IX

DISCUSSION, CONCLUSIONS, AND THOUGHTS FOR MANAGERS

Robert J. Byrne, John D. Boon, III,
Rhonda Waller, and Deborah Blades

A. Discussion

This study presents four lines of evidence which when considered together, provide the basis for inference as to the role of boating activity as a cause of fastland erosion along the tidal shorelines of small coves and creeks. These are:

1.) Direct observation of the fastland and beach changes at five sites in Anne Arundel County over a one-year period.

2.) Estimates of the wind-wave energy throughout the year and that due to boat wakes during the boating season at the five sites.

3.) An inventory of the boating characteristics at five sites reported as having heavy boating traffic.

4.) Field observations at one site of the wave characteristics generated by controlled boat passes at various speeds and distances from the shore.

The purpose of this chapter is to integrate these findings and thereby offer an interpretation of the role boating activity plays in fastland erosion at the tidal shores.

Point 1. Discounting the effects of Tropical Storm David, the direct observation of fastland changes at the five sites (Chapter IV) indicated that only at Site C, in a narrow waterway, was there significant fastland retreat during the boating season. The question naturally arises

as to whether comparable behavior of the fastland at the five sites would have been observed in other one-year periods. To address this we must bear in mind that the total erosion response is a combination of that induced by wind waves plus that induced by boat-wake waves. The magnitude of the wind-wave energy will vary somewhat from year to year as a function of gross weather patterns and storm activity. On the other hand there is no reason to assume that the boating activity during the 1979 boating season was atypical of average conditions over recent years. Thus, between years we expect the total wave energy to be a combination of a constant contribution due to boats and a variable contribution due to wind waves.

More directly, the fastland response is dependent upon the frequency of storm activity which may fluctuate considerably from year to year. Observations for a several-year period which includes this variability in storm activity would be required to estimate the "average" erosion response due to the total wave energy. A hypothetical case will illustrate the point. Suppose at a given site boat-wave energy was responsible for a fastland recession of 0.25 ft. every year but because of variation in storm activity the total yearly recession, over a four year period, was 4 ft., 3 ft., 2 ft. and 1 ft. respectively. The yearly percentage of recession due to boat wakes would then be 6, 8, 12, and 25% respectively. Over the four-year period the total

recession would be 10 ft. with 10% due to boat-wake energy. Thus in any given year there could be appreciable error in estimating the level of erosion attributable to boat wakes.

In spite of the fact that the observations were conducted for only one year, certain inferences can be drawn about the four sites which showed either no erosion, or where the response during the boating season was very slight. Storm activity during the observation year was relatively slight. No major northeast storms with a strong storm surge occurred (the effects of Tropical Storm David which occurred near the end of the period will be discussed separately). This being the case, the contribution of erosion from boat wakes would be amplified relative to a year with high storm frequency.

Thus the results showing negligible impacts due to boats at four of the sites indicates that, in general, boat wakes play a relatively minor role in the total erosion process at those sites. The same conclusion would apply for sites with similar physiography, bank composition, fetch, and boating activity.

The two sites with bluffs, Sites B and D, warrant special discussion. The principal fastland modification which occurred was slumping in winter and early spring and reduction of that material by wave action. The cause of the slumping action was likely percolation of groundwater, and surface runoff during freeze thaw cycles. By late May much of the material in the slumps

had been sujected to wave action and was displaced.

There is no reason to assume that all slumping activity is confined to the winter and spring. Had slumping occurred in early summer then we must assume that the combined wind-wave and boat-wake action would have displaced some of these materials. In such circumstances it would be reasonable to attribute a fraction of the erosion to boat wakes. However, as Table 7.2 indicates, the boat-wake energy appears to be a relatively small percentage of the wind-wave energy (3.6% at Site B and 8.4% at Site D). Such being the case, attribution of erosion to boat wakes would be relatively small.

Point 2. It was previously indicated that only at Site C was there significant fastland retreat during the boating season. Site C, on Broad Creek, is on a narrow channel (600 ft. width) with a relatively steep nearshore gradient. Two of the three profiles showed fastland retreats of 6.8 feet and 5.2 feet (Figure 4.19). Site C received the highest amount of boat-wake energy of the five sites. As well, boat-wake energy accounted for a substantially higher fraction of the total wave energy (Figure 7.7) at Site C than at the other sites.

It is of particular interest to compare Site C and Site B which has a similar nearshore profile, but a wider and shallower channel. The current nautical charts show a MLW depth of 12 feet near Site C and 8 feet near Site B. The two sites received about the same wind-wave energy throughout the year and during the boating season. Site C

was exposed to about 5 times more boat-wake energy than Site B. Inspection of the boating characteristics (Table 6.2) shows that the two sites were very similar with respect to average boating frequency, speeds, boat lengths, and hull types. The striking difference between the boating characteristics at the sites is the distance of passage from shore. At Site B, 80% of the boat passes occurred at distances greater than 500 feet, while at Site C 80% occurred at distances less than 200 feet from the shore. These results illustrate the importance of distance of passage in controlling the level of boat-wake energy at the shore.

The physical setting at Site C, the nature of its fastland, and the low sand supply from adjacent fastland are all conditions conducive to erosion in the presence of wave action. The site is a low terrace composed of unconsolidated sand and gravel capped with a very thin marsh. There is evidence that the site is at least partially composed of fill material. More important however, the site represents a transition point where Broad Creek widens, and very little sand is supplied to Site C from the fastland along the shoreline. Thus the erosion of the beach is not inhibited by the addition of sand.

Point 3. The fastland response at Sites B and D to the passage of Tropical Storm David illustrates the relative importance of extreme events in the erosion process of bluffs along tidal shorelines. At Site D the combined

effects of the storm surge (estimated 2.5 ft.), and wave action generated by the southeast wind, resulted in fastland retreat throughout the year including recession of the bluff face itself. However, at Site B, which is more protected from wave action from the southeast, the steep bank showed no response to the storm passage.

B. Conclusions

This study indicates that a significant contribution to the total wave energy (and potential erosion) from boat wakes is likely only when there is a high frequency of boat passages close to shore. While there may be several circumstances wherein boats pass close to shore, the greatest relative impact is likely to occur in narrow creeks where the channel width forces passage within two or three hundred feet from the shore. Since wind-wave activity is likely to be suppressed in narrow creeks, it is under these circumstances that a high frequency of boat passages would generate a large portion of the total wave energy. But it is not likely that further studies at other sites in Anne Arundel County would show boat wakes contribute more energy for erosion than wind waves.

The level of fastland erosion response depends upon the nearshore depth gradient, the composition of the fastland, and the supply of littoral sands from the adjacent shoreline. The conditions most susceptible to erosion would be the combination of an exposed point of land composed of highly-erodible material such as sand and gravel with a steep nearshore gradient. The site which had the greatest

change in the shoreline profiles (Site C) possessed all these factors. Experiments with controlled boat passes at Site C indicate that for a given water depth the amount of wave energy generated depends principally upon the boat speeds. At low boat speeds the wake energy is quite small. At intermediate speeds (7 to 10 knots) the wave energy was maximum. At higher speeds the wave energy again decreases. The magnitude of the wave energy as a function of distance was of secondary importance for the conditions tested (50 to 200 ft.). The role of this parameter would be more important at larger distances.

The results of the observations at Site C can be generalized in terms of the Froude Number (proportional to the ratio of boat speed to the square root of water depth). Maximum wave energy occurs in the Froude number range of 0.7 to 1.0 with enhanced wave energy in the range of Froude number values of 1.25 to 1.5 (Figures 8.5, 8.6, 8.9, and 8.10). Inspection of various combinations of boat speeds and water depths (Table 8.3) indicates that a boat speed of 6 knots would generate near-maximum wakes when the water depth is less than 6 feet. A boat speed of 8 knots in water depth ranging between 10 and 4 feet would generate maximum or near-maximum wake. Boats travelling at 4 knots, on the other hand, would not generate their highest wakes except when in water depths of 2 feet or less.

For the range of depths frequently found in narrow creeks fringing the shores of Chesapeake Bay, three

particular conclusions may be drawn:

1.) Boats reducing speed to conform to the speed limit pass through the speed range which generates maximum wake.

2.) If the approach to the speed control area is within a narrow creek the shores adjacent to the approach zone will be exposed to the higher wake energies noted in 1.

3.) Boat operators underestimating their speed by only a few knots while in a speed control area could generate a near-maximum wake while transiting the waterway.

C. Thoughts for Managers

Three points which would mitigate the potential erosion impacts due to boats are offered for consideration:

1.) The study shows that depth conditions exist in some creeks wherein maximum boat-wake energies are generated close to the standard 6 knot speed limit. The results can be used to estimate the speeds at which maximum wake is generated for various water depths. In some cases a reduction of the speed limit would decrease the unintentional generation of maximum wake.

