TECHNICAL REPORT H-74-6

LAKE ERIE INTERNATIONAL JETPORT MODEL FEASIBILITY INVESTIGATION

Report 1

SCOPE OF STUDY AND REVIEW OF AVAILABLE DATA

by

D. L. Durham, D. G. Outlaw

July 1974

Sponsored by Lake Erie Regional Transportation Authority [Report 17-1]

Conducted by U. S. Army Engineer Waterways Experiment Station
Hydraulics Laboratory
Vicksburg, Mississippi

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ARMY-MRC VICKSBURG, MISS

FOREWORD

This interim report, Lake Erie International Jetport Model Feasibility Investigation, Part 1, Scope of Study, and Part 2, Review of Available Data, is the first in a series of reports concerning the model feasibility investigation being conducted by the U. S. Army Engineer Waterways Experiment Station (WES) for the Lake Erie Regional Transportation Authority (LERTA). The investigation is a portion of an airport feasibility study being conducted by LERTA for the evaluation of four proposed airport sites, one of which is in Lake Erie near Cleveland, Ohio.

Results and data compiled from numerous sources are presented, and the inclusion of information in this interim report does not necessarily indicate indorsement of the results and findings by the U. S. Army Corps of Engineers.

The report was prepared by Dr. D. L. Durham and Mr. D. G. Outlaw of the Wave Dynamics Division (WDD) under the general supervision of Dr. R. W. Whalin, Chief, WDD, and Mr. H. B. Simmons, Chief, Hydraulics Laboratory.

Acknowledgment is made to the following people for providing technical assistance or information for this study: Mr. Larry Braidech, Geological Survey, Ohio Department of Natural Resources; Mr. Carl Davenport, Gilbert Associates; Mr. Steward Fordyce and Dr. Richard T. Gedney, National Aeronautics and Space Administration Lewis Research Center; Messrs. Robert P. Hartley and Richard Winklhofer, Environmental Protection Agency; Dr. Charles Herdendorf, Ohio State University; Dr. G. H. Keulegan, consultant, WES; Dr. Wilbert J. Lick, Case Western Reserve University; Dr. D. Paskausky, University of Connecticut;

Mr. Berry Pritchard, U. S. Army Engineer District, Buffalo; Mr. R. O. Reid, Texas A&M University; Mr. D. R. Rondy, Lake Survey Center; Mr. Wayne Singley, NUS Corporation; and Dr. Edwin J. Skoch, John Carroll University.

Directors of WES during the conduct of the investigation and preparation of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, METRIC TO BRITISH AND BRITISH TO METRIC UNITS OF MEASUREMENT

Units of measurement used in this report can be converted as follows:

Multiply	By	To Obtain
	Metric to British	
millimeters	0.0394	inches
centimeters	0.3937	inches
centimeters per second	0.3937	inches per second
meters	3.2808	feet
kilometers	0.6214	miles (U. S. statute)
micrograms per liter	0.000015432	grains per liter
milligrams	0.015432	grains
milligrams per liter	0.015432	grains per liter
Celsius degrees or Kelvins	9/5	Fahrenheit degrees*
	British to Metric	
inches	2.54	centimeters
feet	0.3048	meters
square feet	0.09290304	square meters
cubic feet	0.02831685	cubic meters
feet per second	0.3048	meters per second
cubic feet per second	0.02831685	cubic meters per second
cubic yards	0.07645549	cubic meters
miles (U. S. statute)	1.609344	kilometers
square miles (U. S. statute)	2,589,988	square meters
miles per hour	1.609344	kilometers per hour
pounds (mass)	0.4535924	kilograms
Fahrenheit degrees	5/9	Celsius degrees or Kelvins**

* To obtain Fahrenheit (F) readings from Celsius (C) readings, use the following equation: $F = 9/5(C) + 32$. To obtain Fahrenheit from Kelvin (K), use: $F = 9/5(K - 273.15) + 32$.

** To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

SUMMARY

This report presents the scope of the U. S. Army Engineer Waterways Experiment Station's (WES) investigation of the proposed Lake Erie International Jetport and summarizes the data obtained from the literature and private individuals. This report is the first of a series published under the general title "Lake Erie International Jetport Model Feasibility Investigation."

The objectives of the investigation, Part I, include a review of the literature concerning wave activity (wind waves, seiches, and tides) and mass circulation in Lake Erie, preliminary design of necessary hydraulic models, and preliminary application of analytical and/or numerical models to seiching and mass circulation. In order to accomplish the objectives, the investigation is separated into five tasks: (a) review of the literature, (b) seiche analysis, (c) wave refraction and diffraction analyses, (d) mass circulation analysis, and (e) preliminary model design.

