LAKE MICHIGAN STUDIES

Special Report Number LM 12

CURRENTS IN THE SOUTHERN BASIN

June 1963

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Division of Water Supply and Pollution Control
Great Lakes-Illinois River Basins Project

TABLE OF CONTENTS

	Page
INTRODUCTION	1
RESULTS	2
Daily Current Graphs	2
Rotary Currents	3
Prevalence of Movement	3
Synoptic Maps	4
ANALYSIS OF RESULTS	6
Daily Movements	6
Rotary Currents	7
Diffusion or Dispersal	8
Long Term Movements	8
SUMMARY OF ALL PHYSICAL STUDIES	9

TABLES

1. Period of the Inertia Circle
2. Percent of Speed for Station 17

FIGURES

1. Current Meter Stations
2. Two-Hour Envelopes of Speed and Direction, Station 17, Depth 30 Ft.
3. " " " " " 18, " 30 "
4. " " " " " 20, " 50 "
5. " " " " " 20, " 100 "
6. " " " " " 20, " 300 "
7. Central Vector Diagrams
8. Progressive Vector Diagram
9. Prevailing Speed and Direction, Station 17, Depth 30 Ft.
10. " " " " 18, " 30 "
11. " " " " 18, " 100 "
12. " " " " 20, " 50 "
13. " " " " 20, " 100 "
14. " " " " 20, " 300 "
15. " " " " 4, " 60 "
16. " " " " 4, " 90 "
17. Current Pattern and Related Wind Flow
18. Current Pattern and Related Wind Flow

INTRODUCTION

This is the twelfth and last of a series of special reports prepared by the Great Lakes-Illinois River Basins Project relating to the probable effects of returning treated metropolitan wastes from Chicago to Lake Michigan. This report presents additional data pertaining to the movement of waters in the southern basin of Lake Michigan, and relates the new data to the earlier findings.

Data from three additional current meter stations, with records from six current meters, have been evaluated, and compared with information from the three meters discussed in Special Report LM 11. Approximately 38,600 half-hour measurements were recorded between December and April 1963 from the nine meters. In addition, about 15,000 readings made with meters set to record continuously have been processed.

The new data are from Stations 17, 18, and 20 located on a line east of Milwaukee as shown on Figure 1.

A study of the available data has failed to reveal any evidence of a well defined current pattern in the southern basin. It is the purpose of this report, then, to draw such conclusions as can be properly made concerning the movement and presence or absence of advective mixing of waters of the southern basin.

RESULTS

Daily Current Graphs

Figures 2, 3, 4, and 5 show the envelopes of maximum and minimum speeds and directions for each two-hour period during selected six-day periods. One period, February 24 to March 2, 1963 was selected for five meter locations to portray the water movement across the sill area between the southern and northern basins under an ice cover.

Figure 2, Station 17, shows a steady southward flow for nearly 36 hours before the currents shifted to the north for 36 hours. Current velocities were between 0.1 and 0.2 feet per second (fps). During the next two days, the direction changed more or less continuously, exhibiting rotary currents with velocities ranging as high as 0.66 fps. On the last day, the current again moved southward. This station was about 3 miles from shore.

Station 18 is nearly 22 miles from shore and east of Station 17. Figure 3 shows currents at this station, at the 30-ft. depth. During the period shown, rotary currents persisted for six consecutive days. Velocities ranged from nil to more than 0.2 fps. It is interesting to note that the speed varies from near zero to a peak and back again to zero during each complete revolution. The average period of rotation is about 18.1 hours, which is approximately the inertial period, as described in Special Report No. LM 11.

Station 20 did not exhibit rotary currents (Figure 4), although the speed shows a cyclic tendency. Peak speeds up to 1.45 fps occurred. The current generally was from a westerly direction over the six-day period.

Figure 5, Station 20 at the 100-ft. level, shows that the rotary type current can occur at greater depths, although very imperfect as compared to Figure 3. In general, the current was from the west, shifting to the north and remaining from the north over most of the period. Peak velocities reached 1.0 fps.

Figure 6, Station 20 at the 300-ft. level, shows one peak velocity of 1.5 fps but speeds were between 0.1 and 0.2 fps most of the time. In general, the currents were from the northeast to northwest sectors. The tendency toward rotary currents is shown during the last 24 hours, but the prevailing movement was definitely from the north.

Rotary Currents

Figures 7 and 8 show several classic examples of rotary currents in Lake Michigan. Although these currents may occur during all periods of the year, they are to be expected principally during calm periods when external forces are at a minimum. Figure 7, a set of central vector diagrams, shows five of the complete circles as measured between 4:30 P.M. on February 25 and 11:00 A.M. on March 1, 1963. Figure 3 shows the same data in a different form. Table 1 shows that the average period of five rotary current cycles is 18.1 hours. The theoretical period for an inertial rotation at this latitude is 17.6 hours. Figure 8 shows progressive vector summation diagrams for the same period (February 25 to March 2). The total theoretical displacement was about 6,600 feet in 106 hours.

Prevalence of Movement

On Figure 9, data from Station 17 show a bimodal shallow-water flow near the western shore of the lake. The distribution of prevailing direction is 60 percent from the north and 40 percent from the south. East-west components are small, due to the location of the station near the shore.

Figure 10, Station 18 at the 30-ft. level, shows little dominance in direction. About 65% of the time the direction is from the south. Figure 11, data from the same station at 100-ft. depth, shows a pronounced prevalence of direction from the south, with less than 10% from the north.

Figures 12, 13, and 14 depict data from Station 20 at the 30, 100, and 300-foot levels, respectively. Surprisingly, they show a progressive left hand shift in direction from the upper levels toward the bottom.

In order to place all the data in the same perspective, Figures 13 and 14 of Special Report LM No. 9 were redrawn, and are presented herein as Figures 15 and 16. They show a prevailing movement from the northwest during the May to July 1962 period, at Station 4.

To show relationship between speed and direction, not apparent in Figures 9 through 16, the data from Station 17 have been summarized in Table 2. The data in this table show the relationship of speed to direction in a 20 degree sector, one from the north quadrant and one from the south quadrant, as well

as the total observations recorded. The average speed for all observations was 0.25 feet per second and the dominant direction, 340°-360°, has an average speed of 0.24 fps. The secondary sector, 160°-180°, has an average speed twenty percent greater than the speed in the prevailing northerly direction. However, the total flow from the south is still half that from the north. The speed ranges for the individual sectors agreed well with the percentage shown for the total observations and the mean speed. The percentages within a specific speed range exhibited the same type of curve for the data. It is believed that these relationships would hold for all stations, i.e., that the prevailing directions shown on the diagrams are generally indicative of the predominant movements of water.

Synoptic Maps

During the time period when data were simultaneously available from all five current meter stations, several synoptic plots of the two-hour current velocity envelopes were prepared. These plots were made twice daily for upper (50 feet) and lower (100 feet) levels for the times beginning at 0000-0200 hours (CST) and 1200-1400 hours (CST). Figure 17 shows a synoptic map for March 21, 1963. Stations 4, 17, and 18 had data at the 30-ft. level and at Stations 3 and 20 the data shown are for the 50-ft. level. Although some change of direction of flow is likely to occur between the 30-ft. and 50-ft. levels, records from stations where both levels were recorded indicate that this change would not normally be greater than twenty degrees.

The plotted vector is the two-hour average of speed and direction. Figures 17 and 18 are examples of current patterns believed to be resulting from specific wind flow.

Figure 17 shows twenty four-hour prevailing winds and a clockwise current pattern. Figure 18 shows that the water at the 100-ft. level agrees with the upper layers in direction of movement, although flow data at this level are available only at Stations 18 and 20.

The 30-50 ft. chart on Figure 18 shows a variable condition at Stations 3 and 17 near the shore and opposite to the apparent clockwise circulation of the center of the basin.

Additional insight can be gained from the knowledge of sediment distribution. Partical size distribution indicates a flow from the north on the east shore of the lake as far as

Indiana Harbor. The offshore formation of dunes (under water) in the Indiana Harbor area point to the NNE and show a northward movement of water. The sediment distribution agrees with the prevailing flow from the south at Station 4.

Conformal current motion in the southern basin would show that northwest winds which would pile water on the eastern shore would produce a movement around the southern part of the basin and northward along the western shore (1). This movement satisfies the continuity conditions.

ANALYSIS OF RESULTS

Daily Movements

Figures 2 to 6 illustrate the great variability which can occur from station to station as well as the clarity of current patterns which can be shown on a two-hour basis. Figure 17 shows a period in which the anticyclonic whirl in the southern basin was strong and extending beyond the limits of the basin. There is no evidence of any flow from the north on the west shore. From the pattern indicated in Figure 17 it appears that there is no restriction to movement across the basin sill. In fact, Figure 18, the 100 ft. level would indicate that the upper 100 feet of water moves freely between the two basins during this type of circulation. Speeds indicate a slow but much larger mass moving southward into the basin whereas the outflow is a smaller mass but much faster.

A strong northwesterly wind flow was apparently related to this current pattern. This type of anticyclonic flow appears to occur when similar wind data are available. No attempt was made to determine the length of time required to change one current pattern to a new pattern.

Figure 18 at the 100-ft. level shows that the deep water flow moves in the same type of flow as the upper levels. It appears that the anticyclonic flow also occurs in the deeper layers during this period of the year. Speeds at the 100-ft. level were about the same as for the upper layers at the same station.

Figure 18 at the 30-50 ft. level shows an anticyclonic circulation in the main part of the basin but a complete reversal along the west shore of the basin. A light to moderate south-westerly wind persisted through the day, as well as during the preceding two days, and may be responsible for the reverse inshore flow. This pattern was also repeated at other periods for which synoptic current and wind observations were available.

During much of the synoptic study period heavy ice covered the central and northern portions of the lake. Late in February it was estimated that up to 95 percent of the entire lake was ice covered. In March there was a sharp break in the cold weather and temperatures rose to well above normal. Prevailing westerly winds and some periods from the southwest helped to clear the southwest section of the lake early in the month and by the third or fourth week most of the southern basin was free of solid ice cover. It

is noteworthy that current patterns related to wind flow in February had the same relationships as were found in late March. It did not appear that the ice cover was important in changing or shifting the current patterns from the observed wind-current relationships during the ice-free periods.

The winter current pattern indicated in Special Report LM No. 11 and related to wind flow has been given further confirmation by the data from the three additional stations, as reported herein.