2.) Since boats approaching a speed-control zone will pass through the speed which generates maximum wake as they slow from high speed, the speed-limit signs should be placed, when possible, at locations where the creek is so wide that the wake energy can dissipate before reaching the shore.

3.) The study indicates that the greatest potential for erosion impacts due to boat wakes is to be expected

when high frequency boat passages occur within a few hundred feet from the shore. Restrictions in such areas would reduce the potential for shore erosion.

D. Recommended Further Studies

The present study indicates that it is in narrow creeks and other circumstances wherein boats pass close to shore that the highest potential for boat-wake erosion exists. The question then naturally arises, "How close to the shore can boats pass without causing the significant wake energy at the shoreline?" The comparison between two sites, one of which showed dramatic erosion during the boating season and the other very little, provides a partial answer. The two sites had similar boating characteristics with respect to frequency, hull sizes, and speed. The only major difference was the distance from shore at which passage occurred. At the Broad Creek site (Site C), where erosion occurred, about 80% of the traffic occurred within 200 feet or less from the shore. In contrast, at the Goose Island site (Site B) about 75% of the boat passes occurred at distances greater than 500 feet. Consequently, the wave energy at Site B was only about 20% of that experienced at the Site C. Thus it appears that passage distances of at least 500 feet are required to appreciably reduce the level of wake energy at the shoreline.

Further observations of controlled boat passes over a wider range of distance from shore would permit a more

accurate determination of the creek width necessary for negligible wake energy at the shoreline. The controlled boat passes conducted in the present study covered the range of distances from 50 feet to 200 feet at a single site. This range should be extended to at least 500 feet. In addition other sites with constrasting depth gradients should be added to the data set. As well, the range of hull lengths and types, could be extended.

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APPENDIX A

HOUSE JOINT RESOLUTION No. 40

A House Joint Resolution concerning

Anne Arundel County -- Small Creeks and Coves

FOR the purpose of requesting the Department of Natural Resources to design and undertake a study to determine whether continuous high-speed boat traffic is in fact detrimental to small coves and creeks along the Anne Arundel County coastline.

WHEREAS, The Anne Arundel County coastline is highly indented, and the tidal water indentations form shallow, narrow creeks with highly erodible shorelines and fragile biological ecosystems; and

WHEREAS, Continuous high-speed boat traffic may have an injurious effect on the small coves and creeks; now, therefore, be it

RESOLVED BY THE GENERAL ASSEMBLY OF MARYLAND, That starting this year, the Department of Natural Resources is hereby requested to design and undertake a study to determine whether continuous high-speed boat traffic is

in fact detrimental to small coves and creeks; and be it further

RESOLVED, That consideration shall be given to closing at least one cove or creek in South, Severn, and Magothy Rivers at all times to vessels operated at a speed in excess of six (6) knots, for such a period as required to facilitate the scientific study; and be it further

RESOLVED, That the Department of Natural Resources shall submit an interim progress report to each member of the House Environmental Matters Committee and the Senate Economic Affairs Committee annually starting 1977, and the report shall be made available to the public. A final report summarizing the results of the study shall be submitted to the General Assembly not later than the 1981 Session, and shall be made available to the public; and be it further

RESOLVED, That copies of this Resolution be sent to The Hon. James B. Coulter, Secretary, Department of Natural Resources, Tawes State Office Building, Annapolis Maryland 21401.

Approved:

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Governor.

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Speaker of the House of Delegates.

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President of the Senate.

APPENDIX B

WIND-GENERATED WAVES

Deborah Blades, Rhonda Waller,
Thomas Burnett, Michael Perry,
Tristina Deitz, Mark Alderson

A. Introduction

This appendix presents a summary of the wind-generated wave heights which were observed at the study sites. These measured wave heights were used to produce site-specific estimates of the wind-wave energy budget during the year-long period of observations. There have been several previous studies of wave generation by winds in shallow coastal waters, (Johnson, 1948, 1950; Kinsman, 1960; Harris, 1972; Seymour, 1977; and Thompson, 1980), and several mathematical models already exist to predict the charateristics of waves (height and period) if the wind speed, duration, and fetch are known. Two examples of these are shown in Figure B.1.

These models are helpful for forecasting general wave conditions in many areas. But, physical oceanographers and mathematicians continue to discuss which

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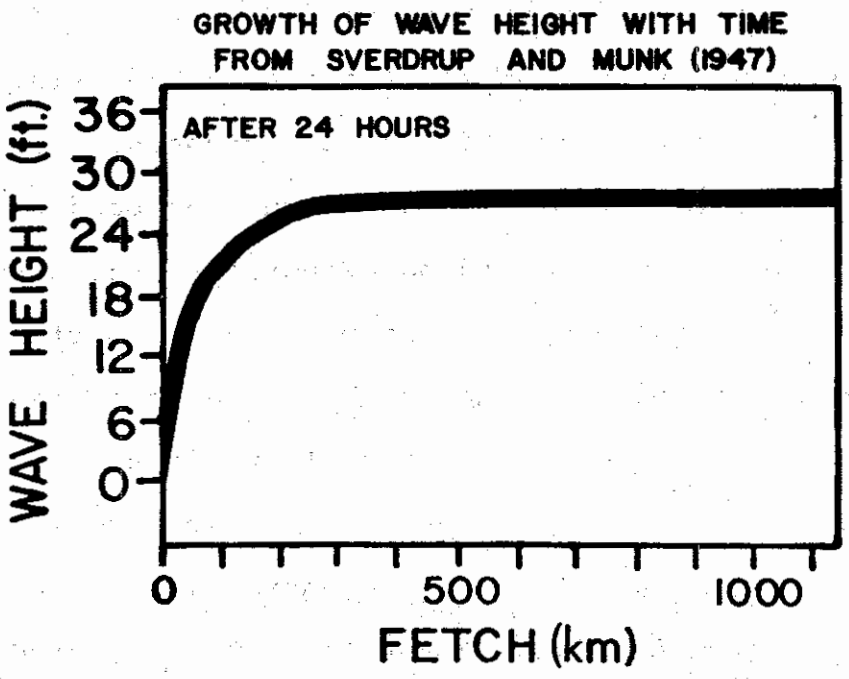
Opposite: Figure B.1 (top) Growth of wave height with time and distance from the upwind edge of a fetch (after Sverdrup and Munk, 1947).

Figure B.1 (bottom) Forecasting curves for shallow water waves in a basin with constant depth equal to 5 feet (from the U.S. Army Corps Shore Protection Manual, 1973).


GROWTH OF WAVE HEIGHT WITH TIME
FROM SVERDRUP AND MUNK (1947)
AFTER 24 HOURS
WAVE HEIGHT (ft.)
36
30
24
18
12
6
0
0
500
1000
FETCH (km)

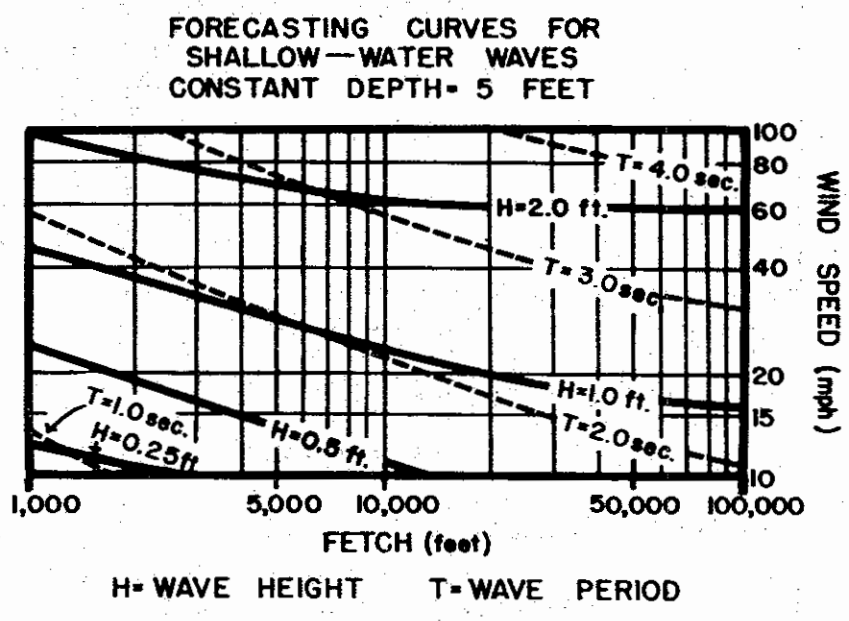

FORECASTING CURVES FOR
SHALLOW—WATER WAVES
CONSTANT DEPTH= 5 FEET
T=4.0 sec.
H=2.0 ft.
T=3.0 sec.
H=1.0 ft.
T=2.0 sec.
T=1.0 sec.
H=0.25 ft.
H=0.5 ft.
100
80
60
40
20
15
10
WIND SPEED (mph)
1,000
5,000
10,000
50,000
100,000
FETCH (feet)
H= WAVE HEIGHT T= WAVE PERIOD

Figure B.1

theoretical approach should be useful to produce the best description of how waves are generated by the wind blowing across the sea surface (Kinsman, 1965; Plate, et al, 1969; Wu, 1972;). As Figure B.1 suggests, none of the existing information is very useful for predicting the wave heights which could be expected at the study sites described in Chapter IV, since none is particularly sensitive to either the range of basin depth or the range of fetch which are present at the study sites.

