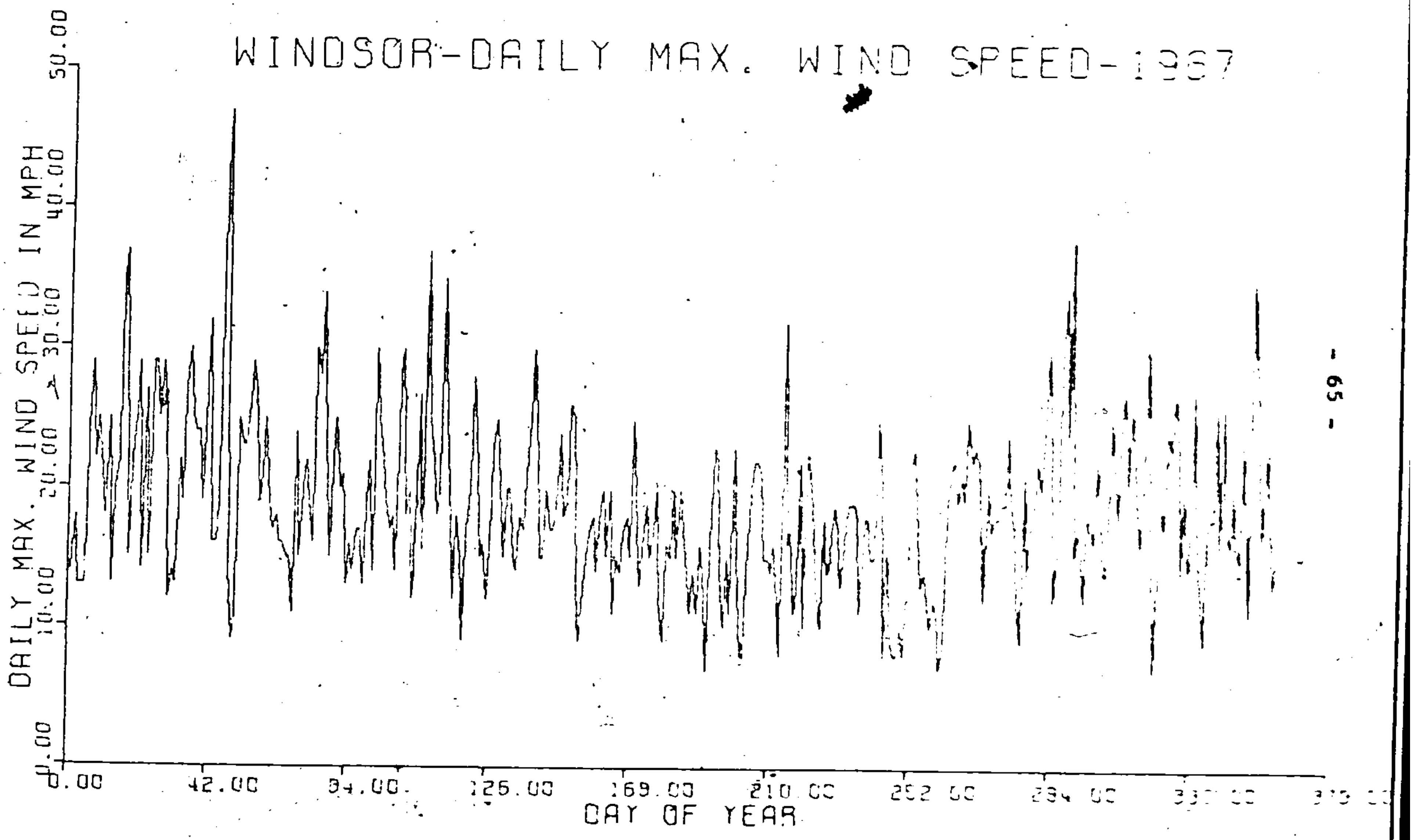

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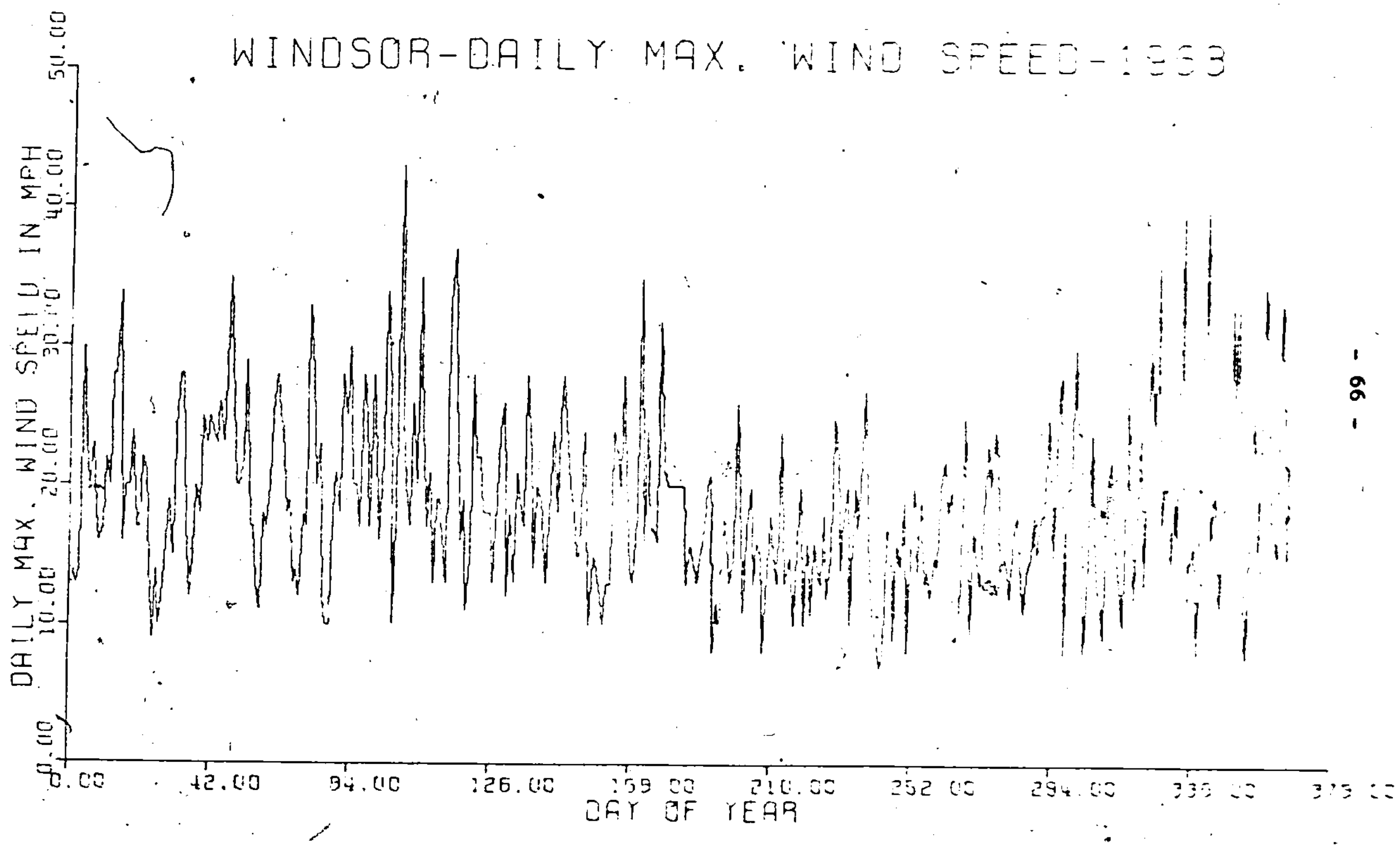

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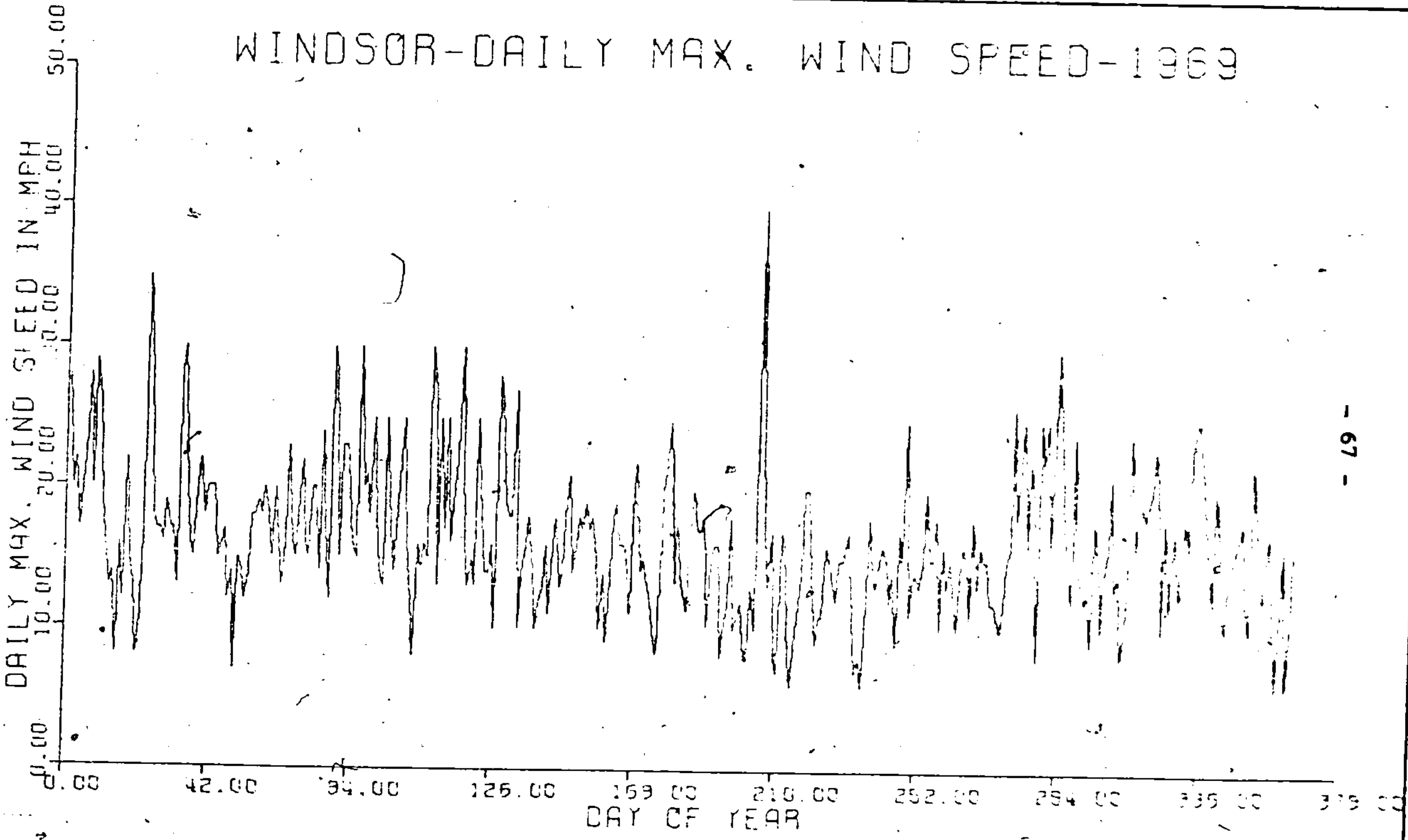
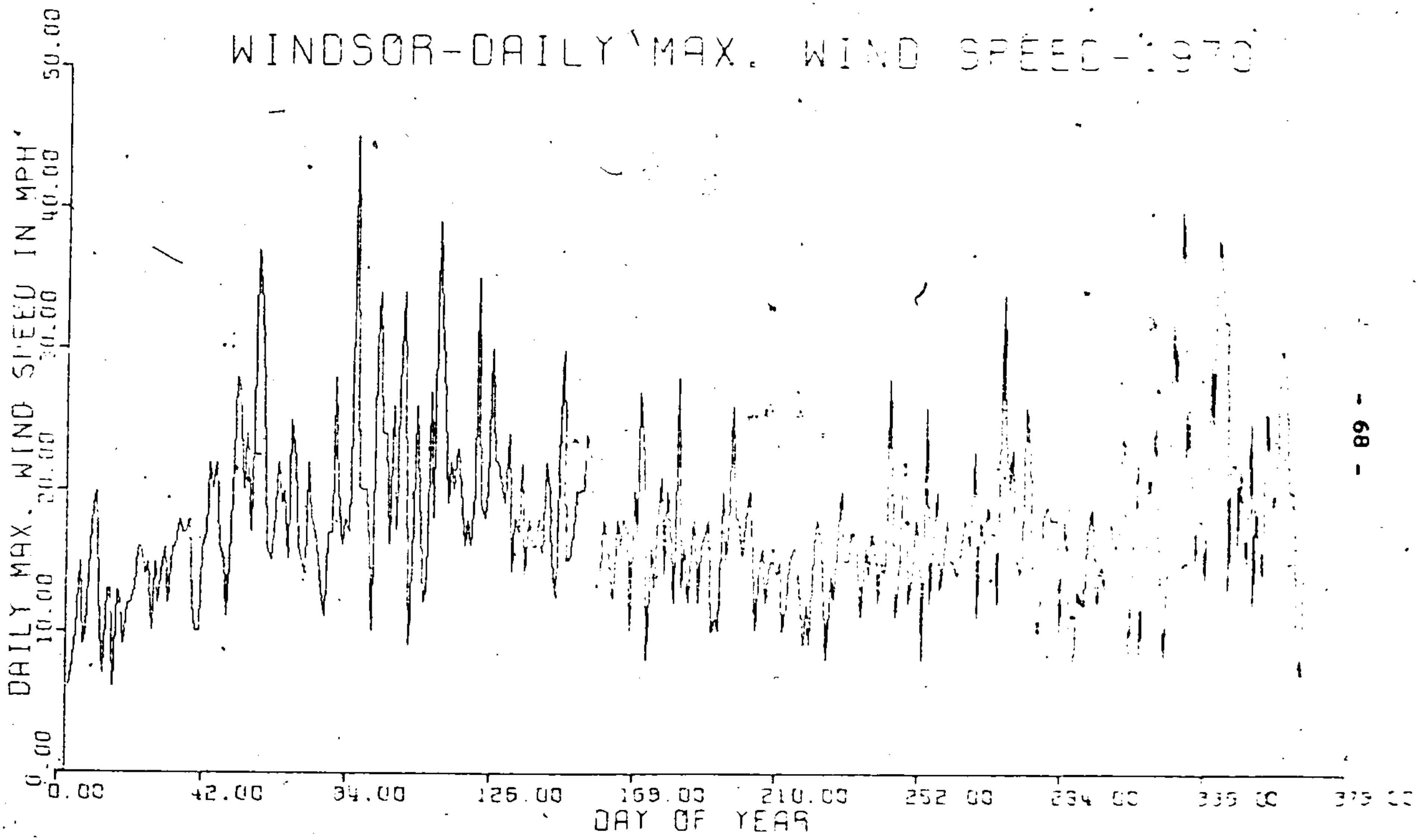