Rotary Currents

As shown in Figures 3, 7 and 8, rotary currents are a part of the general lake circulation. Both Sverdrup and Defant give illustrations of these occurrences in the oceans (2)(3). Although currents of an inertia period were long suspected it was not until 1936 that they were actually noted in the ocean. Defant suggests that the rotary currents found by Gustafson and Kullenberg (2, p. 439) may be related to inertia waves. During the period when the rotary currents were found in the lake the temperature structure was isothermal and the lake had an ice cover. Station 4, May to July 1962, also indicated the presence of these rotary currents. The large eddy mentioned in Special Report LM No. 11 may also have been the inertia-type rotary current; however, its period was apparently interrupted by another pulse or increase in flow. The period was near 18 hours. These rotary currents, in themselves, appear to be of little or no consequence as there is a very small transport involved. This very aspect, of no transport, is of considerable concern when the question of the movement of pollutants or other materials are considered. Present studies show that although calm conditions may permit a buildup of an effluent, a rotary current can do likewise. Both Sverdrup and Defant stress that this type of inertia current frequently occurs during the calm after the passage of a storm front. Thus, the great amount of energy supplied to the lake can create inertia-period rotary currents. Rotary currents do not appear simultaneously everywhere on the lake. They more likely will occur in an area which is not a part of the dominant current system but rather in an area of temporary calms. Significantly, they are more likely to occur on the sheltered side of the lake during ice-free periods rather than on the upwind side.

The ice cover over the lake during the winter of 1962-63 provided the exceptional case of observing water movements not

under the direct influence of the wind. Although current speeds are not exceptionally high, there were relatively few calm periods (less than .03 fps). Energy supplied probably comes from pressure exerted on the ice field by the wind, temperature differentials or stress exerted by variations in atmospheric pressure on the ice.

Diffusion or Dispersal

Recent diffusion dye studies on Lake Huron using dye and drogues pointed up certain aspects that were not found during the Lake Michigan Drogue Study (see Special Report No. LM 10). The major phenomenon not found during this period was the "slick." Slicks or taches d'huile are common to all lakes during moderately calm weather (4). Slicks found on Lake Huron showed that an effluent can be moved with no dispersion. Similar patterns, during stratified conditions, can also occur in Lake Michigan.

Diffusion or dispersal in the longitudinal or vertical axis varies considerably from day to day or during periods of the year. In general, dispersal of particles varies considerably, ranging from no dispersal during periods when slicks occur to great vertical mixing components during the convective overturn in spring and fall. Large scale longitudinal mixing probably occurs during severe weather conditions when strong winds persist. Present studies by the Project and other groups, using dye and drogues find, in general, that mixing during most periods of the year is small.

Long Term Movements

The daily synoptic flow during the winter reinforces the previous hypothesis concerning the long term winter movements in the southern basin. In general, the circulation was anticyclonic (clockwise) in the southern basin with a northerly inflow on the east side of the lake and an outflow on the west side.

Figures 15 and 16 for May-July 1962 show an apparent reversal of the winter 1962-63 pattern. There is reason to believe that a seasonal shift in pattern would occur with a gradual shift in the mean wind flow from winter to summer.

Although certain current patterns appeared to develop and be maintained during specific wind regimes the wind systems can and do change. It would appear that if the wind flows changed for a sufficient period of time there could be counter-clockwise patterns in the winter and clockwise patterns in the summer.

SUMMARY OF ALL PHYSICAL STUDIES

The analysis of nearly 55,000 current observations, mostly winter data, since May 1962 in the southern basin of Lake Michigan has given new insight as to the water movements in the basin.

The data was analyzed by a plot of the two-hour speed and direction envelopes, plotting of synoptic data, graphs of prevailing speed and direction and vector diagrams. The detailed patterns of water movement in the southern basin are still only partially known but the influence of the physical factors on the fate of pollutants are now known in some detail.

In mid-summer a thermocline develops in the southern basin and persists until late fall. Since the thermocline develops rapidly with the onset of summer it is below the fifty foot level in a few weeks. A diffuser site in water depths less than 50 feet would thus be in the epilimnion water for most of the summer and fall months. An effluent which is lighter in density would remain in or on top of the epilimnion. Mixing in the epilimnion no matter how severe, would rarely occur with the lower layers because of the existence of the thermocline. During periods of slicks, which occur in the summer months, any effluent discharged into the upper layers which is lighter than the surrounding water mass would tend to concentrate rather than have any tendency toward dispersion. Drogue studies in the spring of 1963 show that there is no great tendency toward dispersion. In fact, after initial dilution, great or small, only marked meteorological changes would produce sudden mixing in the horizontal or vertical components. Normal turbulent mixing by the moving water mass would account for the dilution over a period of time.

If an effluent were heavier than the upper water mass it would tend to sink into the hypolimnion with little or no mixing. However, upwelling could bring this concentrated effluent into the vicinity of beaches or water intakes. An effluent which has an adjusted density such that it would lie on the thermocline could be brought to the water intakes during periods of upwelling, by internal waves, or by rotary Kelvin waves. Summer currents would usually carry an effluent toward the south but could move in any direction at random. In general, only onshore winds would carry the surface waters directly toward the beaches. An offshore wind would produce upwelling and bring bottom waters to the surface and in the vicinity of beaches or water intakes.

During the winter period an effluent which rises or sinks will not mix any more readily except during high wind conditions. Water temperatures in mid-winter have decreased just below maximum density and thus, no further convective mixing occurs. Currents found in the winter of 1962-63 indicate a clockwise rotation moving the water in a general northward direction near Chicago.

Vector diagrams indicate that rotary currents, as long as six consecutive days, will keep a water mass in one general area. An effluent discharged during such periods would tend to accumulate heavily in the vicinity of the discharge point.

The total picture of the influence of the physical factors on the fate of effluents discharged into the lake would indicate that a great variety of conditions exist which would tend to permit concentrated effluents to move to water intakes, beach areas, or other points of water use, during any period of the year.

REFERENCES

1. Laevastu, T. The Causes and Predictions of Surface Currents in Sea and Lake. Hawaii Inst. of Geophysics, Report No. 21 (1962). p. 54.

2. Sverdrup, H.U. et al. The Oceans. Prentice-Hall, New York (1946). p. 1049.

3. Defant, A. Physical Oceanography, Vol. 1. Pergamon Press, New York (1961). p. 729.

4. Hutchinson, G.E. A Treatise on Limnology. John Wiley and Sons, New York (1957). p. 1015.

TABLE 1

Period of the Inertia Circle*

Circle No.	Start Time	Start Degrees	End Time	End Degrees	Period in Hours
1	1630	56°	1200	37°	19.5
2	1200	37°	0630	37°	18.5
3	0630	37°	2230	36°	16.0
4	2230	36°	1530	42°	17.0
5	1530	42°	1100	34°	19.5
			Average Period		18.1
		Disregarding No. 1 - Average Period			17.6

Theoretical Period, 43° 00 N

Latitude - 17.5 hours

*Figure 7

TABLE 2

Percent of Speed for Station 17

Speed in feet per second	Percent of Total Observations	Percent of 340°-360°	Percent of 160°-180°
0 - 0.1	25.0	15.0	12.9
0.2	37.0	39.5	33.8
0.3	20.0	31.9	26.3
0.4	4.0	4.5	6.7
0.5	4.0	3.2	4.0
0.6	3.5	2.0	4.3
0.7	2.5	0.5	4.6
0.8	1.5	1.0	3.2
0.9	1.0	0.5	1.6
1.0	---	0.7	1.3
1.1	---	---	1.1
Total Observations	5441	915	373
Mean Speed	.25 fps	.24 fps	.30 fps