In this absence of adequate theoretical models, empirical site-specific wind-wave energy models were constructed by making wave observations at the study sites under different wind conditions. Since wind duration is a factor in wave height, three such models were constructed for each site corresponding to short- medium- and long-duration winds. Monthly budgets of wind-wave energy were then developed for each site from these wind-wave measurements.

B. Methods

Throughout the year of study (October 1978-October 1979), measurements of wave characteristics were made at each of the study sites. These observations included:

o Wave Height - an observer visually measured wave heights at the points where the waves broke in

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opposite: Figure B.2 Portions of the continuous meteorological record collected at the United States Naval Academy gauging station in Annapolis.

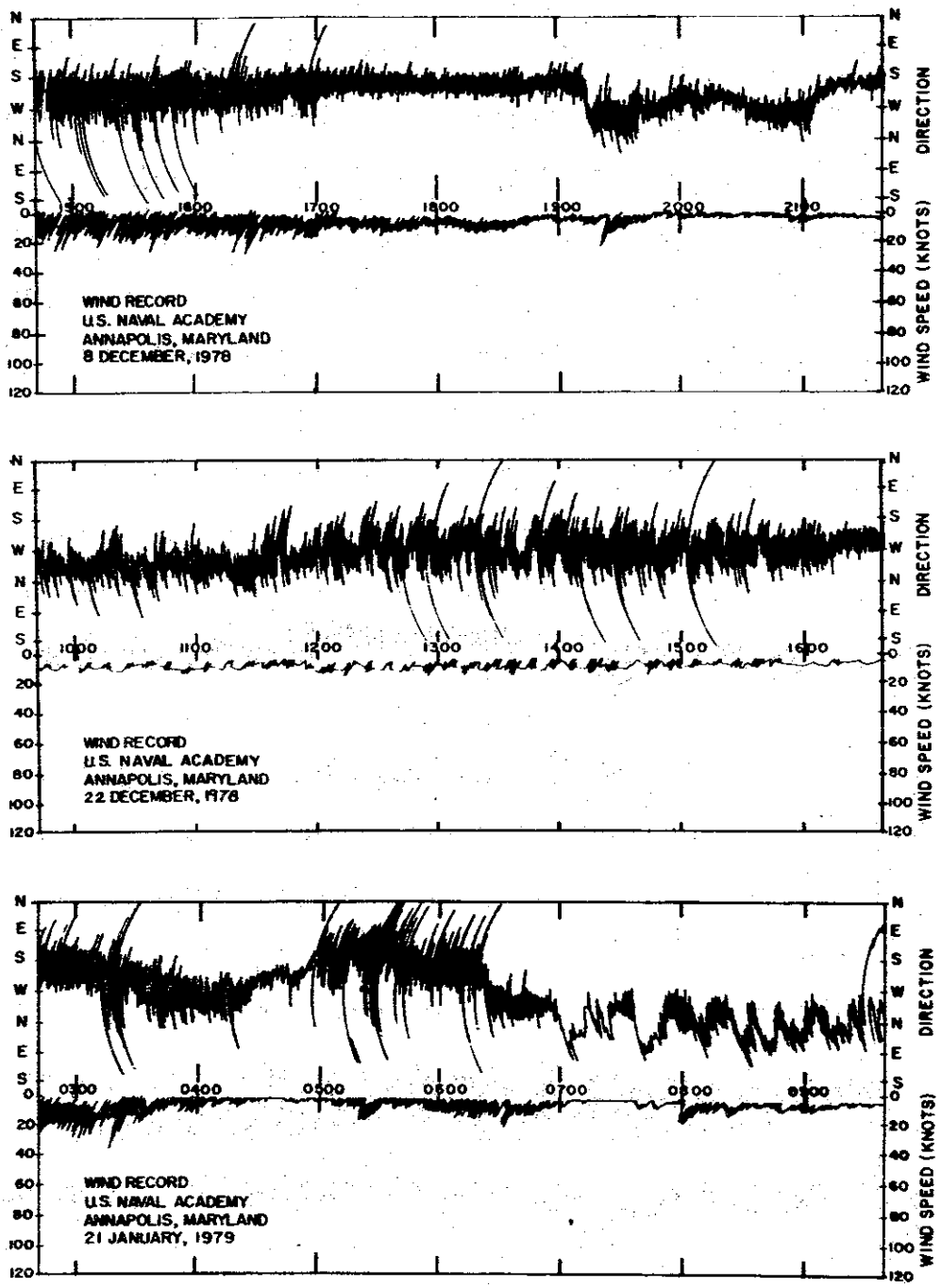
WIND RECORD
U.S. NAVAL ACADEMY
ANNAPOLIS, MARYLAND
8 DECEMBER, 1978
WIND RECORD
U.S. NAVAL ACADEMY
ANNAPOLIS, MARYLAND
22 DECEMBER, 1978
WIND RECORD
U.S. NAVAL ACADEMY
ANNAPOLIS, MARYLAND
21 JANUARY, 1979
DIRECTION
WIND SPEED (KNOTS)

Figure B.2

nearshore or on the beach using a graduated staff. Munk (1944) has found that the average height of waves so estimated by an observer is about equal to the average height of the 1/3 highest waves. This has been defined as significant wave height.

- o Wave Period - An observer timed 11 successive wave crests with a stop watch. This was repeated three times and the average wave period was calculated.
- o Time of Day - measured with a watch.
- o Wind Speed and Direction - an observer placed a Simms hand-held annemometer (model ss) one meter above the water surface and noted the approximate duration of gusts as well as the dominant wind speed. Wind direction was measured by a compass.

The local wind record that was selected for use was taken from the meteorological station at the U.S. Naval Academy at Annapolis (Figure B.2) which is located within 3 miles, 5.5 miles, 4.6 miles, 1.7 miles, and 6.8 miles of study sites A-E respectively. When the wind velocity at the Naval Academy Gauging Station was compared to the wind velocity at each of the study sites (Table B.1), there were minor differences which are attributable to terrain effects, station separation, and measurement correlation between the

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opposite: Table B.1 Comparison of winds at the Naval Academy Gauging Station and at the field sites described in Chapter IV.

Table B.1

SOME COMPARISONS OF WIND MEASUREMENTS

Date	Site	On-Site Wind Description At 1 Meter Above The Water Surface	Naval Academy Gauging Station Hourly Average Wind Speed
March 5, 1980	D	4-5 m/sec gusts to 9 m/sec	6 knots (3 m/sec)
March 5, 1980	A	2-6 m/sec gusts to 9 m/sec	6 knots (3 m/sec)
March 5, 1980	E	5-7 m/sec	8 knots (4 m/sec)
March 5, 1980	D	5-7 m/sec gusts to 10 m/sec	9 knots (4.5 m/sec)
March 10 1980	D	3-5 m/sec gusts 7-10 m/sec	7 knots (3.5 m/sec)
March 10, 1980	A	3-5 m/sec gusts 5-7 m/sec	7 knots (3.5 m/sec)
March 11, 1980	E	1-2 m/sec gusts to 7 m/sec	10 knots (5 m/sec)
March 11, 1980	D	10 m/sec gusts to 13 m/sec	10 knots (5 m/sec)
March 11, 1980	D	10 m/sec gusts to 14 m/sec	8 knots (4 m/sec)
March 11, 1980	E	0 gusts to 4 m/sec	8 knots (4 m/sec)
March 11, 1980	B	4-5 m/sec gusts to 7 m/sec	11 knots (5.5 m/sec)
March 11, 1980	C	4-6 m/sec gusts to 12 m/sec	11 knots (5.5 m/sec)
March 18, 1980	D	7 m/sec gusts to 14 m/sec	12 knots (6 m/sec)
March 18, 1980	E	0-2 m/sec gusts to 5 m/sec	12 knots (6 m/sec)
March 18, 1980	B	3-5 m/sec gusts to 11 m/sec	12 knots (6 m/sec)
March 18, 1980	C	6-7 m/sec gusts to 14 m/sec	12 knots (6 m/sec)
March 18, 1980	A	4-6 m/sec gusts to 10 m/sec	12 knots (6 m/sec)
March 18, 1980	D	7-10 m/sec gusts to 13 m/sec	12 knots (6 m/sec)
March 18, 1980	A	2-4 m/sec gusts to 6 m/sec	12 knots (6 m/sec)

wave height at a particular site and the average hourly wind velocity at the Naval Academy.