WINDSOR-DAILY MAX. WIND SPEED-1969

APPENDIX C cont'd.



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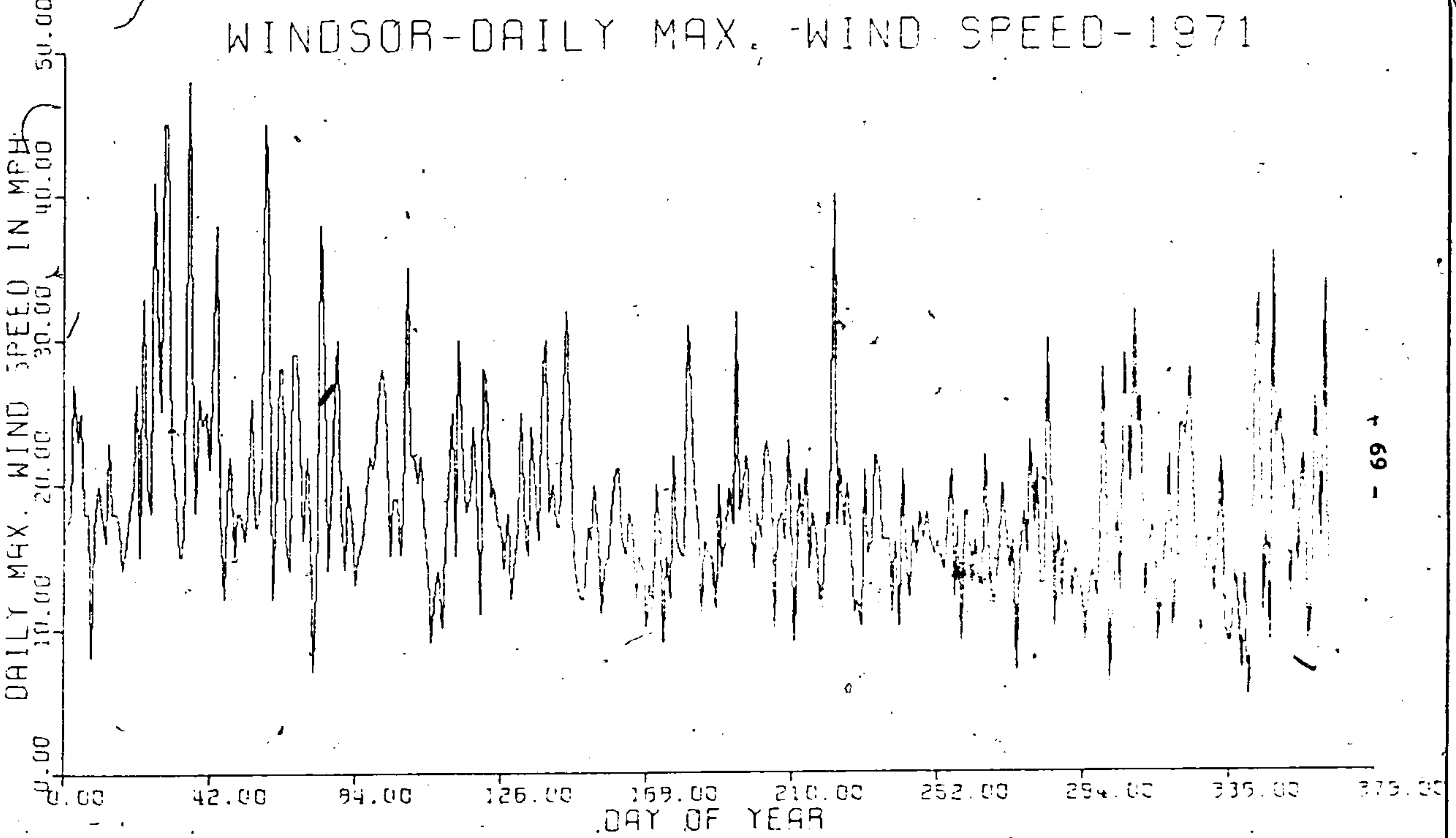
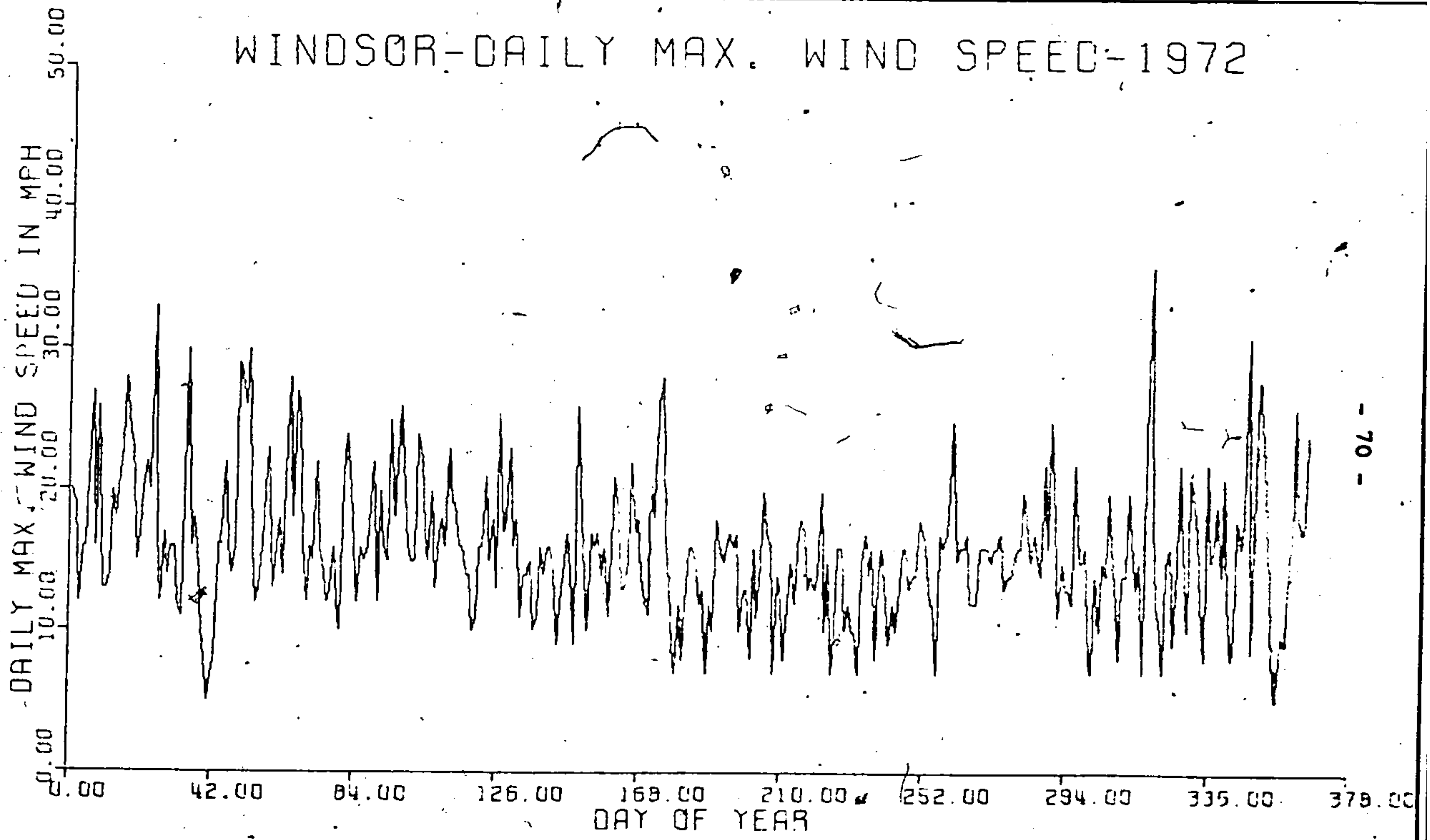
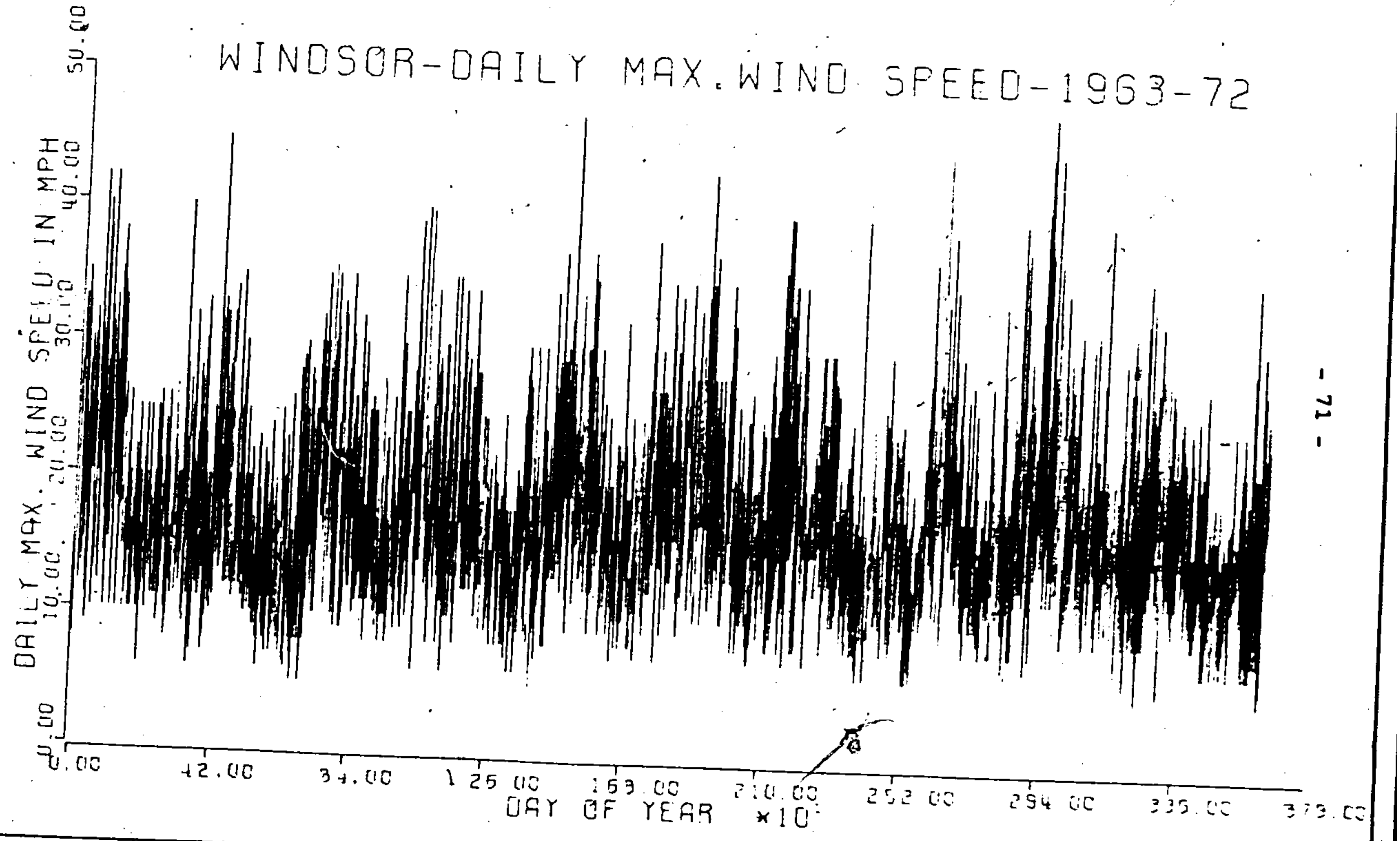