Existing lake geology, climate, bottom and shoreline characteristics, water balance, water temperature, lake levels, lake currents, wave regime, shore erosion, and water quality data in the central basin of Lake Erie near Cleveland, Ohio, are summarized in Part II. Mass flow direction and current speed distributions from 1964-1965 Federal Water Pollution Control Administration (now part of the Environmental Protection Agency) current observations at stations near Cleveland are presented.

Areas of insufficient information found in the literature survey include synoptic and long-term mass circulation data, wind-generated wave hindcast, lake level data, and longshore sediment transport rates.

LAKE ERIE INTERNATIONAL JETPORT MODEL

FEASIBILITY INVESTIGATION

SCOPE OF STUDY AND REVIEW OF AVAILABLE DATA

PART I: SCOPE OF STUDY

Background

1. An offshore jetport in Lake Erie adjacent to Cleveland, Ohio, was initially proposed by the Greater Cleveland Growth Association in a prefeasibility report* published in March 1971. Study recommendations led to establishment of the Lake Erie Regional Transportation Authority (LERTA) in March 1972. After selection of the consultants Howard, Needles, Tammen, and Bergendoff, in association with Landrum and Brown, LERTA initiated a feasibility and site selection study for a major hub airport in the Cleveland service area. The LERTA study includes evaluation of land sites in addition to a lake site. One of the sites will be selected for the jetport after completion of the evaluation. Due to the limited time available and possible selection of the offshore site as the recommended jetport location, the U. S. Army Engineer Waterways Experiment Station (WES) model feasibility investigation was started before the site was selected. The WES investigation is limited to determining the necessary hydraulic models and other procedures for estimating the effects of the jetport on lake hydrodynamics near Cleveland.

2. The initial concept described in the prefeasibility report for the jetport is a diked, landfill island approximately 2 by 3 miles** in dimension, located 5 to 8 miles offshore. In addition to the island, the jetport concept includes an industrial and research park between the island and the shore, an expanded commercial harbor, and additional

* "The Lake Erie International Jetport Project," Pre-Feasibility Technical Report, Mar 1971, Greater Cleveland Growth Association.
** A table of factors for converting British units of measurement to metric units is presented on page ix.

recreational facilities. This concept has been used as the basis of the WES investigation; however, the precise location of the jetport, its shape, and the type of construction are not specified.

3. During portions of the investigation by WES, particularly the seiche and mass circulation analyses, a jetport size and location will be required. Until completion of the site selection analysis, sizes and locations used in these studies will be based on data available from LERTA at the time of these requirements. Until additional information is available, the jetport size and site proposed in the prefeasibility report, approximately 3 miles east of Cleveland, are being used in the investigations.

4. Alternate methods of construction, such as a pile-supported or a floating platform, are not considered in this investigation.

Investigation Objectives

5. The objectives of the WES model feasibility investigation are as follows:

a. Compilation of available data on wave activity (wind waves, seiches, and tides) and mass circulation in Lake Erie with particular emphasis on effects of these two phenomena in and around the vicinity of Cleveland.

b. Selection and preliminary design of necessary hydraulic models for studying various phenomena considered pertinent to the proposed jetport site.

c. Evaluation and preliminary application of analytical and/or numerical models of seiching and mass circulation in a lake to the jetport study.

6. To accomplish the objectives, the investigation was separated into five principal study tasks as follows:

a. Synthesis of available data.

b. Lake seiche analysis.

c. Wave diffraction and refraction analyses, including qualitative effects on littoral transport.

d. Mass circulation analysis.

e. Preliminary design of necessary hydraulic models.

7. A review of available data, task a, was conducted to determine the existence of and to collect the available data on the wave climate, mass circulation, general characteristics of shore erosion, and other pertinent physical features of Lake Erie, particularly in the vicinity of Cleveland. The second study task, lake seiche analysis, is an analytical study to estimate the effects of a landfill jetport complex on the periods and modal shapes of the free oscillations of Lake Erie. The incremental construction of the complex will be considered.

8. The third study task is an estimation of the wave refraction and diffraction patterns offshore of Cleveland for the existing bottom topography, shoreline geometry, and breakwater configuration. Procedures for estimating the wave-pattern changes associated with the construction of a jetport complex are to be examined and evaluated. In addition, present methods of estimating littoral transports will be evaluated for applicability to this study.