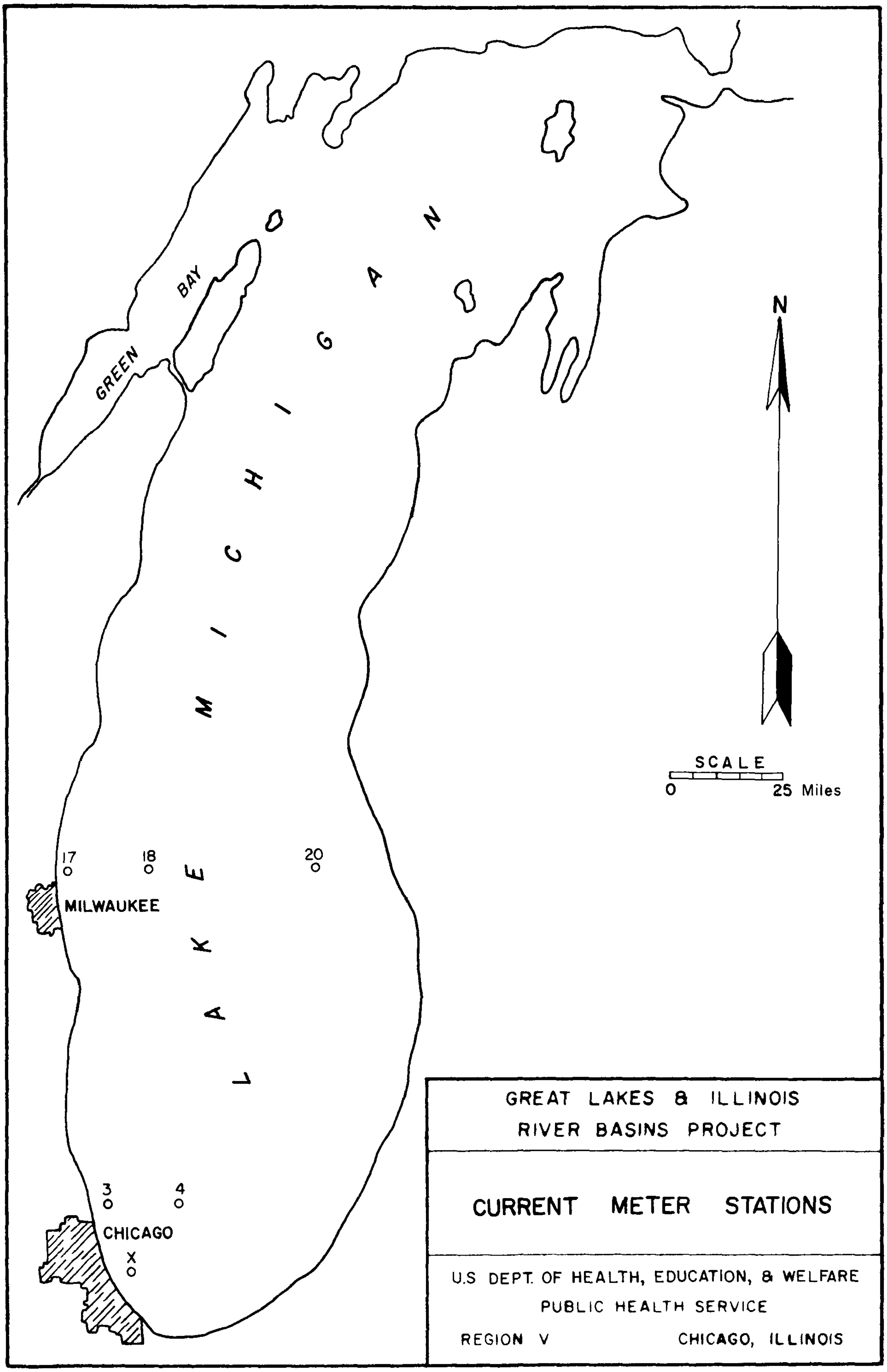
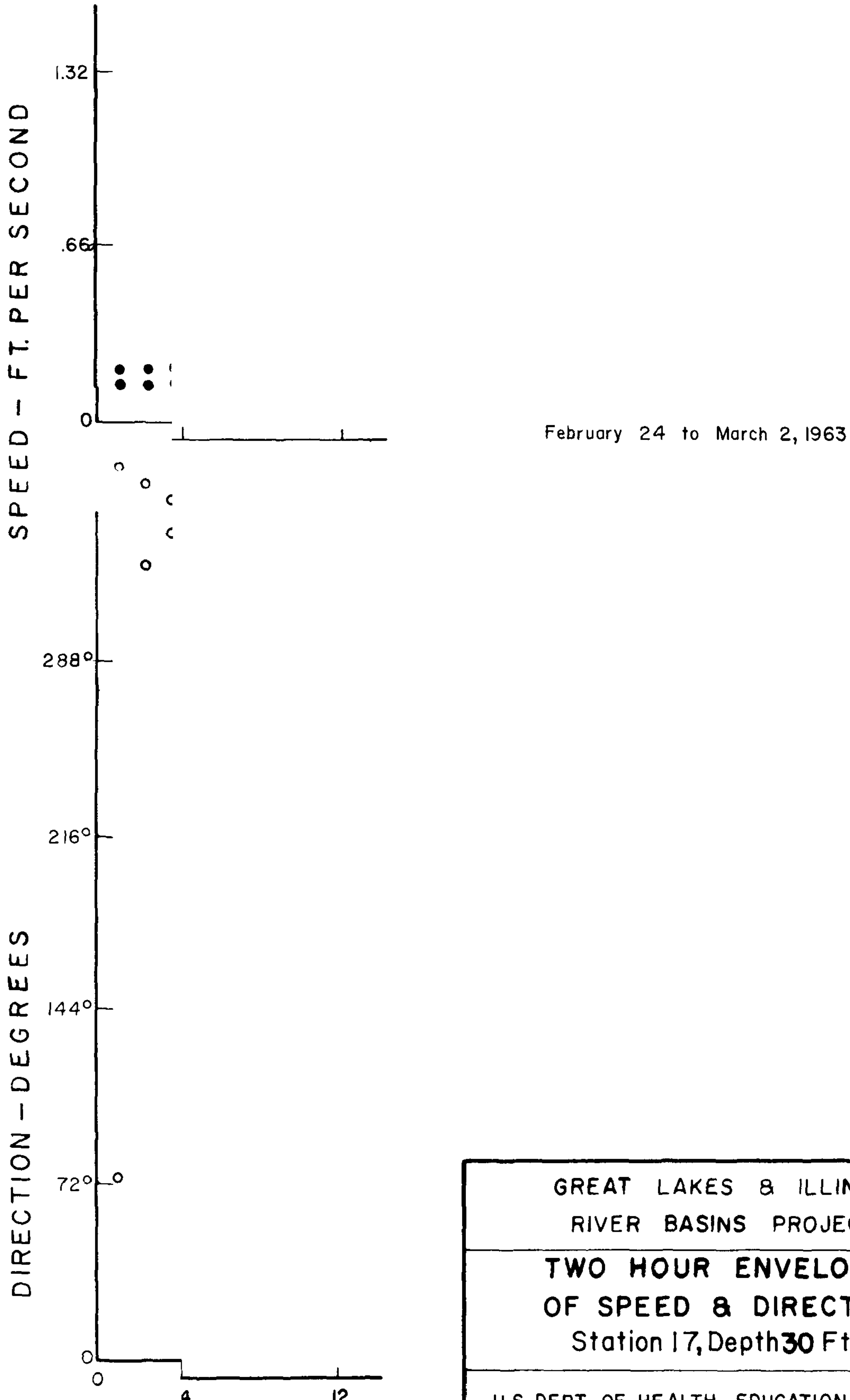

GREEN BAY
LAKE MICHIGAN
N
SCALE
0
25 Miles
17
18
20
MILWAUKEE
3
4
CHICAGO
X
GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT
CURRENT METER STATIONS
U.S DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V
CHICAGO, ILLINOIS

FIGURE 1

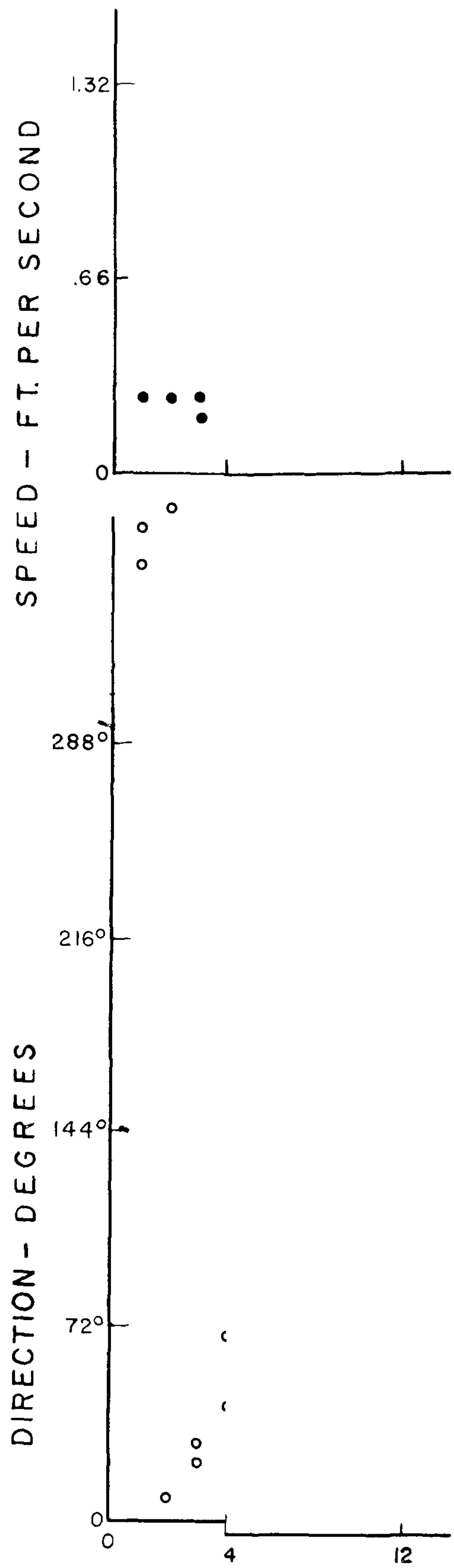


GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

TWO HOUR ENVELOPES OF SPEED & DIRECTION
Station 17, Depth 30 Ft.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 2



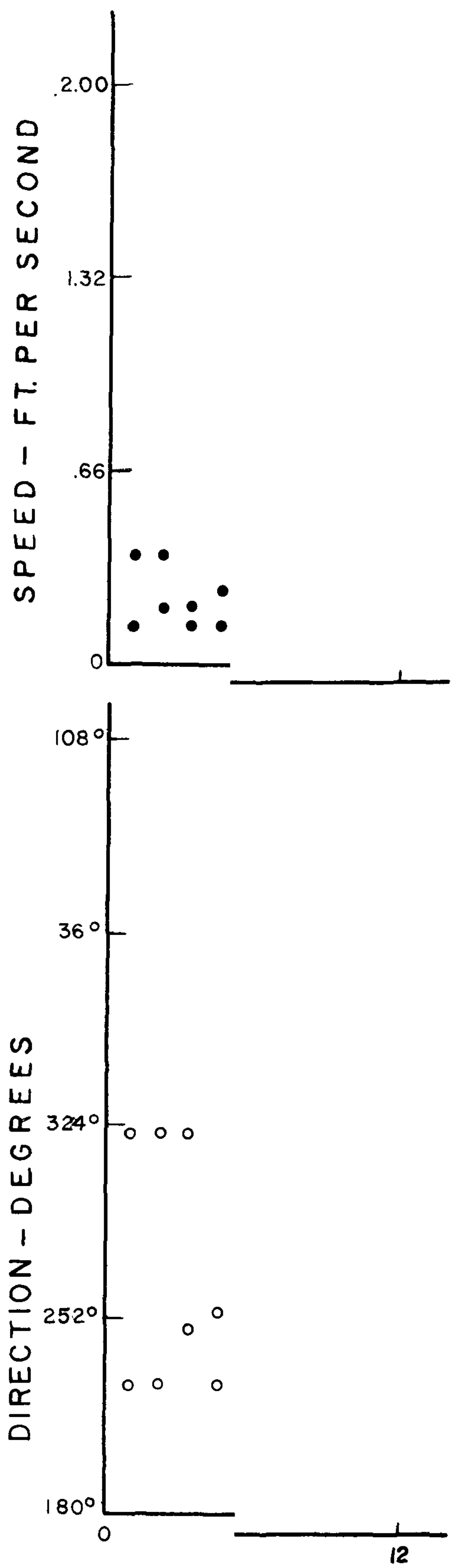
February 24 to March 2, 1963

GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

TWO HOUR ENVELOPES
OF SPEED & DIRECTION
Station 18, Depth 30 Ft.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 3