APPENDIX C cont'd.

WINDSOR-DAILY MAX. WIND SPEED-1972



APPENDIX C cont'd.



APPENDIX D

Shear Stress

January - June - Stable Conditions ($T_A - T_W = +4^{\circ}$)

Wind Velocity (MPH)	Surface τ Shear Stress (F.P.S.)	Bottom τ Shear Stress (F.P.S.)	$\lambda \tau_s$ (F.P.S.)
1	.0000064	.0000006	.0000071
2	.0000470	.0000047	.0000517
3	.0001247	.0000124	.0001372
4	.0002396	.0000239	.0002636
5	.0003916	.0000391	.0004308
6	.0005809	.0000580	.0006390
7	.0008073	.0000807	.0008880
8	.0010709	.0001071	.0011779
9	.0013716	.0001372	.0015088
10	.0017095	.0001709	.0018805
11	.0020846	.0002084	.0022931
12	.0024969	.0002496	.0027466
13	.0029463	.0002946	.0037762
14	.0034339	.0003433	.0037768
15	.0039567	.0003956	.0043524
16	.0045180	.0004518	.004969
17	.0051168	.0005116	.005627
18	.005751	.0005751	.006326
19	.006423	.0006423	.007066
20	.007133	.0007133	.007846
21	.007880	.0007880	.008668
22	.008664	.0008664	.009530
23	.009485	.0009485	.01043
24	.01034	.001034	.01138
25	.01124	.001124	.01236
26	.01217	.001217	.01339
27	.01314	.001314	.01445
28	.01415	.001415	.01556
29	.01519	.001519	.01672
30	.01627	.001627	.01790
31	.0173[illegible]	.001739	.01913
32	.01855	.001855	.02040
33	.01974	.001974	.02172
34	.02097	.002097	.02307
35	.02224	.002224	.02446
36	.02354	.002354	.02590
37	.0248842	.0024884	.027372
38	.02626	.002626	.02889
39	.02768	.002768	.03045
40	.02913	.002913	.03204

Appendix D cont'd.

Wind Velocity (MPH)	τ_s Surface Shear Stress (F.P.S.)	τ Bottom Shear Stress (F.P.S.)	$\lambda\tau_s$ (F.P.S.)
41	.0306222	.0030622	.0336844
42	.0321496	.0032149	.0353646
43	.0337142	.0033714	.0370856
44	.0353159	.0035316	.0388476
45	.0369548	.0036955	.0406504
46	.0386300	.0038630	.042494
47	.040344	.0040344	.044378
48	.0420947	.0042094	.046304
49	.0438823	.0043882	.048270
50	.0457071	.0045707	.0502778

APPENDIX E

Shear Stress

July - August - Neutral Conditions ($T_A - T_W = 0^\circ$)

Wind Velocity (MPH)	Surface τ_s Shear Stress (F.P.S.)	Bottom τ_b Shear Stress (F.P.S.)	$\lambda \tau_s$ (F.P.S.)
1			
2			
3	.000497	.0000049	.0000547
4	.000129	.0000129	.000142
5	.000246	.0000246	.000270
6	.000399	.0000399	.000439
7	.000590	.0000590	.000649
8	.000818	.0000818	.00090
9	.00108	.000108	.00119
10	.001386	.0001386	.00152
11	.00172	.000172	.001898
12	.002100	.0002100	.002310
13	.002516	.0002516	.002768
14	.002967	.0002967	.003264
15	.003455	.0003455	.003801
16	.003981	.0003981	.004379
17	.00454	.000454	.004998
18	.00514	.000514	.005657
19	.00578	.000578	.006358
20	.00645	.000645	.00710
21	.007166	.0007166	.00788
22	.007914	.0007914	.0087059
23	.008700	.0008700	.009570
24	.00952	.000952	.01047
25	.01038	.001038	.01142
26	.01128	.001128	.01241
27	.012214	.0012214	.031435
28	.013186	.0013186	.014504
29	.014194	.0014194	.015614
30	.01524	.001524	.016764
31	.01632	.001632	.01795
32	.01744	.001744	.019188
33	.01860	.001860	.02046
34	.01979	.001979	.02177
35	.021027	.0021027	.02313
36	.02229	.002229	.024525
37	.023[illegible]0	.002360	.025962
38	.024945	.0024945	.02744
39	.026326	.0026326	.028958
40	.02774	.002774	.0305179

Appendix E cont'd.

Wind Velocity (MPH)	τ_s Surface Shear Stress (F.P.S.)	τ_b Bottom Shear Stress (F.P.S.)	$\lambda \tau_s$ (F.P.S.)
41	.029198	.0029198	.032118
42	.030690	.0030690	.033759
43	.032219	.0032219	.0354412
44	.033785	.0033785	.0371641
45	.0353889	.0035388	.0389278
46	.037029	.0037029	.0407325
47	.038706	.0038707	.042578
48	.040422	.0040422	.044464
49	.0412744	.0041274	.0463918
50	.0439636	.0043963	.0483600

APPENDIX F

Shear Stress

September - December - Unstable Conditions ($T_A - T_W = -4^o$)

Wind Velocity (MPH)	Surface τ_s Shear Stress (F.P.S.)	Bottom τ_b Shear Stress (F.P.S.)	$\lambda\tau_s$ (F.P.S.)
1			
2			
3	.0000086	.0000008	.0000094
4	.0000525	.0000052	.0000577
5	.0001335	.0000133	.0001469
6	.0002518	.0000251	.0002769
7	.0004072	.0000407	.0004479
8	.0005997	.0000599	.0006597
9	.0008295	.0000829	.0009124
10	.0010964	.0001096	.0012061
11	.0014005	.0001400	.0015406
12	.0017418	.0001741	.0019160
13	.0021202	.0002120	.0023322
14	.0025368	.0002536	.002789
15	.0029880	.0002988	.003287
16	.0034785	.0003478	.0038264
17	.004006	.0004006	.0044060
18	.004570	.0004570	.005027
19	.005171	.0005171	.005688
20	.005810	.0005810	.006391
21	.006486	.0006486	.007134
22	.0071998	.0007199	.002919
23	.007949	.0007949	.008744
24	.008736	.0008736	.009610
25	.009561	.0009561	.01052
26	.01042	.001042	.01146
27	.01132	.001132	.01245
28	.01226	.001226	.01348
29	.01323	.001323	.01455
30	.01424	.001424	.01566
31	.01529	.001529	.01682
32	.01637	.001637	.01801
33	.0174950	.0017495	.0192445
34	.0186541	.0018654	.0205195
35	.01985	.001985	.02183
36	.0210837	.0021083	.0231920
37	.0223542	.0022354	.0245896
38	.0236619	.0023661	.0260282
39	.0250069	.0025006	.0275076
40	.0263889	.0026388	.0290278

Appendix F cont'd.

Wind Velocity (MPH)	Surface τ_s Shear Stress (F.P.S.)	Bottom τ_b Shear Stress (F.P.S.)	$\lambda\tau_s$ (F.P.S.)
41	.0278082	.0027808	.0305890
42	.0292646	.0029264	.0321911
43	.0307582	.0030758	.0338340
44	.0322889	.0032288	.0355179
45	.0338569	.0033856	.0372426
46	.0354620	.0035462	.0390082
47	.0371043	.0037104	.0408147
48	.0387837	.0038783	.0426621
49	.0405003	.0040500	.0445503
50	.0422541	.0042254	.0464795

Appendix G cont'd.

1967	2	16	0.33	1.04	1.10	1.42	0.97	1.13	1.67	2.10	12.6	12.06	40.	1600.
1967	3	15	0.38	0.44	0.51	0.50	0.41	0.52	0.70	1.02	17.0	12.69	23.	529.
1967	3	17	0.37	0.75	1.08	1.27	0.93	1.03	1.50	1.05	28.5	12.59	26.	676.
1967	4	2	0.55	0.66	0.76	0.89	0.62	0.75	1.05	1.45	20.5	12.10	26.	676.
1967	4	10	0.39	0.28	0.32	0.37	0.25	0.33	0.44	0.67	13.5	13.34	21.	441.
1967	4	22	0.26	0.57	0.55	0.76	0.53	0.66	0.90	1.22	12.6	13.34	31.	961.
1967	5	19	0.23	0.32	0.36	0.42	0.29	0.37	0.49	0.75	17.0	13.49	20.	400.
1967	8	2	0.23	0.11	0.13	0.12	0.10	0.11	0.14	0.23	17.0	13.74	12.	144.
1967	10	20	0.32	0.26	0.29	0.26	0.24	0.24	0.31	0.49	19.0	13.44	17.	289.
1967	11	19	0.43	0.44	0.50	0.43	0.41	0.42	0.56	0.84	20.5	12.98	21.	441.
1967	12	21	0.33	0.31	0.35	0.34	0.29	0.31	0.40	0.62	13.5	13.32	22.	484.
1966	1	27	0.20	0.21	0.24	0.28	0.20	0.25	0.33	0.52	12.6	12.06	18.	324.
1966	1	30	0.05	0.31	0.35	0.41	0.29	0.37	0.49	0.73	13.5	12.06	21.	441.
1966	2	16	0.23	0.31	0.35	0.41	0.29	0.37	0.49	0.74	12.6	12.27	22.	484.
1966	2	17	0.23	0.34	0.39	0.45	0.32	0.40	0.54	0.80	12.6	12.27	23.	529.
1956	3	1	0.47	0.33	0.44	0.51	0.35	0.45	0.60	0.89	12.6	11.86	24.	576.
1966	3	19	0.35	0.34	0.39	0.45	0.31	0.40	0.53	0.80	17.0	12.59	20.	400.
1966	3	23	0.30	0.33	0.38	0.44	0.31	0.40	0.53	0.79	17.0	12.69	20.	400.
1966	4	26	0.51	0.40	0.46	0.54	0.38	0.47	0.64	0.94	19.0	12.94	21.	441.
1966	10	10	0.35	0.13	0.14	0.12	0.12	0.11	0.14	0.23	12.6	12.22	14.	196.
1966	11	2	1.72	1.23	1.40	1.44	1.14	1.14	1.70	2.13	28.5	12.22	29.	841.

Appendix G cont'd.