9. The mass circulation analysis, task d, has three subtasks: (a) the evaluation of presently available numerical models of wind-driven mass circulation and storm surge for well-mixed, constant density conditions of shallow lakes; (b) preliminary application of some of these models to the Lake Erie jetport study for initial estimates of the effects of the jetport on the wind-driven circulation and storm surge in Lake Erie near Cleveland; and (c) consideration of numerical modeling procedures of wind-driven mass circulation for baroclinic lake conditions with respect to application of existing numerical models or models presently being developed. The preliminary application of numerical models to this study (subtask (b)) will be limited to only one configuration of the jetport complex and one pattern of the wind field during these initial efforts of model selection and verification. During the accomplishment of the second subtask, a preliminary verification of the well-mixed, constant density numerical models without the jetport structure will be based on available prototype data. The extent of such a verification procedure will be dependent upon the type and quality of available prototype data which will be defined in task a. In order to utilize numerical models in predicting the effects of a jetport

structure on the wind-driven mass circulation and storm surge in Lake Erie near Cleveland, an extensive verification of such models is required to gain confidence in their results.

10. Task e, the preliminary design of necessary hydraulic models, includes consideration of mass circulation, breakwater stability, wave action, and longshore sediment transport hydraulic models. Model-to-prototype scaling relationships and the feasibility of applying data from each type of model to prototype conditions in Lake Erie are to be presented. Model scales, distortion factors, and boundary limits of specific models cannot readily be determined until the selection by LERTA of a site in Lake Erie and an initial size for the jetport island and the associated facilities. However, physical modeling procedures will be discussed in view of specific application to the jetport study. Based on the current information of the configuration for the jetport complex, typical model layouts for recommended models will be presented.

11. Accomplishment of these five tasks will complete the initial investigation by WES of (a) the synthesis of available data on the hydrodynamics of Lake Erie in the vicinity of Cleveland and (b) a feasibility study of various physical, analytical, and one or more numerical modeling procedures for estimating the effects of a jetport complex on the lake hydrodynamics.

PART II: REVIEW OF AVAILABLE DATA

Introduction

12. The literature survey summarizes data obtained from published reports, Government agencies, private organizations, and individuals relevant to preliminary design of physical hydraulic models and to the evaluation and application of analytical and/or numerical models to the hydraulics of Lake Erie. This survey includes data on Lake Erie geology, climate, lake bottom and shore characteristics, water balance, water temperature, lake levels, lake currents, waves, general features of erosion problems, and water quality. An extensive review of the physical, chemical, and biological characteristics of the entire lake is given in reference 1.

Lake Description

Location and geometric characteristics

13. Lake Erie is the fourth largest in surface area of the five Great Lakes and is a portion of the boundary between the United States and Canada. As shown in the vicinity map in fig. 1, the long axis of the lake has a northeasterly orientation. The lake is the shallowest of the Great Lakes and has about 2 percent of the total Great Lakes storage capacity.

14. The lake is naturally divided into three basins by its bottom topography. The relatively small, shallow western basin is separated from the deeper central basin by the island chain between Pelee Point, Ontario, and Sandusky, Ohio. The central and eastern basins are separated by a ridge about 40 ft under water running from Long Point, Ontario, to Erie, Pennsylvania. The ridge is cut by a channel with depths up to 60 ft just offshore from Pennsylvania. The volume, area, mean and maximum depths, and dimensions of the three basins are shown in table 1 (from reference 2).

Geology

15. The glacial history of Lake Erie, southernmost and oldest of

Fig. 1. Lake Erie vicinity map

the Great Lakes, is described in detail in reference 3 and summarized in reference 1. The bedrock nearest the lake surface is composed of shales, limestone, and some sandstone. The islands and headlands along the shore of the western basin are remnants of resistant shales. The southern Ohio shore is generally underlain by the resistant shales capped by sandstone. At Cleveland, the bedrock is generally 200 to 250 ft below the lake bottom.[4]

16. The drainage area, shown in fig. 2 (from reference 1), lies principally in Ohio, southeastern Michigan, and Ontario, Canada. Except for the area east of Cleveland, the drainage area is relatively flat, broken only by occasional ancient beach ridges and relatively steep valley walls in many of the major tributaries. Generally, soils in the flat portion are relatively impervious clays and silt.