The hourly averages of wind speed and direction were visually determined from continuously recording strip charts (Figure B.2). These were compiled to produce the monthly wind roses shown in Figure B.3. This diagram also contains monthly wind roses documenting wind patterns at the Annapolis Naval Academy over a previous 15 year period. The comparison of the two sets of wind roses contains no evidence to suggest the winds in the study year were substantially different from normal, considering that the present study uses hourly averages, and that the 15 year record used two daily instantaneous measurements (probably infrequently collected at night).

The wind rose data for the year of observation shown in Figure B.3 is presented in another form in Figure B.4. This figure indicates the distribution of winds which were used to construct the models of wind-wave energy.

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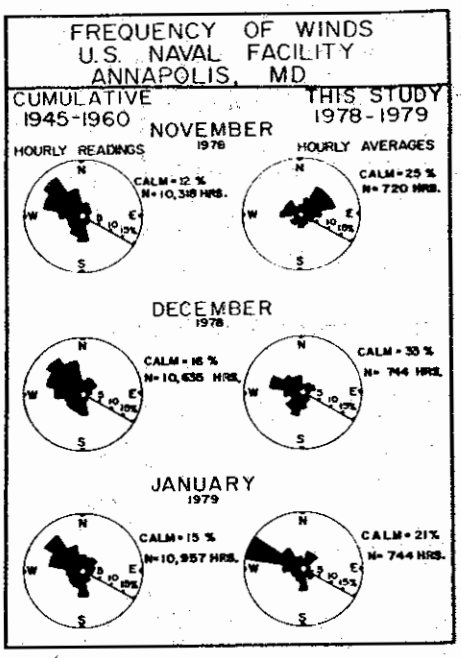
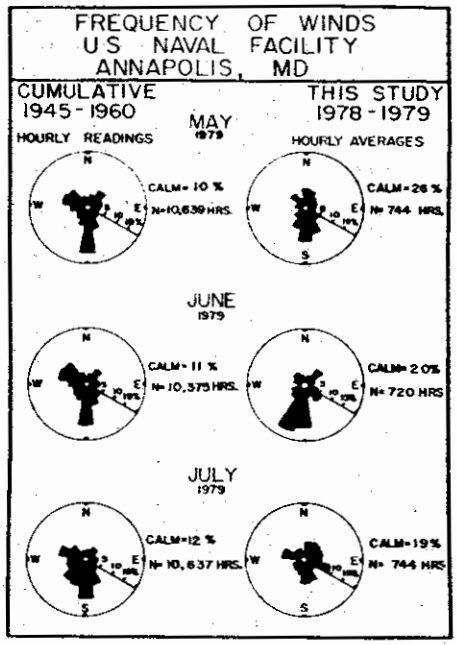
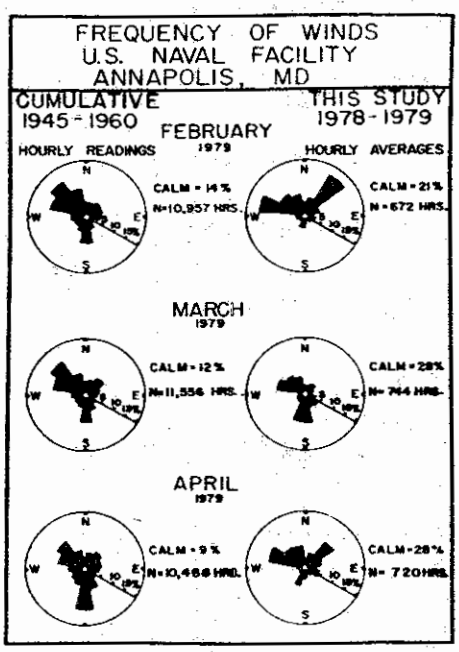
opposite: Figure B.3 Two sets of monthly wind data collected at Annapolis (obtained from the U.S. Dept. of Commerce, National Climatic Center, Asheville, N.C.).

next pages: Figure B.4 (left) Wind distribution at Annapolis, Md from November 1978 through October, 1979.

Figure B.5 (right) Plots of wave measurements at each of the study sites, presented according to the wind speed and direction measured at the Naval Academy gauging station.


FREQUENCY OF WINDS
U.S. NAVAL FACILITY
ANNAPOLIS, MD
CUMULATIVE 1945-1960
THIS STUDY 1978-1979
NOVEMBER 1978
HOURLY READINGS
CALM = 12 %
N = 10,318 HRS.
HOURLY AVERAGES
CALM = 25 %
N = 720 HRS.
DECEMBER 1978
CALM = 16 %
N = 10,636 HRS.
CALM = 33 %
N = 744 HRS.
JANUARY 1979
CALM = 15 %
N = 10,957 HRS.
CALM = 21%
N = 744 HRS.


FREQUENCY OF WINDS
U S NAVAL FACILITY
ANNAPOLIS, MD
CUMULATIVE 1945-1960
THIS STUDY 1978-1979
MAY 1979
HOURLY READINGS
CALM = 10 %
N = 10,639 HRS.
HOURLY AVERAGES
CALM = 26 %
N = 744 HRS.
JUNE 1979
CALM = 11 %
N = 10,375 HRS.
CALM = 20%
N = 720 HRS
JULY 1979
CALM = 12 %
N = 10,637 HRS.
CALM = 19%
N = 744 HRS


FREQUENCY OF WINDS
U.S. NAVAL FACILITY
ANNAPOLIS, MD
CUMULATIVE 1945-1960
THIS STUDY 1978-1979
FEBRUARY 1979
HOURLY READINGS
CALM = 14 %
N = 10,957 HRS.
HOURLY AVERAGES
CALM = 21%
N = 672 HRS.
MARCH 1979
CALM = 12 %
N = 11,556 HRS.
CALM = 28%
N = 744 HRS.
APRIL 1979
CALM = 9 %
N = 10,466 HRS.
CALM = 28%
N = 720 HRS.

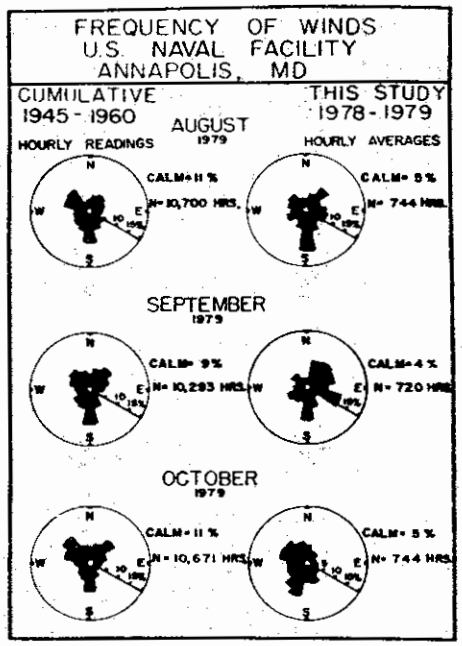

FREQUENCY OF WINDS
U.S. NAVAL FACILITY
ANNAPOLIS, MD
CUMULATIVE 1945-1960
THIS STUDY 1978-1979
AUGUST 1979
HOURLY READINGS
CALM = 11 %
N = 10,700 HRS.
HOURLY AVERAGES
CALM = 9 %
N = 744 HRS.
SEPTEMBER 1979
CALM = 9%
N = 10,293 HRS.
CALM = 4 %
N = 720 HRS
OCTOBER 1979
CALM = 11 %
N = 10,671 HRS.
CALM = 5 %
N = 744 HRS.