1966	11	27	0.46	0.47	0.54	0.52	0.44	0.45	0.62	0.91	19.0	12.14	22.	484.	3
1966	12	23	0.15	0.20	0.23	0.21	0.19	0.17	0.25	0.40	12.6	12.64	18.	324.	3
1966	12	29	0.36	0.79	0.30	0.93	0.74	0.09	0.11	1.59	19.0	12.64	29.	841.	3
1965	1	8	0.37	0.38	0.43	0.51	0.35	0.44	0.60	0.87	12.6	10.97	23.	529.	3
1965	1	11	0.53	0.56	0.64	0.75	0.52	0.64	0.80	1.23	19.0	11.16	23.	529.	3
1965	1	16	0.52	0.61	0.69	0.81	0.55	0.68	0.96	1.31	17.0	10.97	25.	625.	3
1965	1	26	0.30	0.42	0.50	0.65	0.46	0.56	0.77	1.0[illegible]	12.5	10.07	25.	625.	3
1965	1	28	0.15	0.52	0.70	0.92	0.57	0.63	0.97	1.30	17.0	9.94	24.	576.	30
1965	2	10	2.10	0.37	0.42	0.49	0.35	0.43	0.58	0.86	17.0	11.47	20.	400.	34
1965	2	19	0.18	0.75	0.86	1.00	0.70	0.83	1.13	1.57	28.5	11.49	22.	484.	3
1965	2	25	0.13	1.48	1.69	1.99	1.38	1.43	2.35	2.67	28.5	10.86	30.	900.	35
1965	4	12	0.43	0.51	0.59	0.69	0.48	0.59	0.81	1.15	12.6	12.06	28.	784.	35
1965	5	16	0.33	0.63	0.72	0.85	0.59	0.72	1.00	1.38	17.0	12.29	27.	729.	32
1965	9	15	0.36	0.23	0.26	0.24	0.22	0.22	0.29	0.45	14.1	12.34	18.	324.	3
1965	9	29	0.33	0.35	0.40	0.37	0.33	0.33	0.44	0.67	19.0	12.24	19.	361.	3
1965	10	31	0.53	0.44	0.50	0.60	0.41	0.44	0.59	0.87	13.5	12.04	25.	625.	3
1965	11	16	0.58	0.24	0.27	0.25	0.22	0.23	0.30	0.47	12.6	12.04	19.	361.	40
1965	11	17	0.80	0.61	0.69	0.71	0.57	0.62	0.35	1.20	13.5	12.51	30.	900.	32
1965	12	25	1.63	0.51	0.58	0.57	0.47	0.50	0.68	0.99	17.0	12.04	24.	576.	34
1964	1	20	0.20	0.37	0.42	0.49	0.34	0.43	0.57	0.82	13.5	9.22	20.	400.	30.
1964	1	25	0.17	1.16	1.32	1.56	1.08	1.18	1.85	2.15	17.0	9.39	32.	1024.	33

Appendix G cont'd.

1964	3	5	1.17	1.14	1.31	1.54	1.07	1.19	1.33	2.19	17.0	10.74	34.	1156.	4
1964	3	14	0.31	0.30	0.35	0.41	0.29	0.36	0.48	0.72	12.6	11.39	21.	441.	3
1964	3	17	0.38	0.40	0.45	0.53	0.37	0.47	0.63	0.98	12.6	11.34	24.	576.	3
1964	3	26	0.40	0.50	0.57	0.66	0.46	0.57	0.79	1.11	17.0	11.29	23.	529.	3
1964	4	14	0.33	0.33	0.38	0.44	0.31	0.39	0.52	0.77	17.0	11.61	19.	361.	3
1964	4	17	0.29	0.57	0.65	0.77	0.53	0.65	0.91	1.26	17.0	11.61	25.	625.	3
1964	5	26	0.32	0.36	0.41	0.49	0.34	0.42	0.56	0.[illegible]4	19.0	11.89	19.	361.	30
1964	11	28	0.36	0.29	0.33	0.31	0.27	0.28	0.37	0.56	14.1	10.89	19.	361.	30
1963	1	11	0.22	0.69	0.79	0.93	0.64	0.78	1.09	1.49	17.0	12.09	28.	784.	36.
1963	1	12	0.10	0.25	0.29	0.33	0.24	0.30	0.40	0.61	17.0	12.09	17.	289.	33.
1963	1	14	0.55	0.69	0.79	0.93	0.64	0.78	1.09	1.49	17.0	12.09	28.	784.	33.
1963	1	20	0.62	0.69	0.79	0.93	0.54	0.78	1.09	1.49	17.0	12.09	29.	784.	35.
1963	1	24	0.32	0.96	1.10	1.30	0.90	1.03	1.53	1.93	19.0	11.09	30.	900.	33.
1963	2	7	0.01	0.59	0.66	0.78	0.54	0.66	0.92	1.27	17.0	11.44	25.	625.	34.
1963	2	8	0.02	0.68	0.77	0.91	0.63	0.76	1.07	1.45	17.0	11.44	27.	729.	30.
1963	2	14	0.21	0.36	0.42	0.49	0.34	0.43	0.57	0.85	12.6	11.44	23.	529.	30.
1963	2	20	0.23	0.50	0.57	0.67	0.47	0.58	0.80	1.13	12.6	11.44	27.	729.	32.
1963	3	10	0.19	0.27	0.31	0.36	0.25	0.32	0.42	0.65	12.6	11.44	20.	400.	30.
1963	3	21	0.13	0.40	0.46	0.54	0.39	0.47	0.64	0.94	13.5	12.02	24.	576.	32.
1963	4	3	0.41	0.64	0.73	0.86	0.60	0.73	1.01	1.40	19.0	12.54	26.	676.	36.
1963	4	[illegible]	0.41	1.10	1.2[illegible]	1.49	1.02	1.18	1.76	2.20	17.0	12.54	36.	1296.	43.

Appendix G cont'd.

1963	4	9	0.33	0.95	0.63	0.73	0.51	0.63	0.36	1.22	20.5	12.39	23.	529.
1963	4	30	1.45	0.93	1.07	1.26	0.97	1.02	1.40	1.92	20.5	12.34	30.	900.
1963	5	8	0.40	0.91	1.04	1.23	0.85	1.00	1.45	1.89	19.0	12.54	31.	961.
1963	5	10	0.93	0.26	0.30	0.34	0.24	0.31	0.41	0.53	20.5	12.54	16.	256.
1963	5	14	0.20	0.25	0.29	0.33	0.23	0.30	0.39	0.61	12.6	12.54	20.	400.
1963	5	18	0.12	0.37	0.43	0.50	0.35	0.44	0.59	0.87	17.0	12.59	21.	441.
1963	11	23	0.85	0.57	0.77	0.78	0.63	0.66	0.92	1.28	17.0	11.49	27.	729.
1963	12	24	0.24	0.51	0.59	0.70	0.57	0.60	0.92	1.16	17.0	11.82	26.	679.

St. Clair Shores

YEAR	MO	DY	45	ZEE1	ZEE2	HELL	BEAR	HUNT	SAVL	KUEL	FECH	DEPT	VEL	VEL.SQ	
1972	1	25	0.75	0.50	0.57	0.67	0.47	0.59	0.79	1.16	12.0	14.44	31.	961.	33.
1972	2	4	0.15	0.73	0.33	0.97	0.63	0.93	1.15	1.60	25.0	14.54	26.	676.	30.
1972	2	22	0.42	0.40	0.45	0.53	0.37	0.47	0.63	0.94	17.0	14.16	23.	529.	30.
1972	11	14	0.60	0.69	0.79	0.31	0.64	0.70	0.95	1.37	20.0	15.24	29.	841.	36.
1972	12	13	0.35	0.59	0.67	0.66	0.55	0.58	0.79	1.16	25.0	15.29	24.	576.	31.
1971	1	23	0.20	0.22	0.25	0.29	0.21	0.26	0.34	0.54	25.2	13.84	14.	196.	33.
1971	1	26	0.52	1.32	1.50	1.78	1.23	1.40	2.10	2.59	25.2	13.84	34.	1156.	41.
1971	1	27	0.40	1.09	1.25	1.47	1.02	1.19	1.74	2.23	25.2	13.84	31.	961.	33.
1971	1	29	0.71	0.93	0.95	1.11	0.77	0.93	1.32	1.77	25.2	13.84	27.	729.	45.

Appendix G cont'd.

1971	1	30	0.77	1.09	1.25	1.47	1.02	1.19	1.74	2.23	25.2	13.84	31.	961.	45.
1971	2	5	0.40	0.81	0.73	1.09	0.76	0.76	1.05	1.75	20.0	13.84	30.	900.	48.
1971	2	6	0.40	0.48	0.56	0.66	0.45	0.57	0.78	1.13	12.0	13.84	30.	900.	30.
1971	2	27	0.12	0.65	0.74	0.88	0.60	0.75	1.04	1.45	12.0	14.17	35.	1225.	45.
1971	2	28	0.12	0.41	0.47	0.56	0.39	0.49	0.66	0.98	12.0	14.17	28.	784.	39.
1971	3	15	0.45	0.36	0.41	0.48	0.34	0.43	0.57	0.86	12.0	14.04	26.	676.	32.
1971	3	20	0.37	0.62	0.71	0.83	0.58	0.71	0.98	1.39	25.2	14.66	24.	576.	30.
1971	4	9	0.47	0.53	0.61	0.71	0.50	0.62	0.94	1.22	17.0	14.56	27.	729.	35.
1971	4	24	0.59	0.47	0.54	0.63	0.44	0.55	0.75	1.10	25.0	14.54	21.	441.	30.
1971	5	19	0.29	0.35	0.39	0.46	0.32	0.41	0.55	0.93	12.0	14.69	26.	676.	33.
1971	5	25	0.41	0.37	0.43	0.50	0.35	0.45	0.59	0.69	12.0	14.69	27.	729.	32.
1971	6	29	0.45	0.19	0.22	1.08	0.18	0.91	1.28	1.75	20.0	14.94	15.	225.	31.
1971	7	13	0.40	0.76	0.85	0.94	0.70	0.30	1.11	1.54	25.0	13.99	26.	676.	32.
1971	8	10	0.17	0.57	0.65	0.65	0.53	0.57	0.77	1.13	20.0	14.84	26.	676.	40.
1971	10	11	0.32	0.43	0.50	[illegible]	0.41	0.42	0.56	0.84	25.2	14.49	20.	400.	30.
1971	11	5	0.25	0.24	0.23	0.28	0.22	0.25	0.33	0.51	8.0	14.04	25.	675.	32.
1971	12	10	0.57	0.17	0.20	0.19	0.16	0.18	0.22	0.36	8.0	14.11	22.	484.	30.
1971	12	11	0.35	0.31	0.35	0.35	0.29	0.31	0.41	0.63	12.0	14.11	24.	576.	33.
1971	12	15	0.87	0.11	0.13	0.12	0.11	0.11	0.14	0.23	8.0	14.11	18.	324.	36.

Appendix G cont'd.

1971	12	30	0.63	0.47	0.54	0.52	0.44	0.47	0.62	0.93	20.0	14.11	23.	529.	
1970	2	26	0.20	0.55	0.52	0.73	0.51	0.63	0.86	1.23	20.0	13.19	24.	576.	
1970	3	26	0.50	0.26	0.30	0.35	0.24	0.32	0.42	0.64	8.0	13.89	27.	729.	
1970	4	1	0.37	0.23	0.32	0.38	0.26	0.34	0.49	0.69	12.0	13.96	23.	529.	
1970	4	2	0.53	0.45	0.52	0.61	0.42	0.53	0.72	1.06	12.0	13.96	29.	841.	
1970	4	9	0.22	0.04	1.03	1.27	0.88	1.04	1.50	1.98	25.2	14.06	29.	841.	
1970	4	19	[illegible]	0.54	0.73	0.86	0.50	0.73	1.01	1.43	25.0	14.04	24.	576.	
1970	4	20	0.32	0.32	0.93	1.10	0.75	0.92	1.30	1.76	25.2	14.04	27.	729.	
1970	5	1	0.25	0.38	0.44	0.52	0.36	0.46	0.61	0.91	12.0	14.24	27.	729.	
1970	5	26	0.43	0.53	0.50	0.69	0.40	0.61	0.33	1.18	25.2	14.49	22.	484.	3
1970	10	7	0.47	0.62	0.71	0.70	0.58	0.61	0.93	1.21	25.0	14.42	24.	576.	3
1970	11	20	0.63	0.31	0.33	0.94	0.76	0.80	1.11	1.54	25.0	14.06	27.	729.	3
1970	11	22	0.72	0.87	1.00	1.01	0.91	0.86	1.20	1.64	25.0	14.06	28.	784.	4
1970	11	23	0.70	0.62	0.79	0.79	0.65	0.68	0.94	1.33	25.0	14.06	25.	625.	3
1970	12	1	0.39	0.33	0.38	0.38	0.31	0.34	0.45	0.69	12.0	14.04	25.	625.	3
1970	12	3	0.57	0.49	0.56	0.54	0.45	0.48	0.64	0.95	25.0	14.04	21.	441.	3
1970	12	4	0.53	1.07	1.22	1.27	1.00	1.04	1.50	1.98	25.0	14.04	31.	961.	3
1970	12	5	0.95	0.70	0.80	0.80	0.65	0.69	0.94	1.34	25.2	14.04	25.	625.	3
1970	12	6	0.52	0.71	0.81	0.81	0.66	0.70	0.96	1.36	25.2	13.83	25.	625.	3
1970	12	23	0.55	0.58	0.67	0.65	0.54	0.57	0.77	1.13	25.0	14.19	23.	529.	3

Appendix G cont'd.