17. East of Cleveland, the drainage area is relatively flat along the shoreline; but approximately 5 miles inland, the flat section is separated from the Appalachian uplands by a 200- to 300-ft rise in

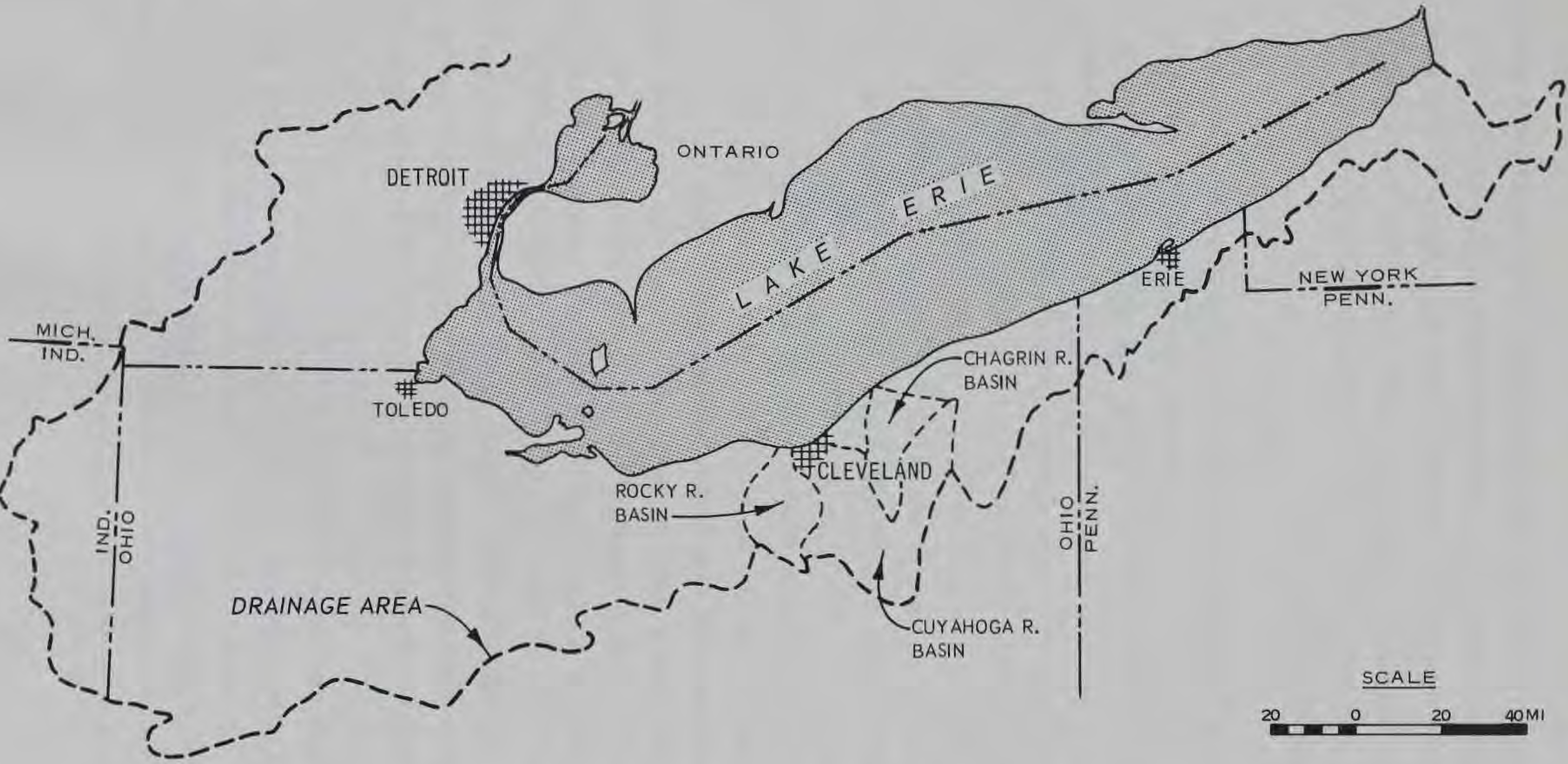


Fig. 2. Lake Erie drainage area (from reference 1)

elevation known as the Portage Escarpment. The escarpment parallels the lake shoreline in this area but turns south at Cleveland.