Figure B.3

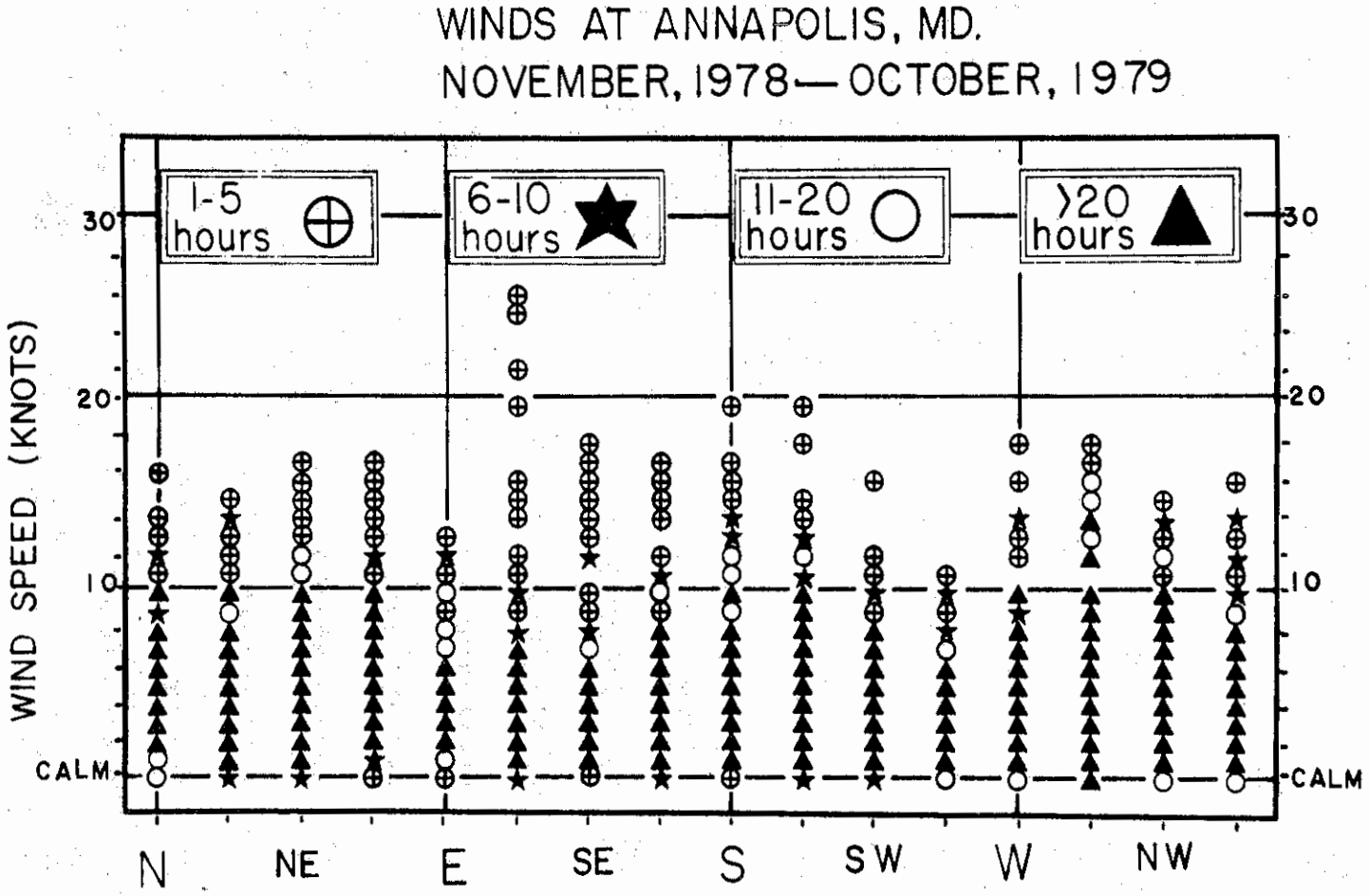

WINDS AT ANNAPOLIS, MD.
NOVEMBER, 1978—OCTOBER, 1979
1-5 hours
6-10 hours
11-20 hours
>20 hours
WIND SPEED (KNOTS)
30
20
10
CALM
N
NE
E
SE
S
SW
W
NW

Figure B.4

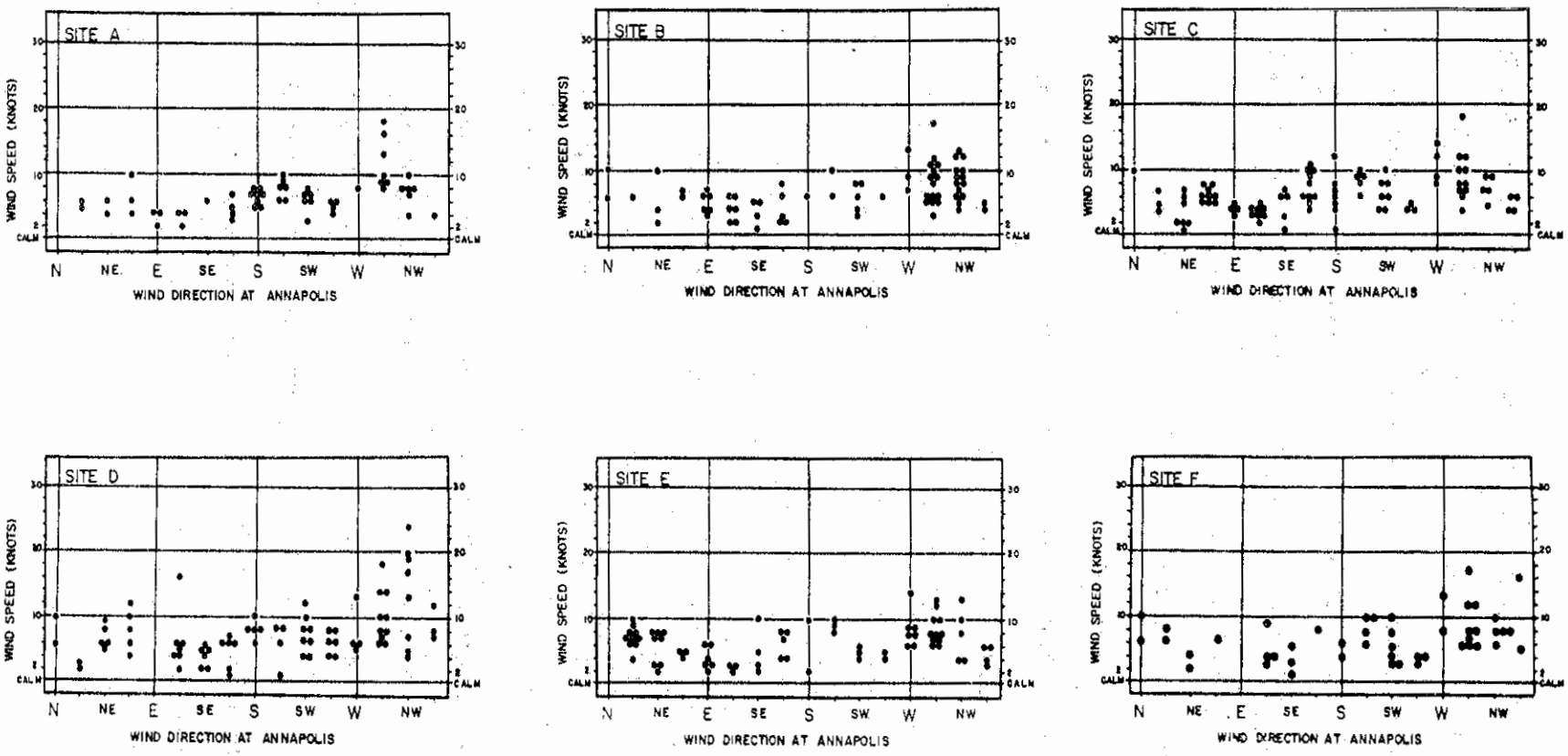

SITE A
SITE B
SITE C
SITE D
SITE E
SITE F
WIND SPEED (KNOTS)
CALM
N NE E SE S SW W NW
WIND DIRECTION AT ANNAPOLIS

Figure B.5

Figure B.5 indicates the range of wind speeds for which on-site measurement of wave heights were collected. This figure shows that few observations were made at the higher wind speeds. As a result, the contours of wave heights at the higher wind speeds in Figure B.6 a-f are shown by dotted lines. These diagrams show the ranges of measured significant wave heights plotted according to the wind conditions recorded at the Annapolis Naval Academy meteorological station. The diagrams also show the fetches at each study site in shaded areas. The site-specific models of wave height are particularly reliable within the range of the most frequent hourly average speeds (0-10 knots).

Three models were prepared for each site for three different velocity durations. The 0-1 hour models were compiled from wave observations collected at times when there was a change in wind velocity greater than 2 knots at the Annapolis Naval Academy gauging station within the hour. The 1-2 hour models were compiled from wave observations collected at times when no change in wind velocity greater than 2 knots occured within the previous two hours. The >2 hour models were compiled from wave observations collected at times when no change in wind velocity greater than 2 knots occurred for more than 2 hours.

C Results

i. Site-specific Models

The largest significant wave heights at each site generally coincide with winds blowing from the directions of greatest fetch. However, at Site B (near Goose Island), the local topography and wave refraction (bending of the wave fronts around irregularities in the shoreline) seem to have influenced the waves so that the largest wave heights were measured when the wind at Annapolis was blowing from a direction with very little fetch at the study site. Site FF located near Site B shows similar behavior in the wind-wave distribution.

Only ripples (wave heights less than 2 cm.) were measured at each study site when the winds at Annapolis were blowing from directions with no fetch. But the diagrams in Figure B.6 a-f show that some wave activity is inferred to be present at the study sites under strong winds greater than 15 knots from these directions of no fetch. It is important to note that Figure B.4 shows there were very few hours of wind speeds higher than 10-15 knots during the year of observations, and many of these hours of higher wind speed were at times when the shoreline sites were covered

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next pages: Figures B.6 a-f Site-specific models of wind-generated waves at each of the five study sites described in Chapter IV. The shaded areas show the distribution of fetch. The wave measurements are plotted according to the wind speed and direction measured at the Annapolis Naval Academy.