February 24 to March 2, 1963

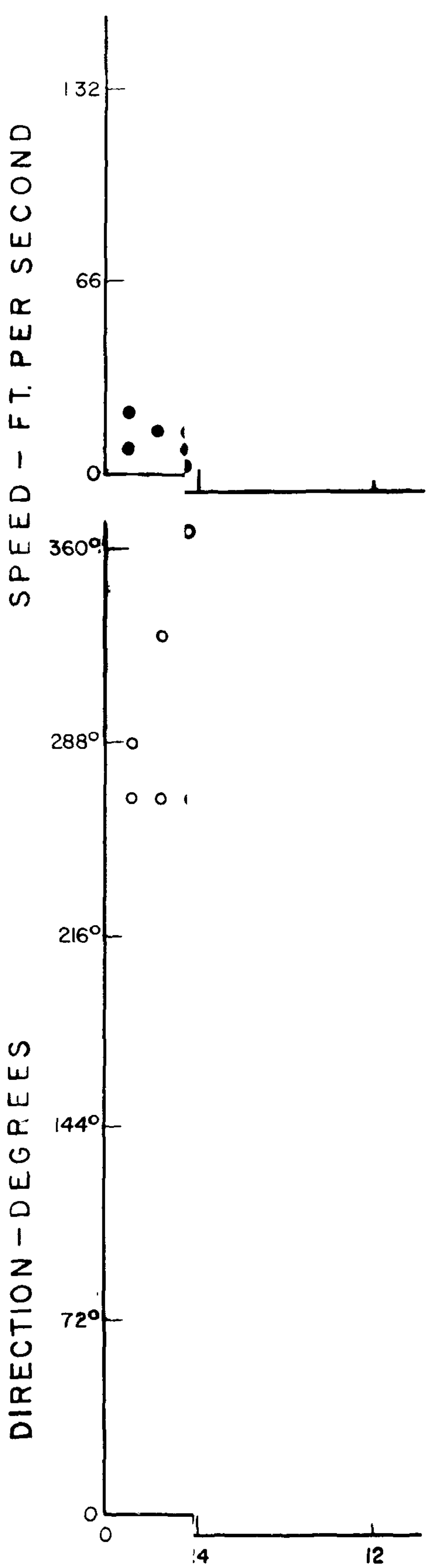
GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

TWO HOUR ENVELOPES OF SPEED & DIRECTION

Station 20 Depth 50 Ft.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 4



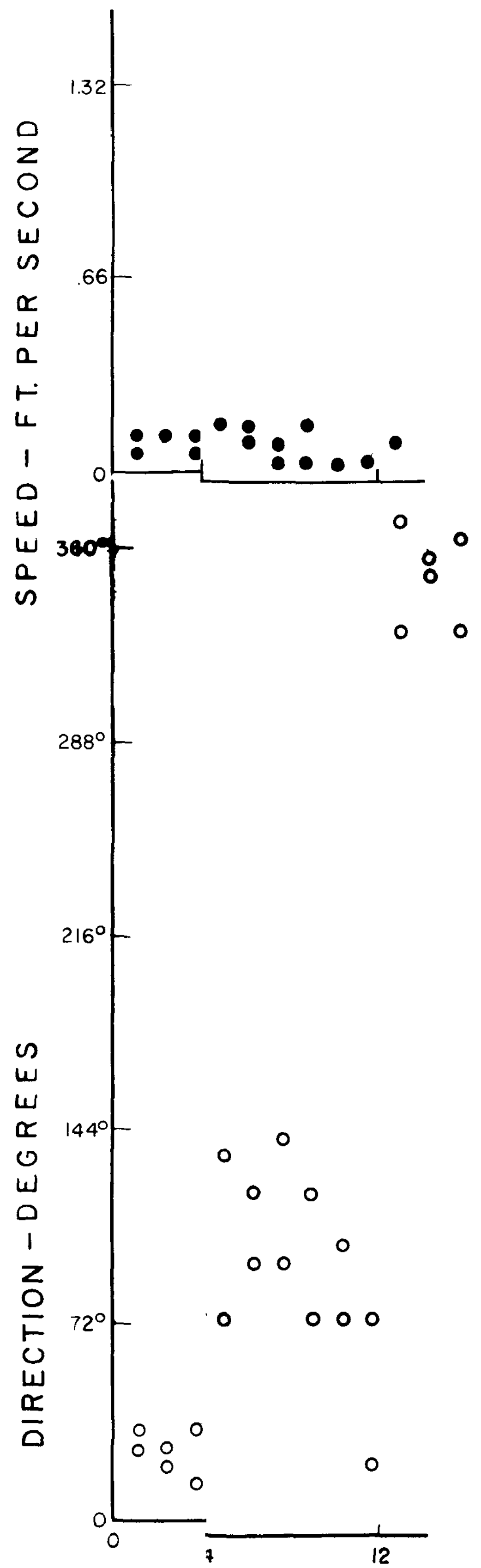
February 24 to March 2, 1963

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

TWO HOUR ENVELOPES OF SPEED & DIRECTION
Station 20, Depth 100 Ft.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 5



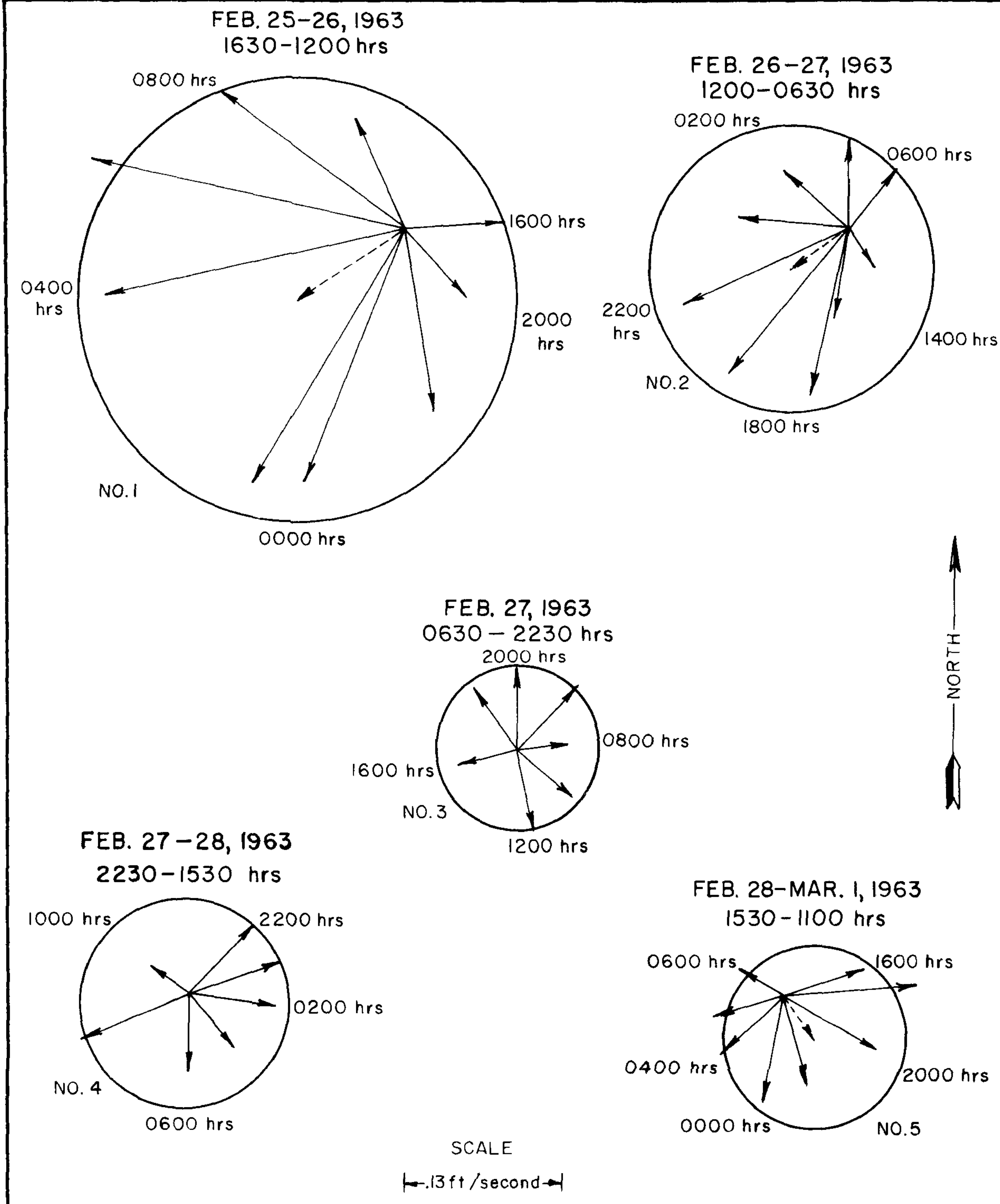
February 24 to March 2, 1963

GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

TWO HOUR ENVELOPES OF SPEED & DIRECTION
Station 20, Depth 300 Ft.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 6



LEGEND
- - - -> Net Vector

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RIVER BASINS PROJECT

CENTRAL VECTOR DIAGRAMS
STATION 18 - DEPTH 30 FT.

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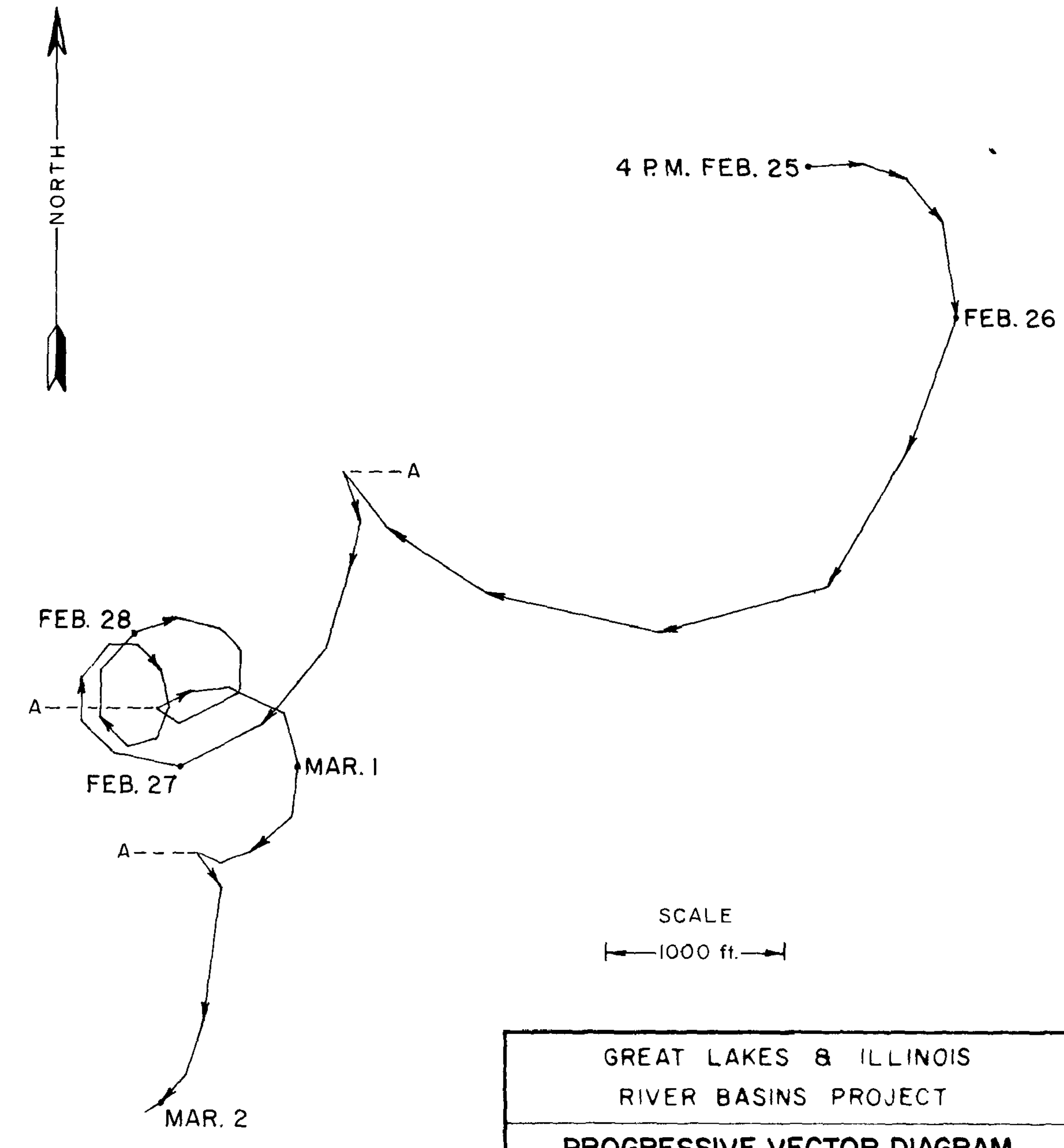
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 7