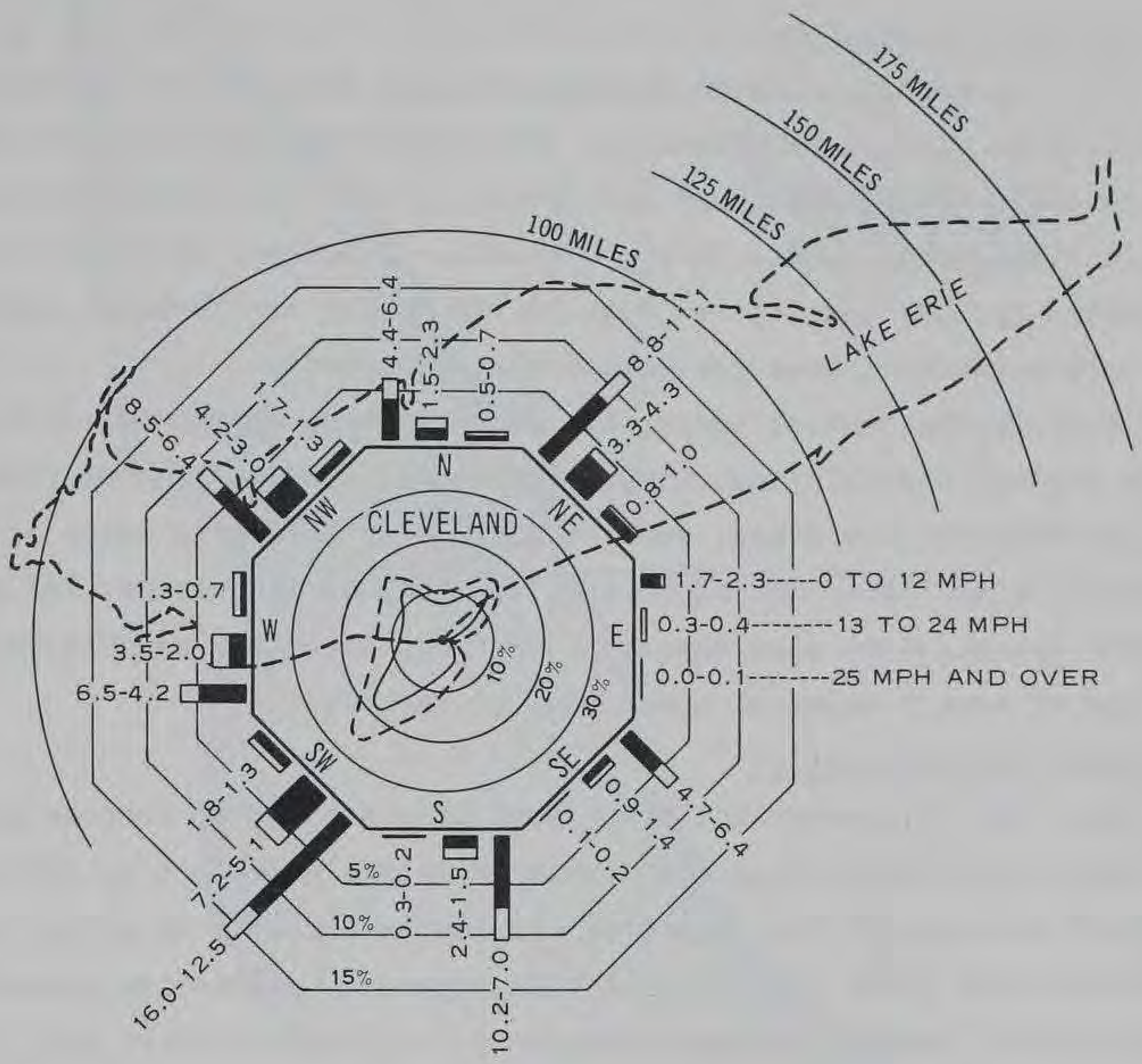
18. The rivers and streams in the drainage area are generally low-gradient and carry large silt loads due to the easily erodible clay flatlands. The tributaries east of Cleveland draining from the uplands carry reduced silt loads.

Climate

19. The climate of the Lake Erie drainage area, discussed in detail in reference 1, is usually controlled by warm, moist air from the Gulf of Mexico in the spring, summer, and fall. Precipitation results when the moist air and the cold air of high-pressure systems from the west and northwest mix. The weather pattern during this period usually occurs in cycles of a few days and is accompanied by south-to-southwest winds that persist for long periods. In the winter the weather is dominated by cold air masses from Canada pushing southeastward. Precipitation, normally snow, is heavier in the southeastern section of the drainage area.