1970	12	24	0.66	0.74	0.85	0.85	0.69	0.73	1.01	1.42	25.0	14.19	26.	676.	3
1969	1	24	0.09	0.34	0.39	0.46	0.32	0.41	0.54	0.82	12.0	13.74	25.	625.	3
1969	2	4	0.35	0.54	0.61	0.72	0.50	0.52	0.35	1.22	25.2	14.19	22.	484.	3
1969	3	20	0.55	0.33	0.33	0.44	0.31	0.39	0.52	0.78	25.0	13.64	17.	289.	3
1969	3	28	0.38	0.51	0.59	0.69	0.48	0.60	0.61	1.18	20.0	14.04	24.	576.	3
1969	4	18	0.44	0.51	0.58	0.68	0.47	0.59	0.80	1.17	20.0	14.16	24.	576.	3
1969	4	27	0.15	0.17	0.19	0.22	0.15	0.20	0.26	0.42	8.0	14.52	22.	484.	3
1969	7	25	0.20	0.17	0.20	0.19	0.16	0.18	0.23	0.37	25.2	15.37	13.	169.	4
1969	10	21	0.21	0.22	0.25	0.21	0.20	0.19	0.25	0.40	25.2	14.14	14.	196.	3
1968	1	4	0.19	0.29	0.33	0.39	0.27	0.35	0.46	0.71	10.2	13.65	25.	625.	30
1968	2	17	0.13	0.70	0.91	1.06	0.74	0.87	1.26	1.70	23.5	13.52	27.	729.	35
1968	3	12	0.29	0.69	0.79	0.93	0.65	0.79	1.10	1.52	17.7	13.44	29.	841.	33
1968	3	24	0.36	0.35	0.39	0.46	0.32	0.41	0.54	0.82	14.3	13.70	23.	529.	30
1968	4	8	0.75	0.90	1.03	1.22	0.84	1.01	1.44	1.92	15.5	13.89	36.	1296.	43
1968	4	14	0.47	0.62	0.71	0.84	0.58	0.72	0.99	1.40	17.7	13.89	28.	784.	35.
1968	4	23	0.46	0.31	0.36	0.41	0.29	0.37	0.49	0.75	15.5	13.71	21.	441.	33.
1968	4	24	0.46	0.63	0.72	0.83	0.59	0.73	1.00	1.38	17.7	13.71	28.	784.	37.
1968	6	25	0.57	0.30	0.35	0.40	0.28	0.36	0.48	0.73	15.5	14.04	21.	441.	32.
1968	10	27	0.31	0.41	0.47	0.46	0.38	0.41	0.55	0.83	15.5	13.59	24.	576.	30.
1968	11	19	0.44	0.58	0.67	0.65	0.54	0.57	0.77	1.12	23.5	13.31	23.	529.	30.

Appendix G cont'd.

1968	11	21	0.45	0.61	0.70	0.72	0.57	0.62	0.85	1.21	15.5	13.31	29.	841.
1968	11	28	0.33	0.13	0.21	0.18	0.17	0.17	0.21	0.34	17.7	13.69	15.	225.
1968	12	5	0.74	0.79	0.90	0.91	0.74	0.78	1.08	1.50	23.5	13.54	27.	729.
1968	12	13	0.54	0.58	0.66	0.65	0.54	0.56	0.76	1.11	23.5	13.44	23.	529.
1968	12	23	0.60	0.65	0.74	0.76	0.60	0.56	0.90	1.28	15.5	13.49	30.	900.
1968	12	28	0.35	0.46	0.52	0.51	0.42	0.46	0.61	0.91	17.7	13.99	24.	576.
1967	1	16	0.33	0.43	0.50	0.58	0.40	0.51	0.69	1.01	10.5	12.72	29.	841.
1967	1	17	0.71	0.50	0.57	0.67	0.46	0.58	0.79	1.13	10.5	12.72	31.	961.
1967	2	5	0.33	0.38	0.44	0.51	0.36	0.45	0.60	0.89	17.7	12.77	21.	441.
1967	2	11	0.26	0.52	0.71	0.83	0.58	0.70	0.98	1.36	23.5	12.53	23.	529.
1967	2	16	0.40	1.92	2.20	2.60	1.79	1.86	3.08	3.36	23.5	12.23	40.	1600.
1967	3	15	0.28	0.27	0.31	0.36	0.26	0.33	0.43	0.66	10.5	12.79	23.	529.
1967	4	2	0.25	0.49	0.57	0.66	0.45	0.58	0.78	1.13	15.5	13.24	26.	676.
1967	4	10	0.40	0.30	0.34	0.39	0.28	0.35	0.46	0.71	14.5	13.54	21.	441.
1967	4	17	0.73	0.86	0.93	1.15	0.80	0.95	1.36	1.81	23.5	13.43	28.	784.
1967	4	22	0.78	1.05	1.20	1.41	0.98	1.14	1.67	2.14	23.5	13.49	31.	961.
1967	5	19	0.22	0.43	0.49	0.57	0.40	0.50	0.67	1.00	23.5	13.66	20.	400.
1967	8	2	0.09	0.09	0.11	0.10	0.09	0.10	0.12	0.20	14.5	13.84	12.	144.
1967	10	20	0.20	0.24	0.27	0.24	0.22	0.22	0.29	0.46	17.7	13.54	17.	289.
1967	10	27	0.85	0.64	0.73	0.72	0.59	0.62	0.85	1.22	23.5	13.29	24.	576.

Appendix G cont'd.

1967	11	19	0.26	0.22	0.25	0.24	0.20	0.22	0.28	0.44	10.2	12.99	21.	441.	30.
1967	12	21	0.40	0.32	0.37	0.36	0.30	0.32	0.42	0.65	14.5	13.59	22.	484.	35.
1966	1	27	0.19	0.24	0.27	0.22	0.22	0.29	0.37	0.58	14.5	12.30	18.	324.	30.
1966	1	30	0.17	0.32	0.37	0.43	0.30	0.33	0.51	0.77	14.5	12.30	21.	441.	30.
1966	2	16	0.13	0.56	0.65	0.75	0.53	0.65	0.89	1.25	23.5	12.59	22.	484.	35.
1966	2	17	0.27	0.52	0.71	0.82	0.58	0.70	0.97	1.36	23.5	12.59	23.	529.	30.
1966	3	1	0.12	0.70	0.30	0.94	0.65	0.73	1.11	1.50	23.5	12.29	24.	576.	35.
1966	3	19	0.59	0.31	0.33	0.41	0.29	0.36	0.48	0.73	15.5	12.63	20.	400.	30.
1966	3	23	0.39	0.21	0.24	0.27	0.19	0.25	0.32	0.51	10.5	12.74	20.	400.	34.
1966	4	26	0.45	0.37	0.43	0.50	0.35	0.44	0.59	0.88	17.7	13.04	21.	441.	30.
1966	4	27	0.91	0.95	1.02	1.27	0.88	1.04	1.51	1.96	23.5	13.04	29.	841.	34.
1966	10	10	0.30	0.23	0.27	0.23	0.22	0.21	0.27	0.42	23.5	12.30	14.	196.	30.
1966	11	27	0.42	0.42	0.49	0.47	0.39	0.41	0.55	0.83	17.7	12.69	22.	484.	30.
1966	12	28	0.52	0.33	0.43	0.39	0.35	0.35	0.47	0.71	23.5	12.69	18.	324.	30.
1966	12	29	0.25	0.74	0.34	0.87	0.69	0.73	1.02	1.41	17.7	12.59	29.	841.	34.
1965	1	8	0.37	0.70	0.30	0.93	0.65	0.77	1.10	1.47	23.5	11.16	23.	529.	30.
1965	1	11	0.33	0.52	0.60	0.69	0.49	0.59	0.92	1.15	17.7	11.24	23.	529.	32.
1965	1	16	0.50	0.54	0.62	0.73	0.51	0.62	0.86	1.20	15.5	11.16	25.	625.	30.
1965	1	26	0.31	0.90	1.03	1.21	0.84	0.96	1.43	1.79	23.5	10.19	25.	625.	35.
1965	2	10	0.50	0.37	0.43	0.50	0.35	0.43	0.59	0.85	15.5	10.3[illegible]	20.	400.	34.

Appendix G cont'd.

1965	12	25	0.75	0.31	0.35	0.35	0.29	0.31	0.41	0.63	10.5	12.19	24.	576.	3
1964	1	20	0.32	0.36	0.41	0.48	0.33	0.42	0.56	0.82	14.5	10.09	20.	400.	3
1964	1	25	0.25	0.98	1.12	1.33	0.92	1.04	1.57	1.92	15.5	10.09	32.	1024.	3
1964	3	5	1.10	1.02	1.16	1.38	0.95	1.09	1.63	2.01	15.5	10.99	34.	1156.	4
1964	3	14	0.54	0.56	0.64	0.75	0.53	0.64	0.89	1.23	23.5	11.49	21.	441.	3
1964	3	15	0.35	0.51	0.58	0.68	0.48	0.58	0.80	1.13	23.5	11.49	20.	400.	3
1964	3	16	0.56	0.46	0.53	0.61	0.43	0.53	0.72	1.04	23.5	11.49	19.	361.	3
1964	3	17	0.45	0.74	0.84	0.98	0.69	0.81	1.16	1.55	23.5	11.49	24.	576.	3
1964	3	26	0.57	0.67	0.76	0.89	0.62	0.75	1.06	1.43	23.5	11.61	23.	529.	3
1964	4	13	0.13	0.41	0.46	0.54	0.38	0.48	0.64	0.94	10.5	11.81	27.	729.	3
1964	4	14	0.47	0.30	0.34	0.40	0.28	0.35	0.46	0.72	15.5	11.81	19.	361.	3
1964	4	17	0.28	0.51	0.59	0.69	0.48	0.59	0.81	1.15	15.5	11.81	25.	625.	34
1964	5	9	0.96	0.96	1.10	1.30	0.90	1.04	1.53	1.95	23.5	11.94	28.	784.	35
1964	5	26	0.15	0.33	0.38	0.44	0.31	0.39	0.52	0.78	17.74	12.04	19.	361.	3
1963	1	[illegible]	0.16	0.42	0.49	0.56	0.39	0.49	0.67	0.97	10.5	12.24	28.	784.	36
1963	1	12	0.18	0.15	0.13	0.20	0.14	0.19	0.24	0.38	10.5	12.24	17.	289.	33
1963	1	14	0.60	0.46	0.52	0.61	0.43	0.53	0.73	1.04	10.5	11.24	28.	784.	33
1963	1	20	0.85	0.46	0.52	0.61	0.43	0.53	0.73	1.04	10.5	11.24	28.	784.	35
1963	1	24	0.85	0.89	1.01	1.19	0.83	0.96	1.41	1.81	17.7	11.24	30.	900.	33.
1963	2	7	0.01	0.36	0.41	0.48	0.33	0.42	0.56	0.83	10.5	11.54	25.	625.	34.

Appendix G cont'd.