A— — — Speed is Zero

GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

PROGRESSIVE VECTOR DIAGRAM
TWO HOUR VECTORS
STATION 18 – DEPTH 30 FT.

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PUBLIC HEALTH SERVICE
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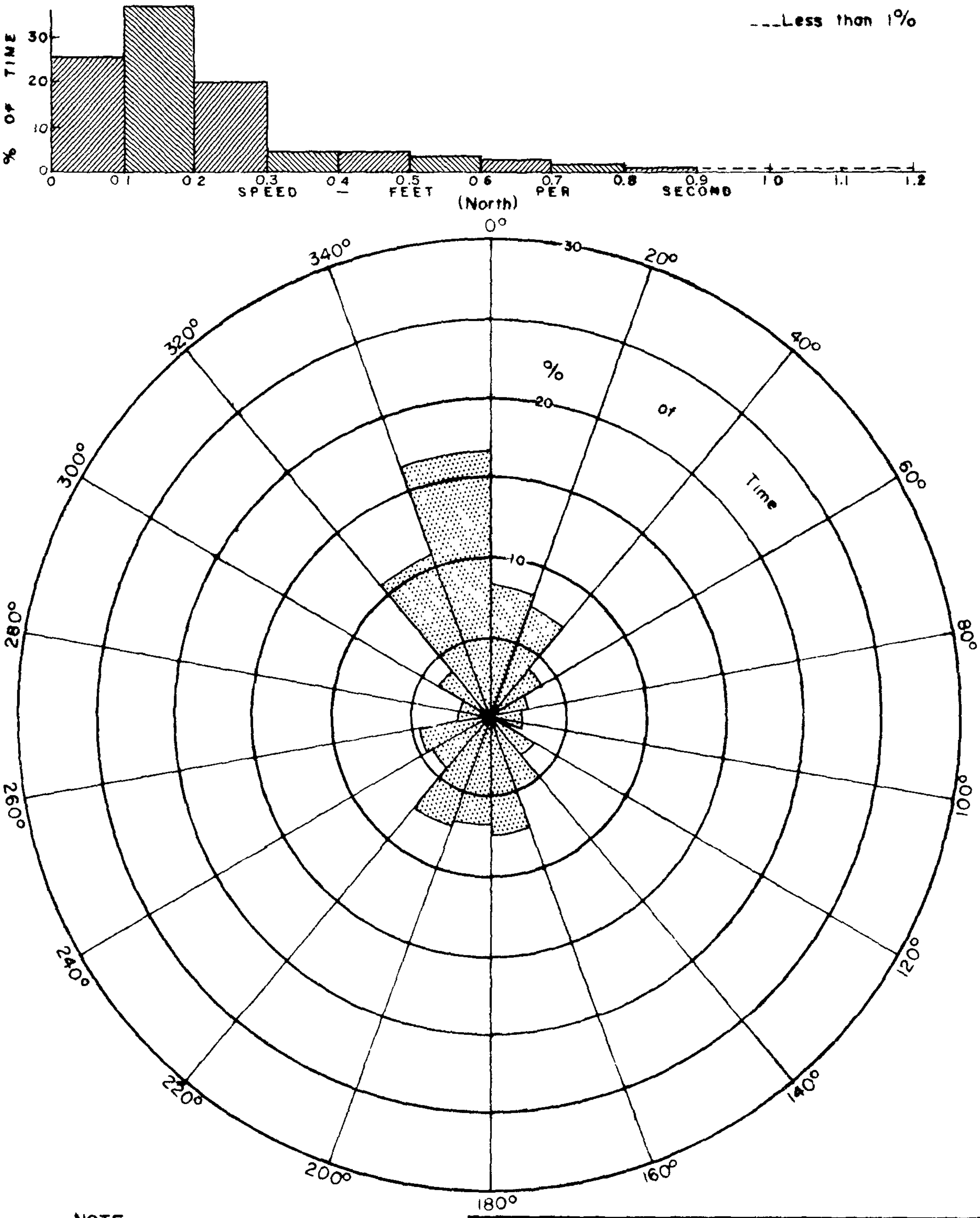
FIGURE 8



NOTE:
Direction is from the sector shaded, toward the center

CURRENT

December 15, 1962 to April 19, 1963

GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION
STATION 17 - DEPTH 30 FT.

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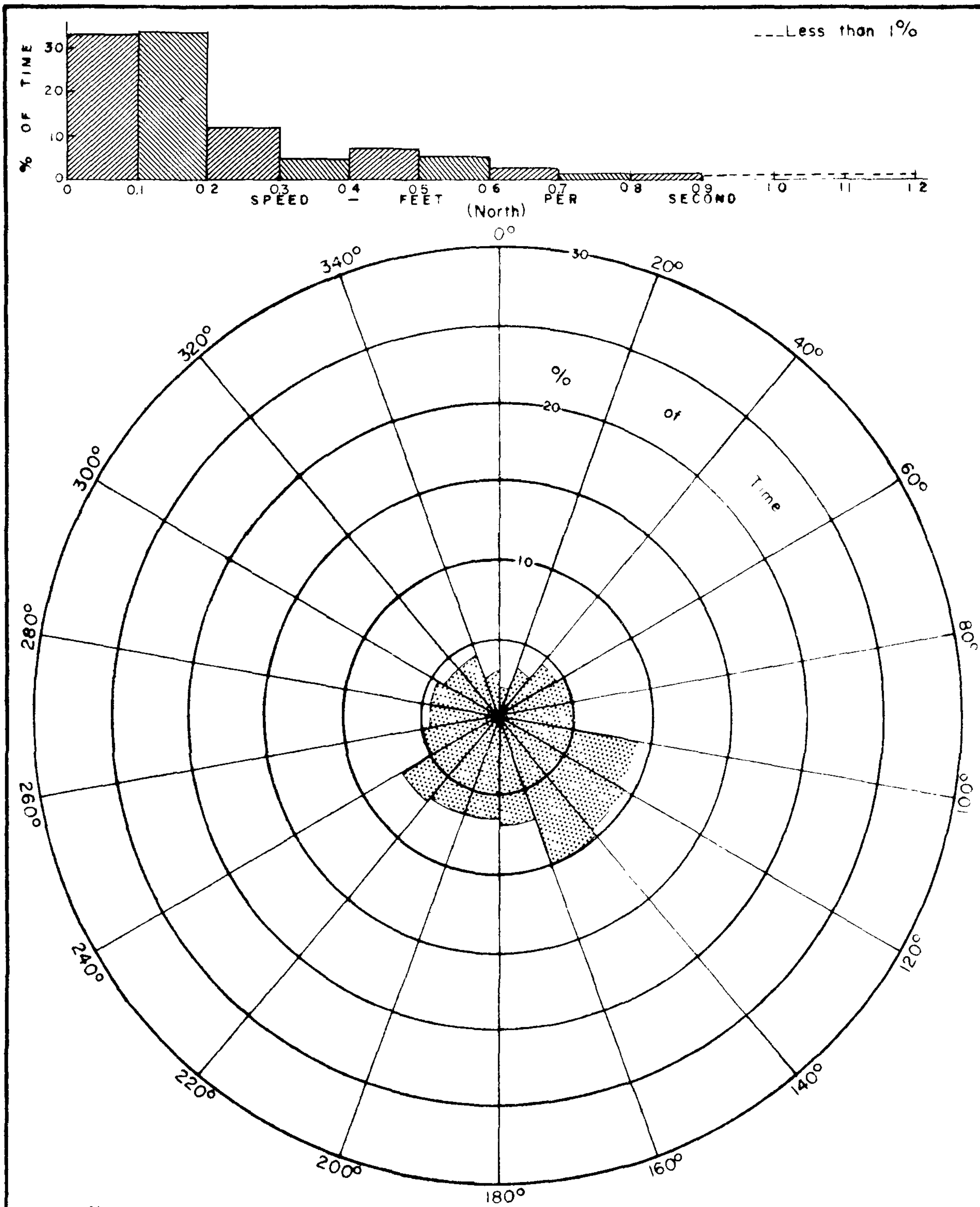
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 9



NOTE:
Direction is from the sector shaded, toward the center.

CURRENT

DEC. 5, 1962 TO APR. 20, 1963

GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION

STATION 18 — DEPTH 30 FT.