20. Wind records gathered by the Cleveland Coast Guard Station have been compiled by the U. S. Army Engineer District, Buffalo (NCB), and the resulting data are presented in Fig. 3. The percent of total duration is shown for each of three velocity groups in each direction. The center of the wind diagram shows the wind movement for each direction in percent of total. Wind movement is a function of both velocity and duration. The diagram indicates that the duration of the higher velocities (25 mph and over) ranges between 0.5 and 1.3 percent of the total duration over the ice-free year from the northeast through north to the southwest. The northwesterly high velocity winds occur most frequently in the fall and winter. Northeasterly high velocity winds occur most frequently during the spring.

21. The average annual precipitation over the entire drainage basin is 34 in., and at Cleveland the annual average is 35.35 in. The average monthly precipitation at Cleveland, shown in table 2 (from reference 5), reaches a maximum during May. The average monthly minimum and maximum temperatures are also shown in table 2.



LEGEND

INDICATES DURATION FOR ICE-FREE PERIOD (MAR-DEC) IN PERCENT OF TOTAL DURATION

INDICATES DURATION FOR ICE PERIOD (JAN-FEB) IN PERCENT OF TOTAL DURATION

INDICATES PERCENT OF TOTAL WIND MOVEMENT OCCURRING DURING ICE-FREE PERIOD

INDICATES PERCENT OF TOTAL WIND MOVEMENT OCCURRING DURING COMBINED ICE AND ICE-FREE PERIODS

NOTE: FIGURES AT ENDS OF BARS INDICATE PERCENT OF TOTAL WIND DURATION FOR ICE-FREE PERIOD AND COMBINED ICE-FREE AND ICE PERIODS, RESPECTIVELY.

WIND DATA BASED ON RECORDS OF THE U.S. COAST GUARD AT CLEVELAND HARBOR, OHIO, FOR PERIOD 1 JAN 1936 TO 31 DEC 1971.

Fig. 3. Wind diagram for Cleveland, Ohio

Lake Bottom and Shore Characteristics

Lake bottom sedimentation

22. In general, bottom deposits in Lake Erie are of two types as shown in fig. 4 (from reference 1). The relatively flat sections of the western and central basins and the deeper part of the eastern basin are covered with recent, soft, silty, clay mud. Ridge-top sections between the basins and the lake bottom near the shoreline are normally overlain with sand containing some gravel and shell fragments.

23. In the central basin, the mud thickness approaches 20 to 25 m in the center[1] and thins out toward the shore. The mud in the central basin is underlain by dense, reddish-gray, clay till or glacio-lacustrine clay. Near the shoreline, the till or lacustrine clay is overlain by nearshore sand deposits. Between Cleveland and Fairport, the sand extends 5 miles or more out into the lake.

Lake shore characteristics

24. The Ohio shoreline from Vermilion eastward to Ashtabula is approximately 90 miles long and varies in elevation from 5 to 60 ft. The bluff sections of the shoreline are composed mostly of either a relatively soft shale or a glacial till topped by lacustrine deposits of sand or silt. Except for approximately 2.5 miles near Vermilion, the soft shale first appears about 4 miles east of Lorain Harbor and gradually rises to about 50 ft east of Avon Point. The shale dips below the lake level 1.5 miles east of the west Cuyahoga County line and reappears east of Porters Creek (Bay Village). The remaining shoreline to Edgewater Park at Cleveland is shale except for a 1-mile section at the Rocky River mouth. East of Cleveland, the only shale outcropping is at the east Cuyahoga County line and is approximately 1 mile long. The shales are not highly resistant to erosion but do erode more slowly than the glacial till.

25. The glacial till at lake level east of Vermilion to the first shale outcropping is a boulder clay that averages only 12 percent coarser than the 0.25-mm (No. 60) sieve and 19 percent coarser than the 0.074-mm (No. 200) sieve. The only major river in this section, the