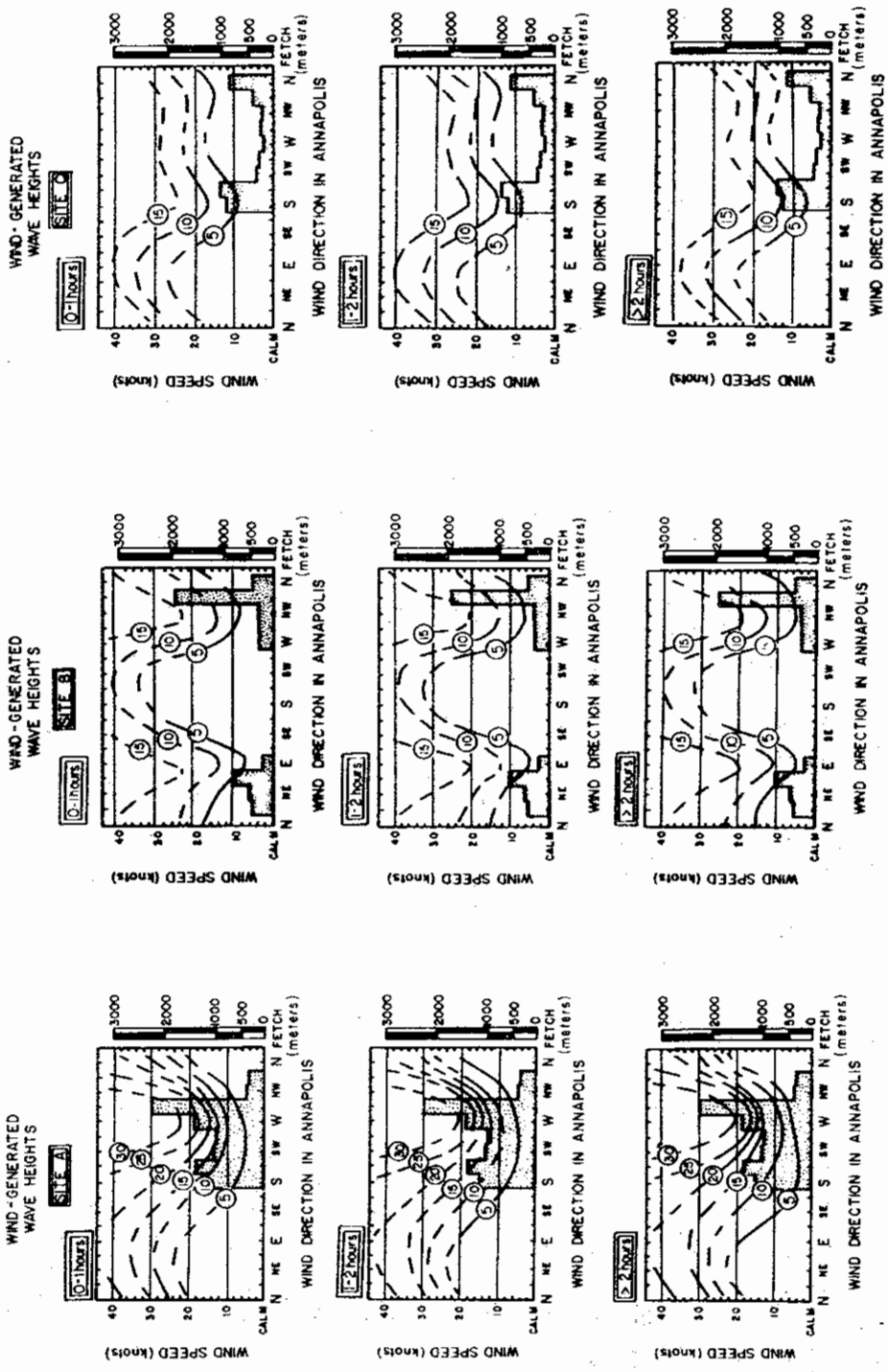
WIND-GENERATED WAVE HEIGHTS
SITE A
SITE B
SITE C
0-1 hours
1-2 hours
>2 hours
WIND SPEED (knots)
WIND DIRECTION IN ANNAPOLIS
FETCH (meters)
CALM
N NE E SE S SW W NW N
0
500
1000
2000
3000
10
15
20
25
30
40

Figure B.6

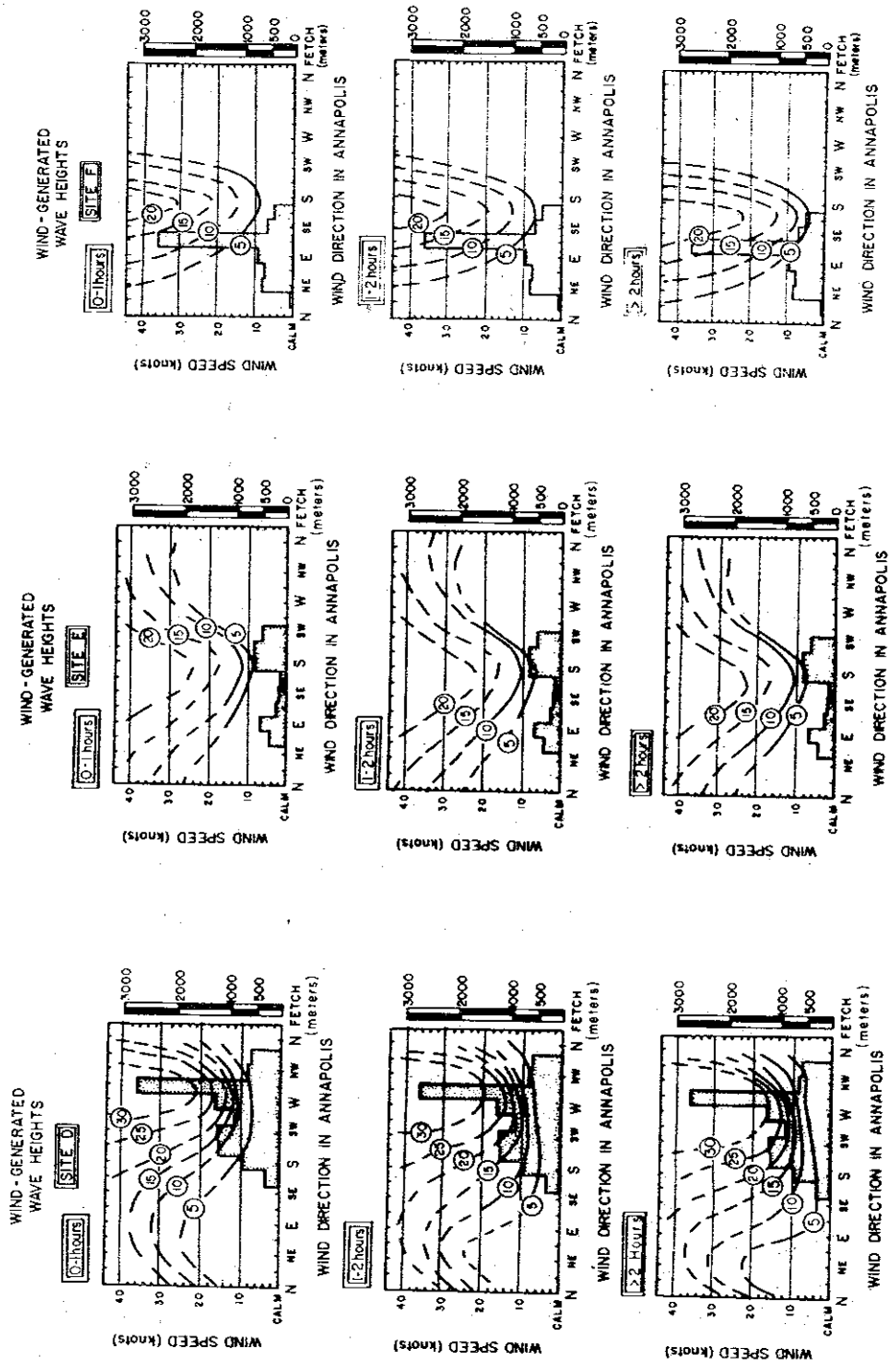
WIND-GENERATED WAVE HEIGHTS
SITE F
SITE E
SITE D
0-1 hours
1-2 hours
≥ 2 hours
WIND SPEED (knots)
WIND DIRECTION IN ANNAPOLIS
FETCH (meters)

Figure B.6

with ice. So, the inferred distribution of wave heights at these large wind speeds does not have any important effect on the computation of the wind-wave energy budget for this study.