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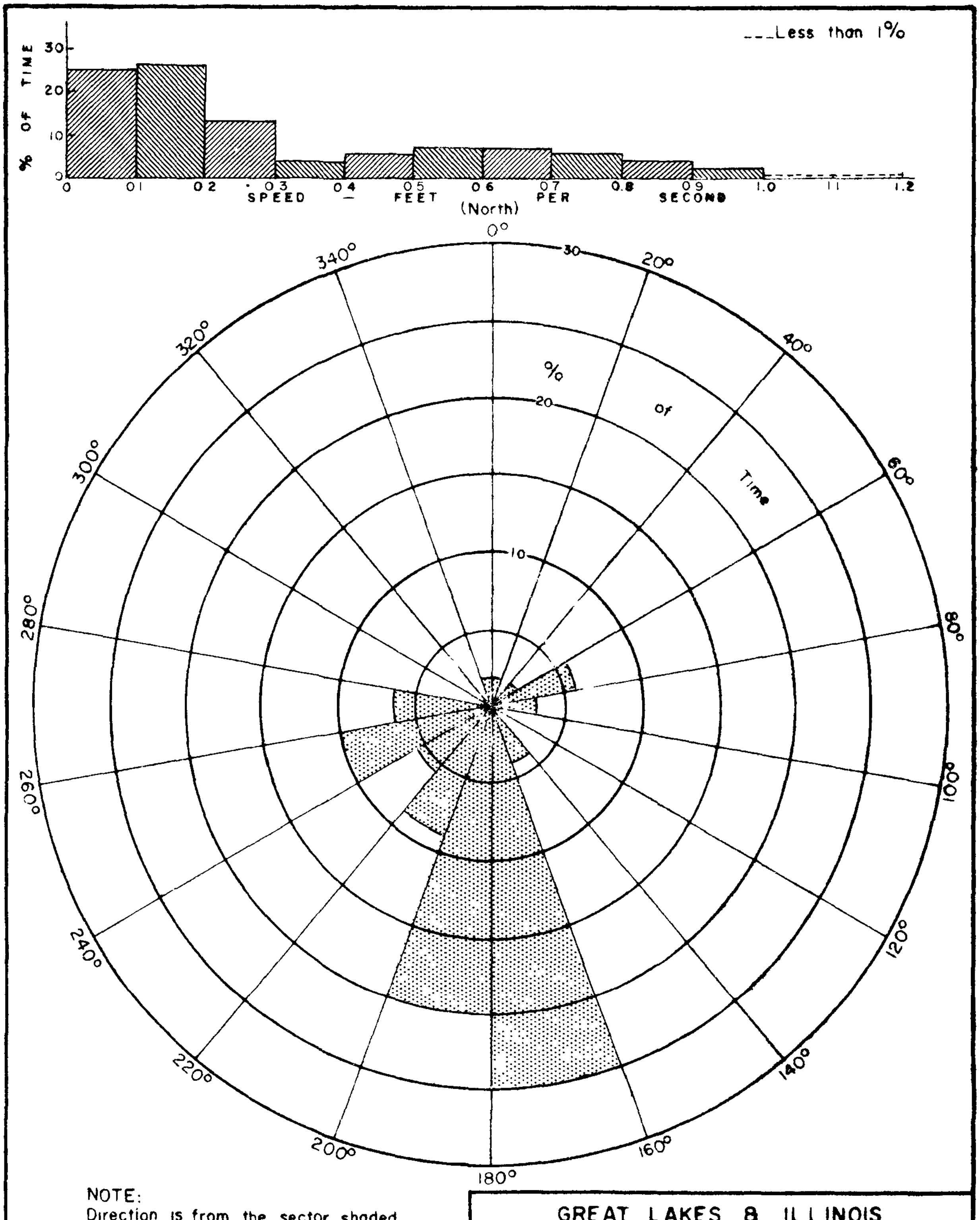
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 10



NOTE:
Direction is from the sector shaded, toward the center.

CURRENT

DEC. 10, 1962 TO APR. 20, 1963

GREAT LAKES & ILLINOIS
RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION
STATION 18 — DEPTH 100 FT.

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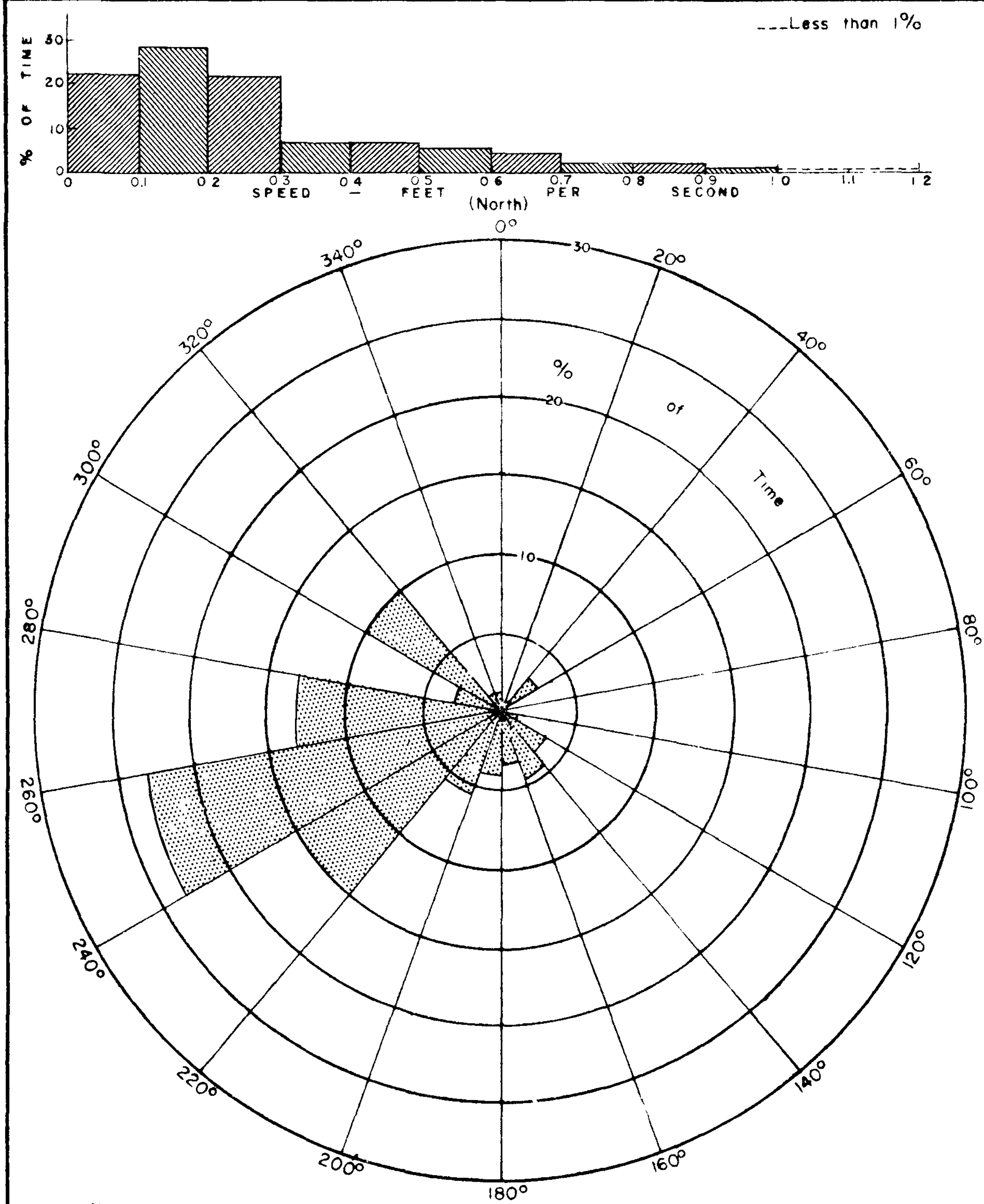
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 11



NOTE:
Direction is from the sector shaded, toward the center.

CURRENT

DEC. 5, 1962 TO APR. 20, 1963

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION STATION 20–DEPTH 50 FT.

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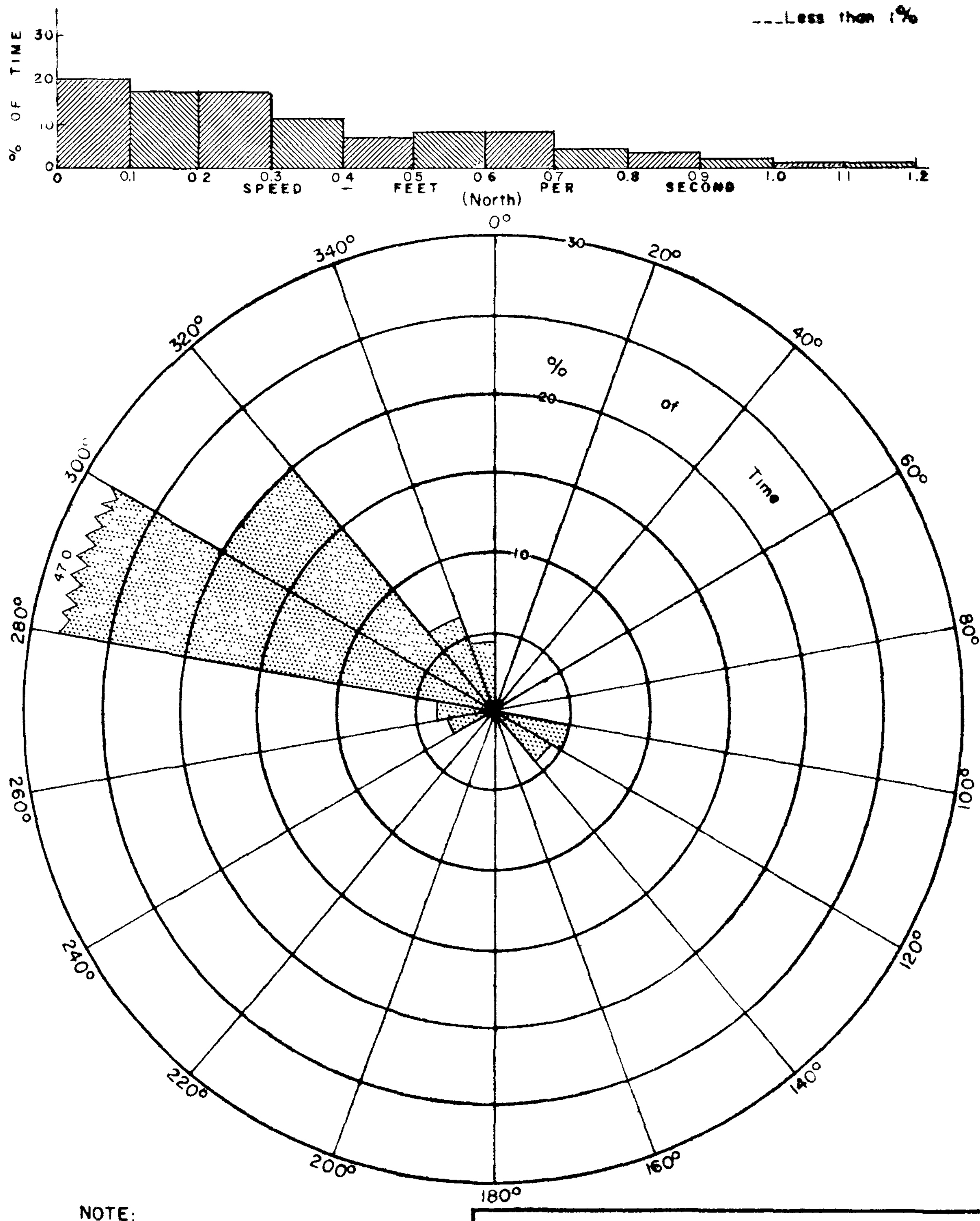
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 12



NOTE:
Direction is from the sector shaded, toward the center.