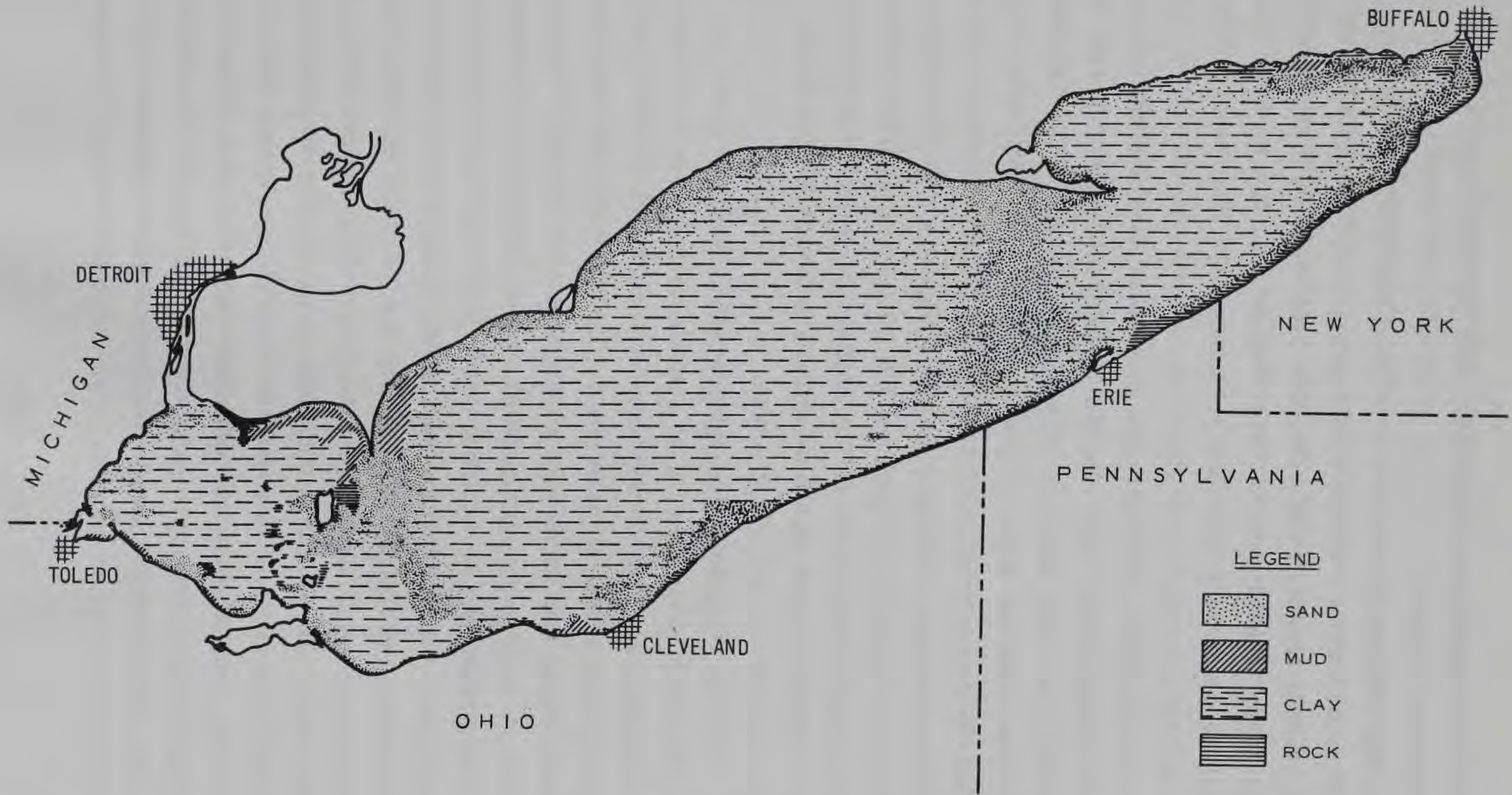


Fig. 4. Lake Erie bottom deposits (from reference 1)

Black, has been dredged for navigation, and the river sand settles out in the navigation channel.

26. Between Avon Point and Cleveland, the bluff sections not composed of shale (about 2 miles total) are lacustrine deposits which average 23 percent sand and the remainder silt and clay. The Rocky River is the only large stream in this section and, due to its flat gradient in the lower reaches, does not contribute much sand to the shoreline.

27. At Cleveland the bluff material is an easily erodible glacial deposit of compacted blue clay overlain by a loosely consolidated silt and clay. The blue clay averages 48 percent retained on a 0.149-mm (No. 100) sieve, and the upper stratum averages 2 to 10 percent retained on the 0.149-mm (No. 100) sieve. The upper limit of the blue clay is 8 ft above the low water datum, and it extends 60 ft or more below the low water datum. Dredging records by NCB indicate that most of the sand from the Cuyahoga is deposited in the navigation channel before reaching the harbor. Other streams at Cleveland are too small to carry any significant amounts of sand to the lake.