1963	2	8	0.03	0.41	0.47	0.56	0.39	0.49	0.66	0.95	10.5	11.54	27.	729.	3
1963	2	14	0.19	0.67	0.77	0.90	0.63	0.75	1.06	1.44	23.5	11.54	23.	529.	3
1963	2	20	0.20	0.73	1.06	1.24	0.86	1.00	1.47	1.88	23.5	11.54	27.	729.	3
1963	2	21	0.20	0.87	0.99	1.16	0.81	0.94	1.37	1.78	23.5	11.44	26.	676.	3
1963	3	6	0.01	1.32	2.03	2.47	1.70	1.79	2.92	3.19	23.5	11.64	38.	1444.	4
1963	3	10	0.05	0.50	0.57	0.66	0.45	0.57	0.78	1.11	23.5	11.84	20.	400.	3
1963	3	17	0.47	1.51	1.72	2.04	1.40	1.53	2.41	2.78	23.5	11.94	35.	1225.	4
1963	3	20	0.47	0.71	0.81	0.95	0.66	0.79	1.12	1.51	23.5	11.94	24.	576.	3
1963	3	21	0.16	0.43	0.49	0.57	0.40	0.50	0.68	0.99	14.5	12.19	24.	576.	3
1963	4	3	0.71	0.59	0.68	0.79	0.55	0.68	0.94	1.31	17.7	12.64	26.	676.	3
1965	3	18	0.45	1.26	1.45	1.71	1.18	1.32	2.02	2.42	23.5	11.89	32.	1024.	33
1965	3	22	0.35	0.60	0.68	0.80	0.56	0.68	0.94	1.31	23.5	11.89	22.	484.	32
1965	4	11	0.25	0.48	0.55	0.64	0.45	0.55	0.76	1.09	23.5	12.19	20.	400.	30
1965	4	12	0.91	0.94	1.08	1.27	0.88	1.03	1.50	1.93	23.5	12.19	28.	784.	35.
1965	5	16	0.30	0.86	0.99	1.16	0.81	0.95	1.37	1.80	23.5	12.39	27.	729.	32.
1965	5	27	0.26	0.80	0.92	1.07	0.75	0.89	1.27	1.69	23.5	12.39	26.	676.	30.
1965	9	20	0.27	0.32	0.37	0.34	0.30	0.31	0.41	0.63	17.7	12.38	19.	361.	30.
1965	10	31	0.61	0.46	0.53	0.53	0.43	0.46	0.62	0.92	14.5	12.24	25.	625.	39.
1965	11	16	0.55	0.44	0.50	0.47	0.41	0.41	0.55	0.82	23.5	12.09	19.	361.	40.
1965	11	17	0.94	0.67	0.77	0.79	0.63	0.68	0.94	1.31	14.5	12.09	30.	900.	32.

Appendix G cont'd.

1963	4	4	0.71	0.9[illegible]	1.14	1.34	0.93	1.08	1.59	2.03	15.5	12.64	36.	1296.	4
1963	4	9	0.28	0.27	0.30	0.36	0.25	0.32	0.42	0.65	10.2	12.64	23.	529.	3
1963	4	20	0.50	0.62	0.71	0.83	0.58	0.70	0.98	1.36	23.5	12.54	23.	529.	3
1963	4	21	0.25	0.52	0.59	0.69	0.48	0.59	0.81	1.16	23.5	12.54	21.	441.	3
1963	4	30	0.15	0.40	0.45	0.54	0.37	0.47	0.53	0.93	10.2	12.54	28.	784.	3
1963	5	8	0.25	0.35	0.97	1.14	0.79	0.94	1.35	1.78	17.7	12.54	31.	961.	4.
1963	5	14	0.12	0.45	0.53	0.61	0.43	0.54	0.73	1.05	23.5	12.69	20.	400.	3
1963	5	18	0.32	0.27	0.31	0.36	0.25	0.33	0.43	0.67	15.5	15.69	21.	441.	3
1963	11	23	1.20	0.61	0.69	0.70	0.57	0.60	0.33	1.17	15.5	11.64	27.	729.	4
1963	12	24	0.39	0.55	0.63	0.64	0.52	0.55	0.75	1.08	15.5	11.82	26.	676.	32

NOTATIONS

MO = Month
DY = Day

AS = Actual Set-up
ZEE1 = Zuider Zee Eqn, for set-up
ZEE2 = Zuider Zee Eqn. for total set-up
HELL = Hellstrom's Eqn
BERB = Beach Erosion Board Eqn.
HUNT = Hunt's Eqn.
SAVL = Saville's Eqn.
KUEL = Kuelegan's Eqn.

FECH = Fetch
DEPT = Depth
VEL = Mean wind speed
VEL.SQ. = Mean wind speed square
MAXSP = Maximum wind speed

Appendix H.