CURRENT

December 3, 1962 to April 20, 1963

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION

STATION 20 - DEPTH 100 FT.

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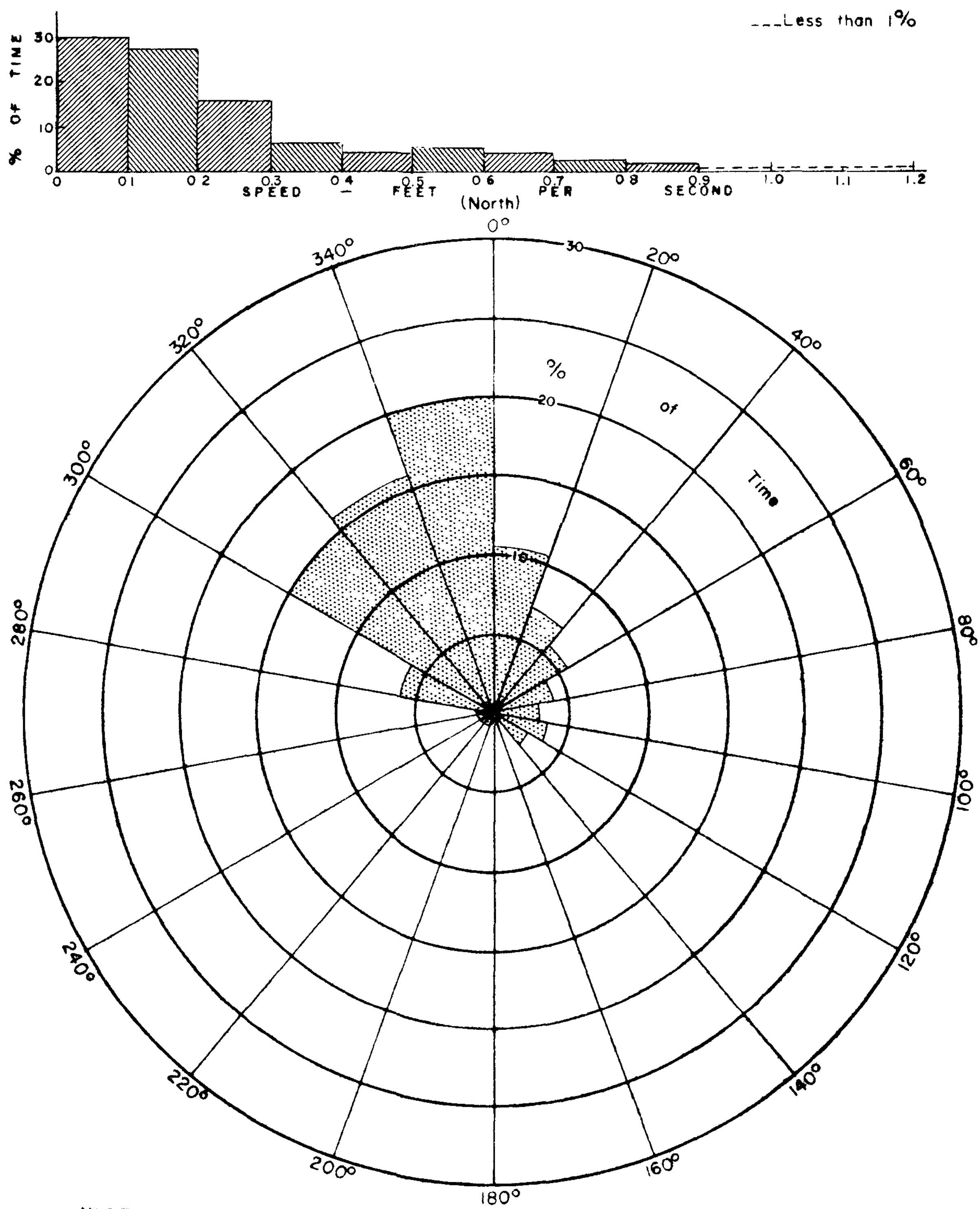
FIGURE 13



NOTE:
Direction is from the sector shaded, toward the center.

CURRENT

JAN 25, 1963 TO APR 20, 1963

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION

STATION 20 — DEPTH 300 FT.

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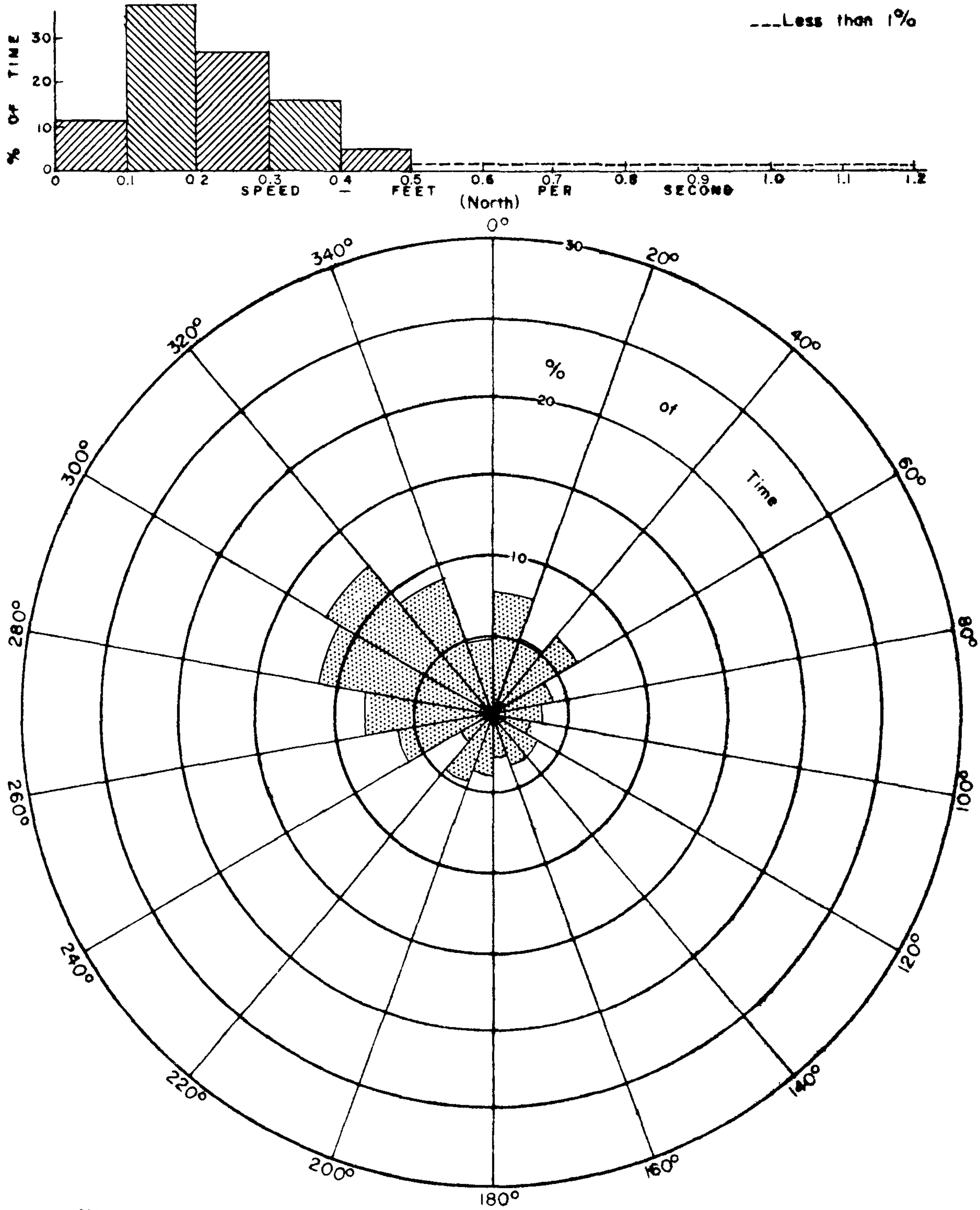
REGION V CHICAGO, ILLINOIS

FIGURE 14



NOTE:
Direction is from the sector shaded, toward the center.