ii. Computation of Wave-Energy Budget

In order to be able to transform wave height into wave energy, the following experiment was conducted. Both the electrical resistance continuous wave height recorder and a graduated staff were used simultaneously to measure wave heights over a range of wave conditions. From the wave recorder strip chart, the RMS wave height was determined for each parcel of waves measured. This in turn was converted into a measure of energy by the equation:

$$E_w = \frac{1}{8} \rho g N H^2_{rms} \qquad \text{B.1}$$

where:

E_w = average energy per unit surface area (ft-lbs/ft);

H_{rms} = Root mean square wave height;

$= (\Sigma H_i^2/N)^{1/2}$, $i = 1,2,\ldots,N$;

ρg = Specific gravity of water

$= 62.5 \quad lbs/ft^3$

Figure B.7 shows the relationship between observed breaking wave height as measured by the graduated staff, and total energy in the corresponding individual wave packets as measured by the wave recorder. The dotted line in Figure B.7 is the least square polonomial regression line which models the relationship between these two quantities. The equation for this model is:

$$E_w = -2.877 + 3.867\ h - .068\ h^2 \qquad B.2$$

where: E_w = wave energy (ft-lbs/ft/min)

h = observed wave height in centimeters

The presence of a negative leading term on the right hand side of this equation suggests there is negative wave energy at zero wave height. This spurious result shows the model is approximate, and is a consequence of sampling error and measurement error. In practice, this is of no consequence as all wave heights leading to negative energies were assigned zero energy.

On the basis of the above formula, wave heights at 1 cm. intervals were transformed to wave energies and summed within months. In this manner, monthly wind-wave energy budgets for each of the sites were developed, and are shown in Tables 7.2, 7.3, and Figure 7.7.

iii. Precision of Wave-Energy Estimates

One important question about the wave energy budget is: What is the precision with which the monthly total wind-wave energy is estimated by the above method? The following discussion presents a rough estimate of this precision.

Total Energy "E_h" is the sum over the hours in the month "M" of the energy-per-hour resulting from waves of a given height "h" which were generated by a wind of velocity "V" at Site "S". This can be symbolically represented by:

$$\text{Total Energy}_{M,S} = \sum_{\substack{\text{hours in} \\ \text{month}}} \text{Energy } (h(V,S))$$

The relationship h(V,S) is given by the models displayed in Figure B.6 a-f. A relationship between wave energy and wave height is given by the graph in Figure B.7 The variability associated with each hour of estimated wave energy is an accumulation of:

- o the errors in estimating the average hourly wind velocity;
- o the variability in observed wave height for a given wind velocity;
- o the variability in energy per hour as a function of observed wave height.

In the analysis of the study data, the average hourly wind speed on the strip charts was estimated to within $\pm$ 1 knot, and the average wind direction was estimated to within $\pm$ 22.5°. These magnitudes of error in measuring wind speed and direction typically translate into a wave height error of $\pm$ 1 cm. on the wave height models of Figure B.6 a-f. The data from which these wave height models were developed also had typical variabilities which were estimated as follows:

- $\pm$ 1 cm. for wave heights measured at wind velocity <5 knots
- $\pm$ 2 cm. for wave heights measured at winds between 5 knots and 10 knots
- $\pm$ 4 cm. for wave heights measured at winds greater than 10 knots

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opposite: Figure B.7 Observed breaking wave heights plotted against the energy in the waves.

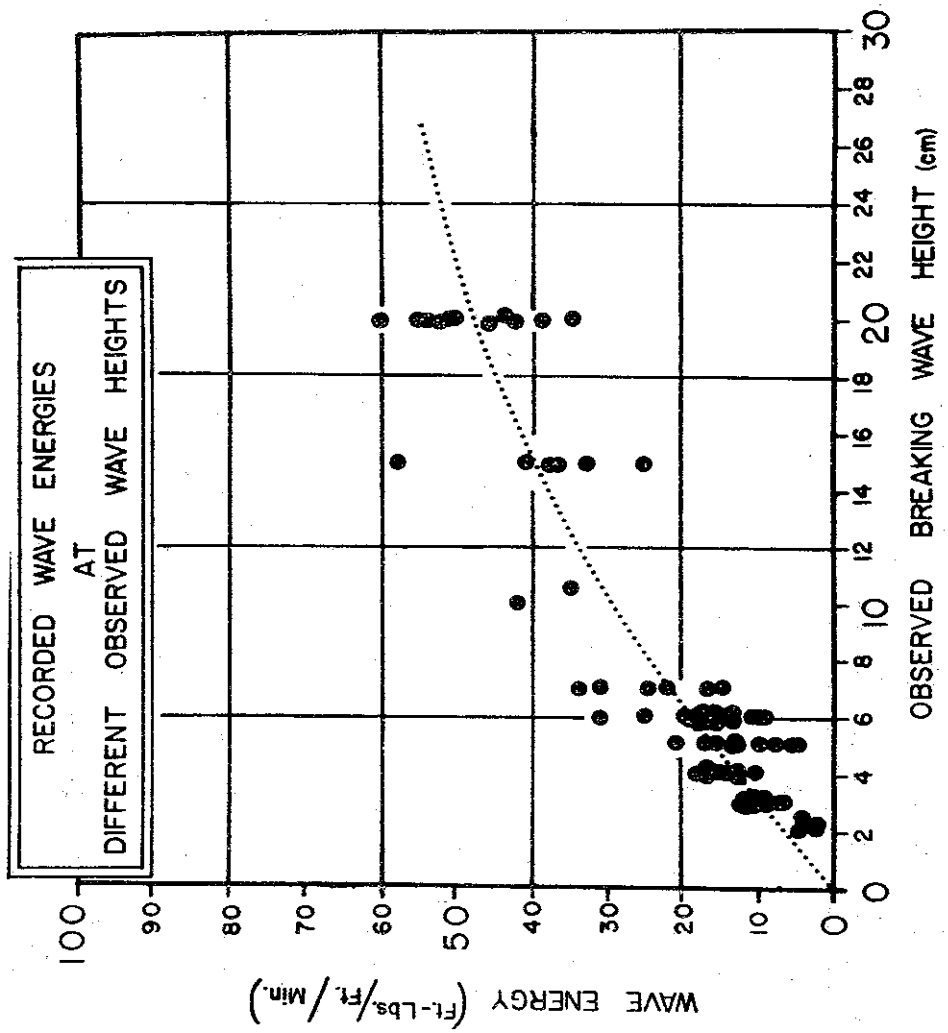
RECORDED WAVE ENERGIES
AT
DIFFERENT OBSERVED WAVE HEIGHTS
WAVE ENERGY (Ft.-Lbs./Ft./Min.)
OBSERVED BREAKING WAVE HEIGHT (cm)
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30

Figure B.7

The errors in measuring wave heights and in correlating wave height to wind speed and direction together result in an error in wave height of $\pm$ 2 cm. associated with waves of 5 cm.; an error in wave height of $\pm$ 3 cm. associated with 5-10 cm. waves, and an error in wave height of $\pm$ 5 cm. associated with >10 cm. waves. This variability in wave height translates into a variability in wave energy which is shown in Figure B.7. For example, waves of 5 $\pm$2 cm. have an estimated energy within $\pm$6 ft-lb/ft/min; and waves of 8 $\pm$3 cm. have an estimated energy within $\pm$8 ft-lb/ft/min. For a single value of $\pm$8 ft-lb/ft/min. (equivalent to $\pm$480 ft-lb/ft/hr), there is a standard deviation of 240 ft-lb/ft/hour, assuming $\pm$ 480 represents $\pm$ 2σ . Summing this variability over 720 independent hourly energy estimates for the month gives a total variance of: $720\ (240)^2$ = 41,472,000 ft-lb/ft/month^2 or a standard deviation of 6440 ft-lb/ft/month.

Since total wave energy for any month is typically on the order of 400 000 ft-lb/ft/month (Table 7.3), the error $\pm 2\sigma$ in the calculation of total energy "Eh" by the method described in this chapter yields a precision of 2(6440/400,000). This is equivalent to an error of $\pm$ 3.2%.

This estimate is rough, but it is very unlikely to be off by any factor greater than 2. Even in such a case, the precision of monthly wave-energy estimates are judged to be quite good.

APPENDIX C

SHALLOW WATER WAVE GAUGE

A shallow water wave gauge was constructed by CEA based on a design by McGoldrick (1969). The sensing element of the device is a capacitance probe featuring a loop of Teflon-coated wire (No. 20) mounted on a supporting rod. The Teflon insulation forms the dielectric and the central conductor and conducting fluid surrounding the wire form electrical plates. If the insulation is uniform and end effects are negligible, then the capacitance varies linearly with the proportion of the wire length immersed in the conducting fluid (sea water). A transistorized detector (Figure C.1) converts changes in capacitance into a variable D.C. voltage which is routed to a strip chart recorder (linear model 142). Teflon must be used as the insulating material because of its high resistance to "wetting" by films of water that would otherwise delay the response of the gauge in sensing the rapid fall in water level following the passage of a wave.