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C     PROGRAM COMPUTES THE WIND SET-UPS FOR STATION AT PULLE RIVER
C     WIND VELOCITY IS AVERAGED OVER SIX HOURS AND IS IN MPH.
C     FETCH IS IN MILES.
C     DEPTH IS IN FEET
      INTEGER ~~YR,MO~~,DY
      REAL MASP,MDL,LSHEAR,OVEL,N
      DIMENSION AVSP(135),AS(135),FATCH(135),DEPTH(135),TSHEAR(135)
      DIMENSION YR(135),MO(135),DY(135)
      DIMENSION MDL(135),S5(135),S6(135),S7(135),S8(135)
      DIMENSION LSHEAR(135),OVASP(135),OVEL(135),VEL(135)
      DIMENSION FETCH(135),MASP(135)
      DIMENSION S1(135),S2(135),S3(135),S4(135),S9(135)
      DIMENSION HS1(135),HS2(135),S10(135)
      SPWT=62.4
      N=1.3
      ALPHA=1.04
      PRINT 3
    3 FORMAT('-','YEAR',2X,'MO',2X,'DY',6X,'AS',5X,'ZEE1',2X,'ZEE2',3X,'
     1HELL',3X,'BEB3',3X,'HUNT',3X,'SAVL',3X,'KUEL',3X,'FECH',2X,'DEPT',
     22X,'VEL',2X,'VEL.SQ.',2X,'MAXSP.')
      DO 1 I=1,135
      READ 2,YR(I),MO(I),DY(I),MASP(I),OVASP(I),MDL(I),AS(I),FATCH(I),DE
     2PTH(I),TSHEAR(I),LSHEAR(I)
    2 FORMAT(I4,2I2,F2.0,F2.0,2X,F5.2,F3.2,F3.1,F4.2,2F6.6)
      AVSP(I)=OVASP(I)*OVASP(I)
      OVEL(I)=OVASP(I)*1.466
      VEL(I)=OVEL(I)*OVEL(I)
      FETCH(I)=FATCH(I)*5280.
C     S1 IS ZUIDER ZEE EQN. FOR TOTAL SET-UP
      S1(I)=(AVSP(I)*FATCH(I))/(800.*DEPTH(I))
      S5(I)=S1(I)/2.
C     HS1 IS ZUIDER ZEE EQN. FOR SET-UP
      HS1(I)=(AVSP(I)*FATCH(I))/(1400.*DEPTH(I))
C     HS2 IS HELLSTROM EQN. FOR SET-UP
      HS2(I)=(LSHEAR(I)*FETCH(I))/(2.*SPWT*DEPTH(I))
C     S2 IS BEACH EROSION BOARD EQN. FOR TOTAL SET-UP
      S2(I)=(1.165*.001)*((AVSP(I)*FATCH(I))/DEPTH(I))
      S6(I)=S2(I)/2.
C     S3 IS HUNT'S EQN. FOR TOTAL SET-UP
      S3(I)=(-DEPTH(I)+SQRT((DEPTH(I)*DEPTH(I))+(4.*((ALPHA*TSHEAR(I)*FE
     3TCH(I))/SPWT))))/2.
      S7(I)=S3(I)/2.
C     S4 IS SAVILLE'S EQN. FOR TOTAL SET-UP
      S4(I)=(N*FETCH(I)*TSHEAR(I))/(SPWT*DEPTH(I))
      S8(I)=S4(I)/2.
C     S9 IS KUELEGAN'S EQN. FOR TOTAL SET-UP
      S9(I)=(-DEPTH(I)+SQRT((DEPTH(I)*DEPTH(I))+(4.*((LSHEAR(I)*FETCH(I)
     1)/SPWT*2.)))))/2.
      S10(I)=S9(I)/2.
      PRINT 4,YR(I),MO(I),DY(I),AS(I),S5(I),HS1(I),HS2(I),S6(I),S7(I),S8
     1(I),S10(I),FATCH(I),DEPTH(I),OVASP(I),AVSP(I),MASP(I)
    4 FORMAT('0',I4,2X,I2,2X,I2,5X,F4.2,2X,F5.2,2X,F5.2,2X,F5.2,2X,F5.2,
     12X,F5.2,2X,F5.2,2X,F5.2,2X,F4.1,2X,F5.2,2X,F3.0,2X,F6.0,2X,F3.0)
    1 CONTINUE
      STOP
      END
```

APPENDIX I

Linear Equations*

Station: Belle River

TOTSAM = 0.329 + 0.0001 WIND SQ

TOTSAM<1 = 0.324 + 0.00008 WIND SQ

ICE = 0.168 + 0.00006 WIND SQ

WOICE = 0.263 + 0.004 WIND SQ

WOICE<1 = 0.270 + 0.0003 WIND SQ

Station: St. Clair Shores

TOTSAM = 0.287 + 0.0002 WIND SQ

TOTSAM<1 = 0.303 + 0.0001 WIND SQ

ICE = 0.141 + 0.0001 WIND SQ

WOICE = 0.204 + 0.0004 WIND SQ

WOICE<1 = 0.266 + 0.0004 WIND SQ

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* The equation for mean wind speed is similar to the one's for square of the mean wind speed and have not been included here.

APPENDIX I

* Significant at .01 level
\+ Significant at .05 level
/ Not Significant

Stepwise Regression

Station: Belle River

Equation: Set Up = Fetch (x_2) + Depth (x_3) + Mean Wind Speed (x_4)

		Included Variables								Variables Not Included		
Step	Sample Condition	Variable	R	Standard Error or Estimate	R^2	Increase	X_0 Intercept	Regression Coefficient	Standard Error	Variables	Partial Correlation Coefficient	Partial Coefficient of Determination
1	TOTSAM	x_2	0.145/	0.325	0.021	0.021/	0.222	b_2 = 0.011/	0.006	x_3 x_4	-0.044 0.100	0.002 0.010
2		x_4	0.176/	0.324	0.176	0.031/	0.084	$b_{2.4}$ = 0.010/ $b_{4.2}$ = 0.006/	0.006 0.005	x_3	-0.038	0.001
3		x_3	0.180/	0.325	0.180	0.032/	0.217	$b_{2.34}$ = 0.010/ $b_{3.24}$ = 0.010/ $b_{4.23}$ = 0.006/	0.006 0.023 0.005			
1	TOTSAM<1	x_3	0.138/	0.223	0.019	0.019/	0.039	b_3 = 0.026/	0.016	x_2 x_4	0.050 0.108	0.003 0.012
2		x_4	0.175/	0.222	0.030	0.011/	-0.084	$b_{3.4}$ = 0.026/ $b_{4.3}$ = 0.004/	0.016 0.003	x_2	0.038	0.001
3		x_2	0.179/	0.223	0.032	0.001/	-0.107	$b_{2.34}$ = 0.002/ $b_{3.24}$ = 0.026/ $b_{4.23}$ = 0.004/	0.004 0.016 0.003			
1	ICE	x_3	0.373+	0.113	0.139	0.139+	-0.206	b_3 = 0.034+	0.013	x_2 x_4	0.123 0.065	0.015 0.004
2		x_2	0.390+	0.113	0.152	0.013/	-0.221	$b_{2.3}$ = 0.002/ $b_{3.2}$ = 0.031+	0.003 0.014	x_4	0.058	0.003
3		x_4	0.394/	0.115	0.155	0.002/	-0.244	$b_{2.34}$ = 0.002/ $b_{3.24}$ = 0.030* $b_{4.23}$ = 0.001/	0.003 0.014 0.004			
1	NOICE	x_2	0.303*	0.334	0.091	0.091*	-0.011	b_2 = 0.031*	0.010	x_3 x_4	-0.268 0.232	0.072 0.080
2		x_4	0.405*	0.322	0.164	0.072*	-0.407	$b_{2.4}$ = 0.028* $b_{4.2}$ = 0.018*	0.009 0.006	x_3	-0.256	0.066
3		x_3	0.468*	0.313	0.219	0.055*	0.610	$b_{2.34}$ = 0.028* $b_{3.24}$ = 0.075* $b_{4.23}$ = 0.017*	0.009 0.029 0.006			
1	NOICE<1	x_4	0.335*	0.212	0.112	0.112*	0.096	b_4 = 0.015*	0.004	x_2 x_3	-0.205 -0.089	0.042 0.008
2		x_2	0.386*	0.208	0.149	0.037+	-0.119	$b_{2.4}$ = 0.013+ $b_{4.2}$ = 0.014*	0.006 0.006	x_3	-0.100	0.010
3		x_3	0.397*	0.209	0.158	0.008/	0.135	$b_{2.34}$ = 0.013+ $b_{3.24}$ = -0.019/ $b_{4.23}$ = 0.014*	0.006 0.020 0.004			

Appendix J cont'd

Stepwise Regression

Station: Belle River

* Significant at .01 level
\+ Significant at .05 level
/ Not Significant

Equation: Set Up = $\overset{(x_2)}{\text{Fetch}} + \overset{(x_3)}{\text{Depth}} + \overset{(x_4)}{\text{Mean Wind Speed}}{}^2$

			Included Variables							Variables Not Included		
Step	Sample Condition	Variable	r	Standard Error of Estimate	R^2	Increase	X_0 Intercept	Regression Coefficient	Standard Error	Variables	Partial Correlation Coefficient	Partial Coefficient of Determination
1	TOTSAN	x_2	0.145/	0.325	0.021	0.021/	0.222	b_2 = 0.012/	0.007	x_3 x_4	-0.044 0.096	0.002 0.009
2		x_4	0.174/	0.323	0.030	0.009/	0.162	$b_{2.4}$ = 0.0106/ $b_{4.2}$ = 0.0001/	0.006 0.0001	x_3	-0.039	0.002
3		x_3	0.178/	0.326	0.031	0.001/	0.297	$b_{2.34}$ = 0.010/ $b_{3.24}$ = -0.010/ $b_{4.23}$ = 0.0001/	0.006 0.023 0.0001			
1	TOTSAN<1	x_3	0.138/	0.223	0.019	0.019/	0.039	b_3 = 0.026/	0.016	x_2 x_4	0.052 0.097	0.003 0.009
2		x_4	0.168/	0.223	0.028	0.009/	-0.018	$b_{3.4}$ = 0.026/ $b_{4.3}$ = 0.00009/	0.016 0.00008	x_2	0.042	0.002
3		x_2	0.173/	0.223	0.030	0.002/	-0.046	$b_{2.34}$ = 0.002/ $b_{3.24}$ = 0.025/ $b_{4.23}$ = 0.00008/	0.004 0.016 0.00008			
1	ICE	x_3	0.373+	0.113	0.139	0.139+	-0.206	b_3 = 0.034+	0.013	x_2 x_4	0.123 0.078	0.015 0.006
2		x_2	0.391+	0.113	0.152	0.013/	-0.221	$b_{2.3}$ = 0.002/ $b_{3.2}$ = 0.031+	0.003 0.014	x_4	0.070	0.005
3		x_4	0.396/	0.115	0.157	0.004/	-0.229	$b_{2.34}$ = 0.002/ $b_{3.24}$ = 0.030* $b_{4.23}$ = 0.00003/	0.003 0.014 0.00007			
1	NOICE	x_2	0.303*	0.334	0.091	0.091*	-0.011	b_2 = 0.031*	0.010	x_3 x_4	-0.268 0.283	0.072 0.080
2		x_4	0.406*	0.322	0.165	0.073*	-0.201	$b_{2.4}$ = 0.029* $b_{4.2}$ = 0.0004*	0.009 0.0001	x_3	-0.259	0.067
3		x_3	0.470*	0.312	0.221	0.056*	0.807	$b_{2.34}$ = 0.028* $b_{3.24}$ = -0.076* $b_{4.23}$ = 0.0003*	0.009 0.029 0.0001			
1	NOICE<1	x_4	0.328*	0.212	0.107	0.107*	0.270	b_4 = 0.0003*	0.0001	x_2 x_3	0.210 -0.095	0.044 0.009
2		x_2	0.384*	0.209	0.147	0.039+	0.042	$b_{2.4}$ = 0.013+ $b_{4.2}$ = 0.0003*	0.006 0.0001	x_3	-0.106	0.011
3		x_3	0.396*	0.209	0.157	0.009/	0.310	$b_{2.34}$ = 0.014* $b_{3.24}$ = -0.020/ $b_{4.23}$ = 0.0003*	0.006 0.020 0.0001			

Appendix J cont'd

* Significant at .01 level
\+ Significant at .05 level
⁄ Not Significant

Stepwise Regression

Station: St. Clair Shores

Equation: Set Up = $\overset{(x_2)}{\text{Fetch}}$ + $\overset{(x_3)}{\text{Depth}}$ + $\overset{(x_4)}{\text{Mean Wind Speed}}$

Included Variables										Variables Not Included		
Step	Sample Condition	Variable	R	Standard Error or Estimate	R^2	Increase	X_0 Intercept	Regression Coefficient	Standard Error	Variables	Partial Correlation Coefficient	Partial Coefficient of Determination
1	TOTSAN	x_4	0.255*	0.237	0.065	0.065*	0.120	b_4 = 0.012*	0.003	x_2 x_3	0.128 0.073	0.016 0.005
2		x_2	0.284*	0.236	0.080	0.015⁄	0.006	$b_{2.4}$ = 0.005⁄ $b_{4.2}$ = 0.013*	0.003 0.003	x_3	0.066	0.004
3		x_3	0.291*	0.236	0.084	0.004⁄	−0.168	$b_{2.34}$ = 0.005⁄ $b_{3.24}$ = 0.013⁄ $b_{4.23}$ = 0.013*	0.003 0.016 0.003			
1	TOTSAN<1	x_4	0.228*	0.226	0.051	0.051*	0.158	b_4 = 0.010*	0.003	x_2 x_3	0.155 0.131	0.024 0.017
2		x_2	0.273*	0.224	0.074	0.022+	0.029	$b_{2.4}$ = 0.006+ $b_{4.2}$ = 0.011*	0.003 0.003	x_3	0.124	0.015
3		x_3	0.298*	0.223	0.089	0.014⁄	−0.286	$b_{2.34}$ = 0.006+ $b_{3.24}$ = 0.024⁄ $b_{4.23}$ = 0.011*	0.003 0.015 0.003			
1	ICE	x_2	0.468*	0.159	0.219	0.219*	−0.029	b_2 = 0.014*	0.004	x_3 x_4	0.275 0.274	0.076 0.075