CURRENT

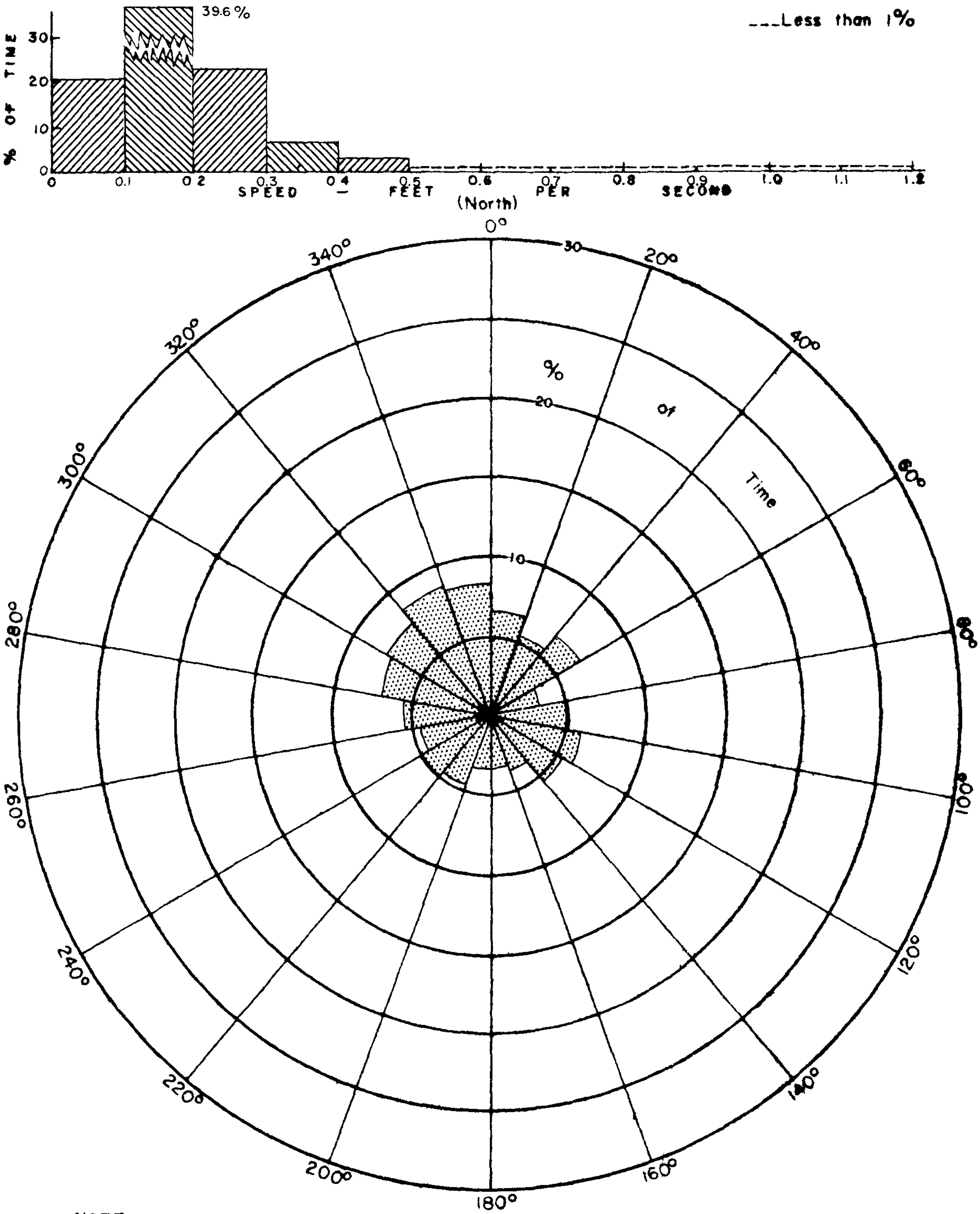
May 25, 1962, to July 26, 1962

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION
STATION 4 — DEPTH 60 FT.

U.S. DEPT OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 15



NOTE:
Direction is from the sector shaded, toward the center.

CURRENT

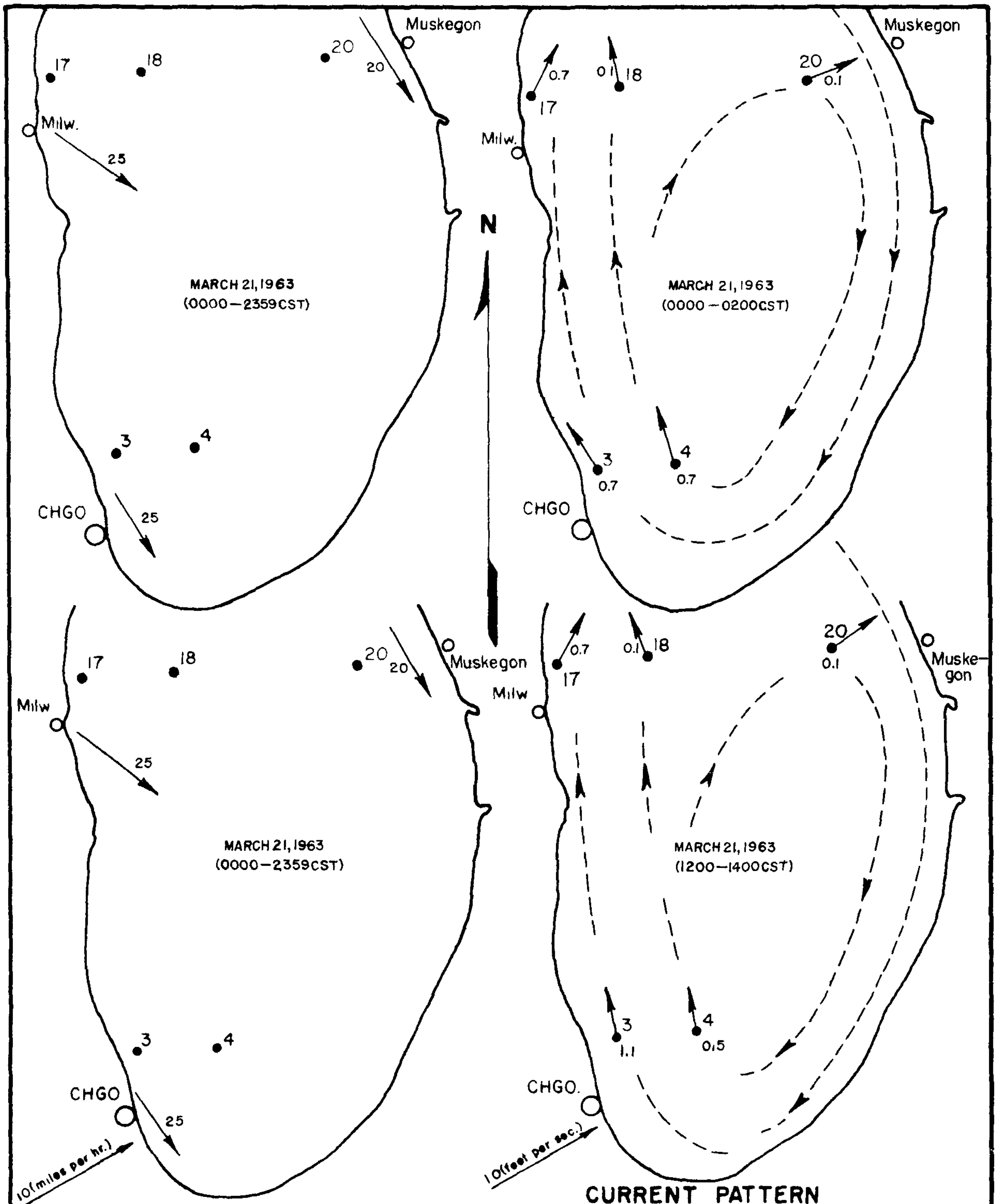
May 25, 1962, to July 26, 1962

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

PREVAILING SPEED & DIRECTION
STATION 4 — DEPTH 90 FT.

U.S. DEPT. OF HEALTH, EDUCATION, & WELFARE
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 16



WIND FLOW

WIND: Prevailing Direction and Mean Speed in Miles Per Hour for 24 Hour Period

CURRENT PATTERN: Two Hour Mean Vector

– – – – Stream Lines Estimated.

LEVEL: 30ft. and 50ft.

SCALE

0 25 50 Miles

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

CURRENT PATTERN AND RELATED WIND FLOW

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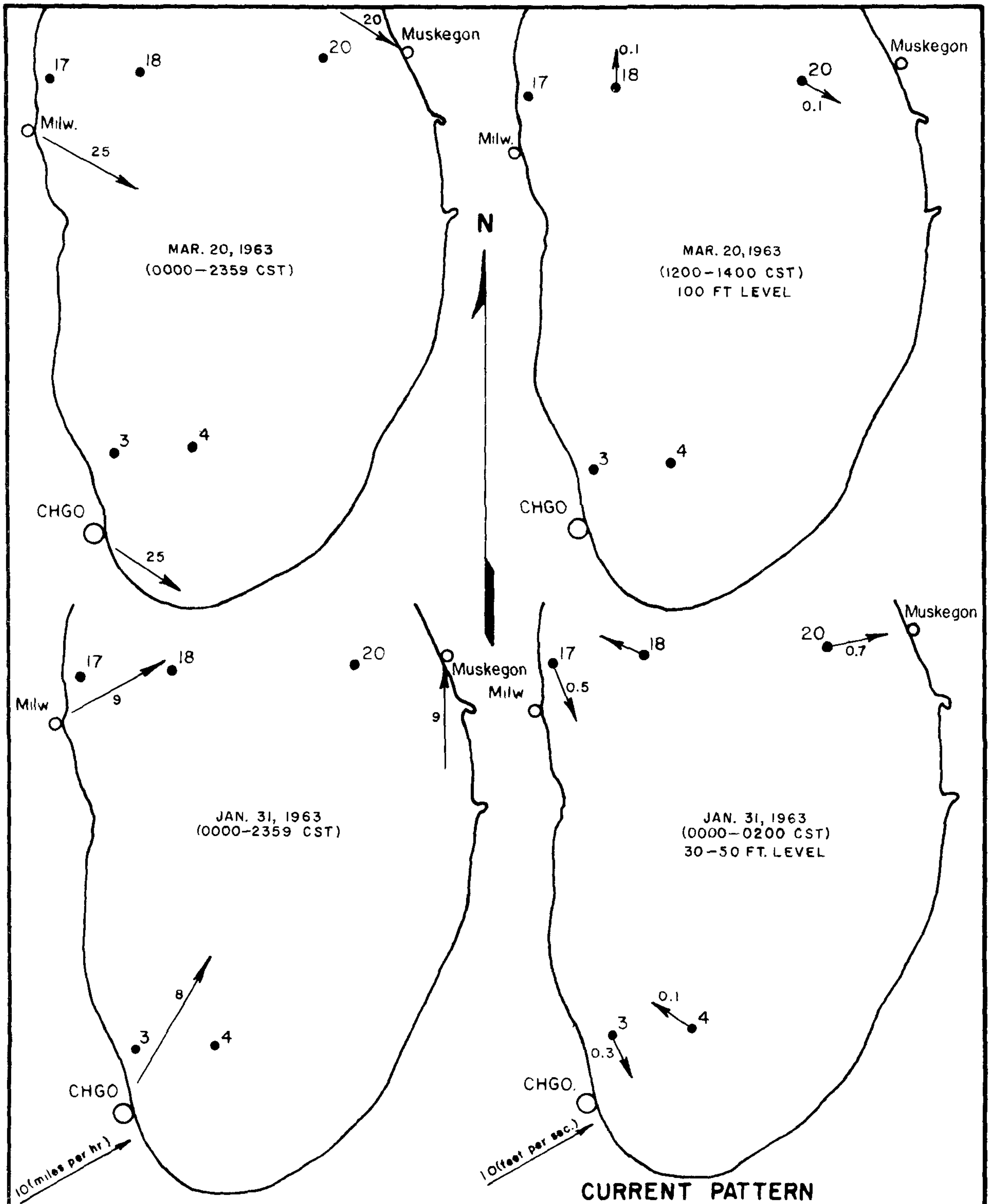
PUBLIC HEALTH SERVICE
REGION V CHICAGO, ILLINOIS

FIGURE 17



WIND: Prevailing Direction and Mean Speed in Miles Per Hour for 24 Hour Period

CURRENT PATTERN Two Hour Mean Vector

– – – – Stream Lines Estimated

SCALE

0 25 50 Miles

GREAT LAKES & ILLINOIS RIVER BASINS PROJECT

CURRENT PATTERN AND RELATED WIND FLOW

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REGION V CHICAGO, ILLINOIS

FIGURE 18