The CEA wave gauge is designed primarily for shallow-water applications in small estuaries and creeks. The sensing unit containing the detector and wire loop is a

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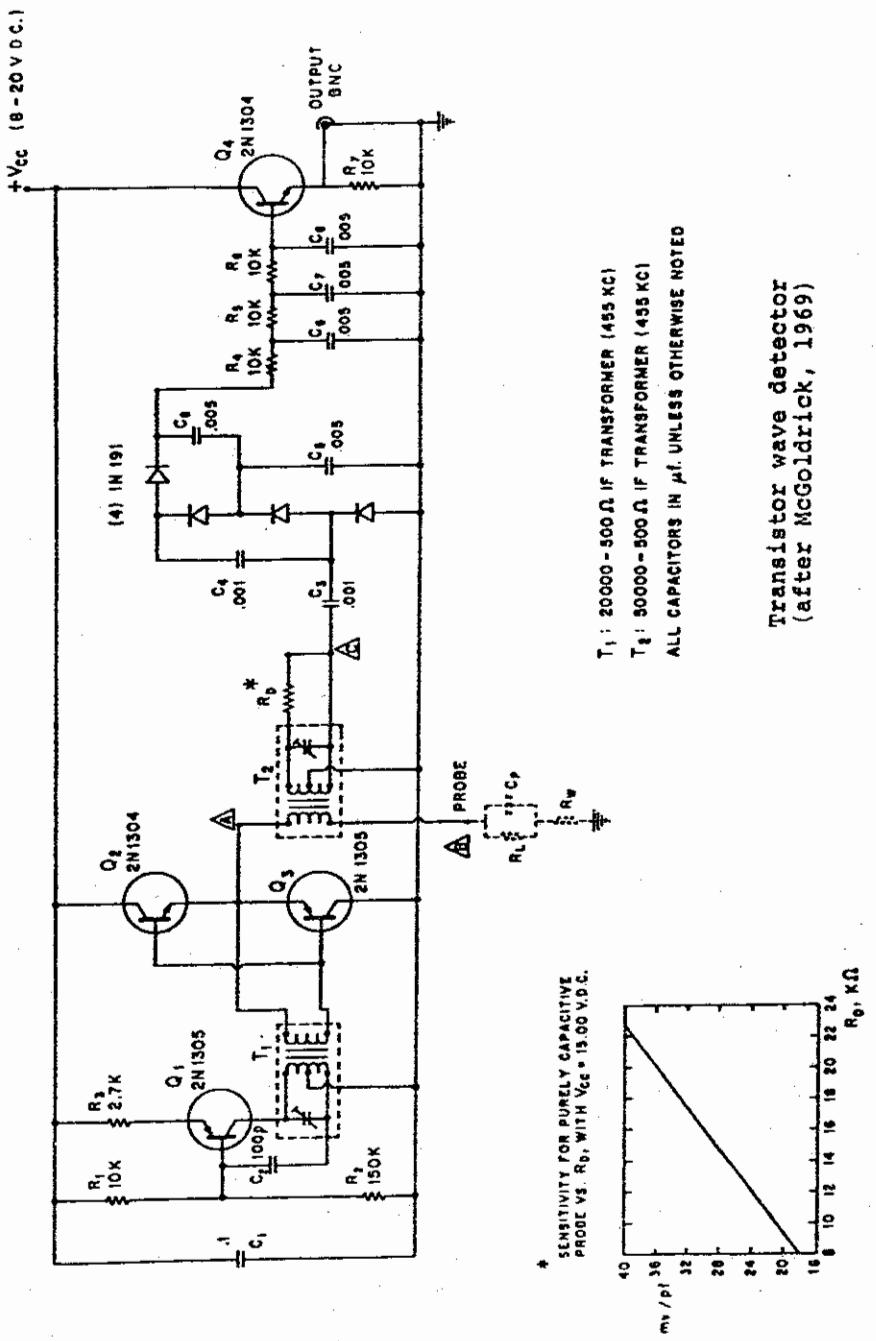
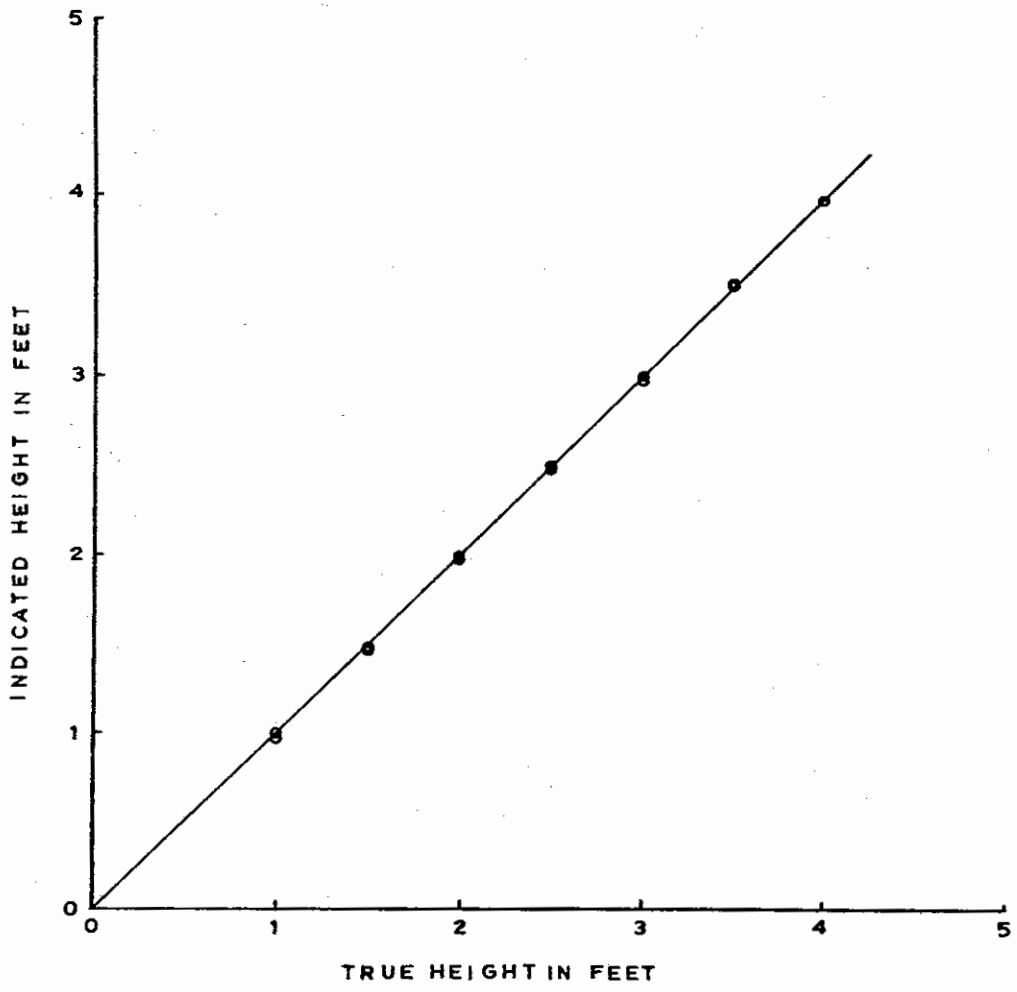
Next pages: Figure C.1. (left) Transistor Wave Detector (after McGoldrick, 1969).

Figure C.2 (right) Wave gauge calibration data.



Transistor wave detector
(after McGoldrick, 1969)

Figure C.1



WAVE GAUGE CALIBRATION DATA

Figure C.2

1-inch diameter PVC rod installed by thrusting its sharpened end into the bottom. A circular footplate mounted 18 inches above the bottom of the rod aids in the installation and provides added stability to the probe in maintaining a vertical position. A 100-foot conductor cable attached just above the foot plate carries the D.C. voltage output of the detector back to the recording unit on shore. The sensing unit can be installed in depths varying between 1 and 3 feet and will sense changes in water level over a vertical range of 4 feet. Markings on the rod at half-foot intervals are provided to allow field calibration checks to be obtained as necessary. Calibration checks should be performed in calm water by holding the probe at 2 or more depths for several seconds and noting the indicated depth intervals on the recorder. Calibration adjustments are made by adjusting the signal attenuation control until the intervals agree.

The detector circuitry is housed in a water-resistant casing at the top of the probe. The unit is activated by means of a switch exposed when the housing cap is removed. Power is supplied by a 9-volt transistor battery located inside the casing. This battery should be replaced after each 50 hours of use. The circuit diagram of the detector unit is presented in Figure C.1.

Laboratory tank calibration tests show excellent linearity in gauge response over the full 4-foot depth range (Figure C.2).