2		x_3	0.527*	0.155	0.278	0.059⁄	−0.480	$b_{2.3}$ = 0.014* $b_{3.2}$ = 0.035⁄	0.004 0.021	x_4	0.271	0.073
3		x_4	0.576*	0.151	0.331	0.053⁄	−0.665	$b_{2.34}$ = 0.013* $b_{3.24}$ = 0.034⁄ $b_{4.23}$ = 0.008⁄	0.004 0.020 0.004			
1	NOICE	x_4	0.446*	0.213	0.199	0.199*	−0.061	b_4 = 0.023*	0.004	x_2 x_3	0.197 −0.075	0.039 0.006
2		x_2	0.480*	0.210	0.230	0.031+	−0.241	$b_{2.4}$ = 0.007⁄ $b_{4.2}$ = 0.024*	0.003 0.004	x_3	−0.096	0.009
3		x_3	0.487*	0.210	0.237	0.007⁄	−0.010	$b_{2.34}$ = 0.008* $b_{3.24}$ = −0.017⁄ $b_{4.23}$ = 0.024*	0.003 0.017 0.004			
1	NOICE<1	x_4	0.419*	0.203	0.175	0.175*	−0.012	b_4 = 0.020*	0.004	x_2 x_3	0.222 −0.011	0.049 0.0001
2		x_2	0.465*	0.199	0.216	0.040+	−0.204	$b_{2.4}$ = 0.008* $b_{4.2}$ = 0.022*	0.003 0.004	x_3	−0.033	0.001
3		x_3	0.466*	0.200	0.217	0.0009⁄	−0.128	$b_{2.34}$ = 0.008* $b_{3.24}$ = 0.005⁄ $b_{4.23}$ = 0.022*	0.003 0.016 0.004			

Appendix J cont'd

* Significant at .01 level
\+ Significant at .05 level
≠ Not Significant

Stepwise Regression

Station: St. Clair Shores

Equation: Set Up = Fetch (x_2) + Depth (x_3) + Mean Wind Speed (x_4)

		Included Variables								Variables Not Included		
Step	Sample Condition	Variable	R	Standard Error of Estimate	R^2	Increase	a_o Intercept	Regression Coefficient	Standard Error	Variables	Partial Correlation Coefficient	Partial Coefficient of Determination
1	TOTSUM	x_4	0.237*	0.238	0.056	0.056*	0.287	b_4 = 0.0002*	0.00008	x_2 x_3	0.123 0.071	0.015 0.005
2		x_2	0.266*	0.237	0.070	0.014≠	0.184	$b_{2.4}$ = 0.005≠ $b_{4.2}$ = 0.0002*	0.003 0.0008	x_3	0.064	0.004
3		x_3	0.273*	0.237	0.074	0.003≠	0.013	$b_{2.34}$ = 0.005≠ $b_{3.24}$ = 0.013≠ $b_{4.23}$ = 0.0002*	0.003 0.016 0.00008			
1	TOTSUM<1	x_4	0.207*	0.227	0.043	0.043*	0.303	b_4 = 0.0002*	0.00007	x_2 x_3	0.149 0.129	0.022 0.017
2		x_2	0.253*	0.226	0.064	0.021+	0.185	$b_{2.4}$ = 0.006+ $b_{4.2}$ = 0.0002*	0.003 0.00007	x_3	0.123	0.015
3		x_3	0.280*	0.225	0.078	0.014≠	-0.126	$b_{2.34}$ = 0.005+ $b_{3.24}$ = 0.023≠ $b_{4.23}$ = 0.0002*	0.003 0.015 0.00007			
1	ICE	x_2	0.469*	0.159	0.219	0.219*	-0.029	b_2 = 0.014*	0.004	x_3 x_4	0.274 0.253	0.075 0.064
2		x_3	0.528*	0.155	0.278	0.059≠	-0.480	$b_{2.3}$ = 0.014* $b_{3.2}$ = 0.035≠	0.004 0.021	x_4	0.254	0.065
3		x_4	0.571*	0.152	0.325	0.046≠	-0.555	$b_{2.34}$ = 0.013* $b_{3.24}$ = 0.034≠ $b_{4.32}$ = 0.0001≠	0.004 0.020 0.00009			
1	NOICE	x_4	0.446*	0.213	0.199	0.199*	0.203	b_4 = 0.0004*	0.00009	x_2 x_3	0.194 -0.077	0.038 0.006
2		x_2	0.479*	0.210	0.229	0.030+	0.043	$b_{2.4}$ = 0.007+ $b_{4.2}$ = 0.0005*	0.003 0.00009	x_3	-0.099	0.010
3		x_3	0.487*	0.210	0.237	0.007≠	0.280	$b_{2.34}$ = 0.008* $b_{3.24}$ = -0.018≠ $b_{4.23}$ = 0.0005*	0.003 0.017 0.00009			
1	NOICE<1	x_4	0.415*	0.204	0.172	0.172*	0.226	b_4 = 0.0004*	0.00009	x_2 x_3	0.219 -0.016	0.048 0.0002
2		x_2	0.460*	0.200	0.211	0.039*	0.055	$b_{2.4}$ = 0.008* $b_{4.2}$ = 0.0004*	0.003 0.00009	x_3	-0.038	0.001
3		x_3	0.461*	0.201	0.212	0.001≠	0.143	$b_{2.34}$ = 0.008* $b_{3.24}$ = -0.006≠ $b_{4.23}$ = 0.0004*	0.003 0.016 0.00009			

APPENDIX K

Linear Equations

Station: Belle River

TOTSAM = 0.321 + 0.191 ZEE1
TOTSAM = 0.321 + 0.166 ZEE2
TOTSAM = 0.344 + 0.113 HELL
TOTSAM = 0.321 + 0.204 BERB
TOTSAM = 0.332 + 0.154 HUNT
TOTSAM = 0.342 + 0.098 SAVL
TOTSAM = 0.323 + 0.087 KUEL

TOTSAM<1 = 0.358 + 0.033 ZEE1
TOTSAM<1 = 0.358 + 0.028 ZEE2
TOTSAM<1 = 0.365 + 0.014 HELL
TOTSAM<1 = 0.358 + 0.034 BERB
TOTSAM<1 = 0.357 + 0.032 HUNT
TOTSAM<1 = 0.364 + 0.013 SAVL
TOTSAM<1 = 0.351 + 0.021 KUEL

ICE = 0.188 + 0.042 ZEE1
ICE = 0.188 + 0.038 ZEE2
ICE = 0.188 + 0.032 HELL
ICE = 0.187 + 0.047 BERB
ICE = 0.180 + 0.049 HUNT
ICE = 0.189 + 0.026 SAVL
ICE = 0.173 + 0.031 KUEL

WOICE = 0.196 + 0.669 ZEE1
WOICE = 0.198 + 0.584 ZEE2
WOICE = 0.228 + 0.470 HELL
WOICE = 0.198 + 0.714 BERB
WOICE = 0.207 + 0.594 HUNT
WOICE = 0.226 + 0.405 SAVL
WOICE = 0.190 + 0.316 KUEL

WOICE<1 = 0.263 + 0.414 ZEE1
WOICE<1 = 0.264 + 0.361 ZEE2
WOICE<1 = 0.278 + 0.296 HELL
WOICE<1 = 0.264 + 0.441 BERB
WOICE<1 = 0.262 + 0.380 HUNT
WOICE<1 = 0.276 + 0.258 SAVL
WOICE<1 = 0.251 + 0.202 KUEL

Appendix K cont'd.

Linear Equations

Station: St. Clair Shores

TOTSAM = 0.329 + 0.186 ZEE1
TOTSAM = 0.330 + 0.163 ZEE2
TOTSAM = 0.351 + 0.115 HELL
TOTSAM = 0.329 + 0.200 BERB
TOTSAM = 0.331 + 0.168 HUNT
TOTSAM = 0.350 + 0.098 SAVL
TOTSAM = 0.320 + 0.096 KUEL

TOTSAM<1 = 0.333 + 0.164 ZEE1
TOTSAM<1 = 0.333 + 0.144 ZEE2
TOTSAM<1 = 0.352 + 0.100 HELL
TOTSAM<1 = 0.333 + 0.177 BERB
TOTSAM<1 = 0.334 + 0.150 HUNT
TOTSAM<1 = 0.352 + 0.086 SAVL
TOTSAM<1 = 0.323 + 0.086 KUEL

ICE = 0.130 + 0.177 ZEE1
ICE = 0.130 + 0.155 ZEE2
ICE = 0.135 + 0.127 HELL
ICE = 0.131 + 0.189 BERB
ICE = 0.107 + 0.191 HUNT
ICE = 0.138 + 0.106 SAVL
ICE = 0.084 + 0.115 KUEL

WOICE = 0.136 + 0.498 ZEE1
WOICE = 0.136 + 0.435 ZEE1
WOICE = 0.262 + 0.349 HELL
WOICE = 0.235 + 0.534 BERB
WOICE = 0.245 + 0.437 HUNT
WOICE = 0.262 + 0.295 SAVL
WOICE = 0.233 + 0.235 KUEL

WOICE<1 = 0.249 + 0.455 ZEE1
WOICE<1 = 0.249 + 0.398 ZEE2
WOICE<1 = 0.272 + 0.321 HELL
WOICE<1 = 0.248 + 0.489 BERB
WOICE<1 = 0.256 + 0.402 HUNT
WOICE<1 = 0.272 + 0.271 SAVL
WOICE<1 = 0.244 + 0.216 KUEL

APPENDIX L

Equations for Two Dimensional, Unsteady, Open Channel Flow

Based on the definition sketch for Equations of Motion (Figure 15), Henderson (1966) expressed his equation as,

$$\frac{\delta H}{\delta x} + \frac{1}{g}\ \frac{\delta v}{\delta t} + \frac{v^2}{C^2R} = 0 \qquad \text{where } \frac{v^2}{C^2R} = S_f.$$

$$\text{or } S_e + S_a + S_f = 0 \qquad \text{(eq. 20)}$$

where S_e = energy slope
S_a = acceleration slope
S_f = friction slope

The equation when reinstated (Henderson, 1966) with bed slope S_o equal to $-\frac{\delta z}{\delta x}$ and $h = z + y$, can be expressed as,

$$S_o - \frac{\delta y}{dx} - \frac{v}{g}\ \frac{\delta v}{\delta x} - \frac{1}{g}\ \frac{\delta v}{\delta t} = \frac{v^2}{C^2R} \qquad \text{(eq. 21)}$$

If bed slope is considered zero and $\frac{v^2}{C^2R}$ is expressed in terms of surface (τ_s) and bottom (τ_o) shear (Figure15), the equation can be written as,

$$-\frac{\delta y}{\delta x} - \frac{v}{g}\,\frac{\delta v}{\delta x} - \frac{1}{g}\,\frac{\delta v}{\delta t} = \frac{-\tau_s\left(\frac{\tau_s}{\tau_o}+1\right)}{\gamma y} = \frac{-\bar{\tau}}{\gamma y}\,(\tau_s, \tau_o) \qquad \text{(eq. 22)}$$

using the equation of continuity,

$$v\frac{\delta y}{\delta x} + y\,\frac{\delta v}{\delta x} + \frac{\delta y}{\delta t} = 0 \qquad \text{(eq. 23)}$$

and following the method of characteristic,[1] the above equations can be augmented by the following equations,

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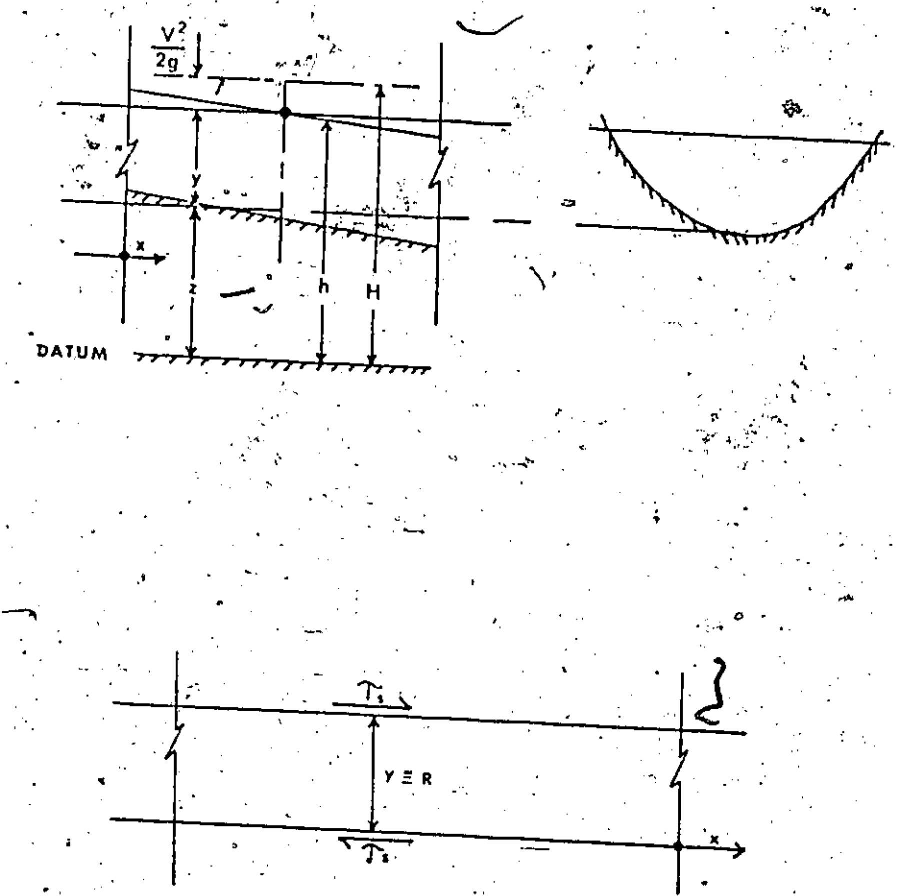
[1] J. A. McCorquodale and M. S. Nasser, Numerical Methods for Unsteady Non-Darcy Flow, Finite Element Methods in Flow Problems, J. T. Aden, et. al., (eds.).

FIG. 15

DEFINITION SKETCHES FOR THE EQUATIONS OF MOTION



Source : HENDERSON, Open Channel Flow, 1970

$$dv = \frac{\partial v}{\partial t}\, dt + \frac{\partial v}{\partial x}\, dx \qquad \text{(eq. 24)}$$

$$dy = \frac{y}{t}\, dt + \frac{y}{x}\, dx \qquad \text{(eq. 25)}$$

Using Cramer's Rule,[1] the characteristic directions of the solution, α and β can be solved by,

$$\alpha = \left(\frac{dx}{dt}\right)_{\alpha} = v + c = v + \sqrt{gy} \qquad \text{(eq. 26)}$$

$$\beta = \left(\frac{dx}{dt}\right)_{\beta} = v - c = v - \sqrt{gy} \qquad \text{(eq. 27)}$$

$$\frac{d}{dt}\ (v+2c) = +\bar{\tau}/\gamma y \ \text{along } \alpha \qquad \text{(eq. 28)}$$

$$\frac{d}{dt}\ (v-2c) = -\bar{\tau}/\gamma\, y \ \text{along } \beta \qquad \text{(eq. 29)}$$

Assuming the initial conditions on water velocity and set-up to be zero, $c = \sqrt{gy} = \sqrt{gy_o}$ (Figure 16), the following equations can be used to solve for v and y along α, A to P.

$$\Delta(v+2c) = (\bar{\tau}/\gamma y)\,\Delta t$$

$$(v_p+2C_p) - (v_A+2C_A) = (\bar{\tau}/\gamma y)\ (t_p-t_A) \qquad \text{(eq. 30)}$$

along β, B to P.

$$\Delta(v-2c) = (\bar{\tau}/\gamma y)\,\Delta t$$

$$(v_p-2C_p) - (v_B+2C_B) = (\bar{\tau}/\gamma y)\ (t_p-t_B) \qquad \text{(eq. 31)}$$

Once the points are determined, a stepwise method can be followed to locate the next set of points.

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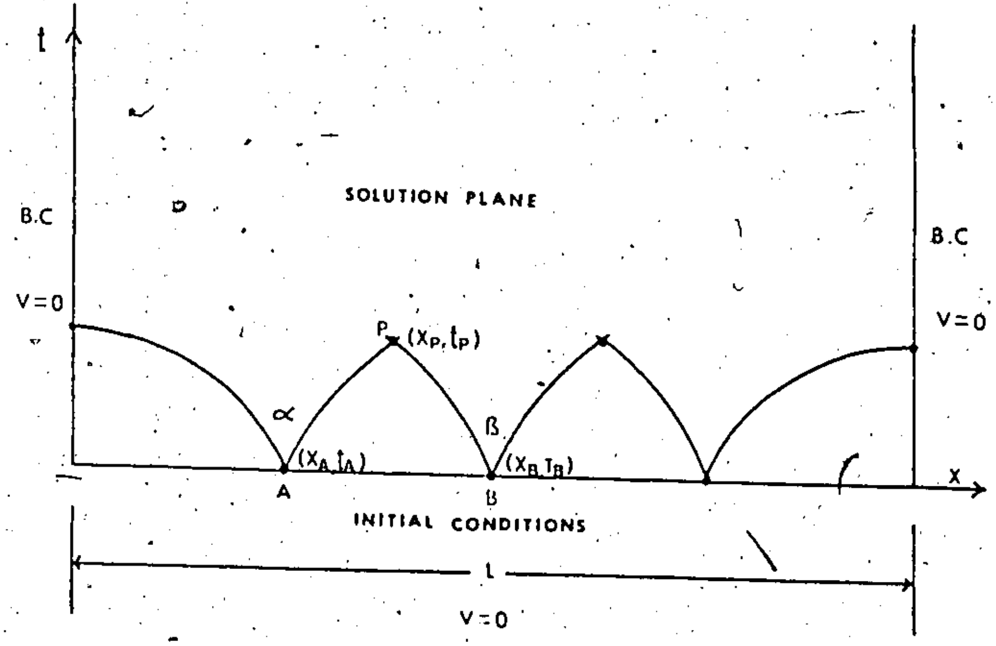
[1] J. A. McCorquodale and M. S. Nasser, Numerical Methods for Unsteady Non-Darcy Flow, Finite Element Methods in Flow Problems, J. T. Oden, et. al., (eds.).

FIG. 16

DEFINITION SKETCH SHOWING INITIAL AND BOUNDARY CONDITIONS



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