28. East of the last shale section along the Ohio shore to Fairport, the bluff material is blue boulder clay fairly resistant to erosion. Samples from four locations along the bluff in this section had an average of 27 percent retained on the 0.105-mm (No. 140) sieve. Some sand for beach nourishment is supplied by the Chagrin River in this section, but it is only a small portion of the total littoral drift.

29. From Fairport to Ashtabula, the bluffs are composed of boulder clay overlain by gravel, sand, silt, clay, or combinations of these materials. The boulder clay in the middle third of this reach is generally only 1 to 3 ft above lake level, exposing the strata above the boulder clay to wave attack. Samples from all the strata show that an average of 29 percent of the material is retained on a 0.074-mm (No. 200) sieve, but that the amount retained varies from 7 to 88 percent, depending on the composition of the bluff. The two rivers in this section, the Grand and the Ashtabula, have been improved for navigation, and dredge samples indicate that sediment reaching the lake is

composed of fine silts and clays. Other streams between Fairport and Ashtabula are smaller and contribute only a little sediment.

30. Beaches between Vermilion and Avon Point are typically small and impounded by groins or other types of shore structure. East of Lorain tc Cleveland, beaches, which are narrow during periods of high water, are found in front of the lacustrine (nonshale) bluffs. Generally, beaches are not formed in front of the bluffs unless impounded by groins. At Cleveland, beaches are typically short and are found in shoreline indentions or trapped by groins. East of the Chagrin River, beaches are typically narrow and are not found continuously along the shoreline although several long natural beaches have been formed between Fairport and Ashtabula. Beaches have also been formed at all major shoreline structures and breakwaters. The sand in all the beaches varies widely in median grain size but contains no more than 2 to 5 percent sand by weight finer than a 0.064-mm (No. 200) sieve. The bluff samples from the glacial till sections show that only 20 to 30 percent of the bluff material could be used for beach nourishment.

Lake Water Supply and Discharge

31. Inflow to Lake Erie is principally from Lake Huron through the St. Clair and Detroit Rivers. The Detroit inflow is approximately 80 percent of the total water supply to the lake and averages 187,450 cfs. Lowest flows usually occur in February and average 159,000 cfs. The highest flows, normally in July or August, average 199,000 cfs.

32. The remaining inflow is due mainly to precipitation over the lake and tributary runoff from the draining area. Ground water effects on the inflow are normally considered negligible for a lake. Water balance calculations[1] show that precipitation over the lake contributes 9 percent and runoff, 11 percent, of the remaining inflow. The water balance calculations also show that the lake outflow averages 202,776 cfs (86 percent) through the Niagara River, 7,000 cfs (3 percent) diverted to the Welland Canal, and 25,200 cfs (11 percent) lost by evaporation.

33. The tributary inflow to the central basin is 2.73 percent of the total lake inflow. The significant tributaries in the central basin near Cleveland are the Cuyahoga, Rocky, and Chagrin Rivers. Average flow in the Cuyahoga River is 801 cfs; in the Rocky River, 250 cfs; and in the Chagrin River, 313 cfs. Flood discharge recurrence intervals for the three rivers have been determined by the State of Ohio Department of Natural Resources[6] and are shown in figs. 5, 6, and 7. The percent of time a discharge was equalled or exceeded was also determined and is shown in table 3.

Water Temperatures

34. The surface water temperatures normally vary with lake depth and the surface air temperature. The surface temperature is cooler over the deeper lake depths except in the fall and early winter. During this period, the surface water loses heat to the atmosphere and the deeper lake sections can maintain a higher surface temperature.

35. During the winter ice season, approximately 1 January to 1 April, the central basin temperature is nearly constant at 33 F. The temperature gradually rises in the spring with frequent, small, sharp increases. A stable thermocline is normally formed near the first of June and disappears again by the last of September. Secondary thermoclines may develop to a depth of 20 to 23 ft during this period due to changes in air temperature, but these thermoclines will be destroyed several times by summer storms in June and July. In August the epilimnion begins to cool and the primary thermocline density gradient begins to decrease. The formation and disappearance of the thermocline in the central basin are shown in fig. 8.[1] Typical temperatures are also shown. Measurements made in the summer of 1970[7] indicate that the hypolimnion water started approximately 10 miles offshore at Cleveland and that the thermocline was approximately 46 ft deep at its highest point during August.

36. The thermocline will normally have a slight tilt to north with an average surface elevation difference of approximately 6.5 ft[7] in

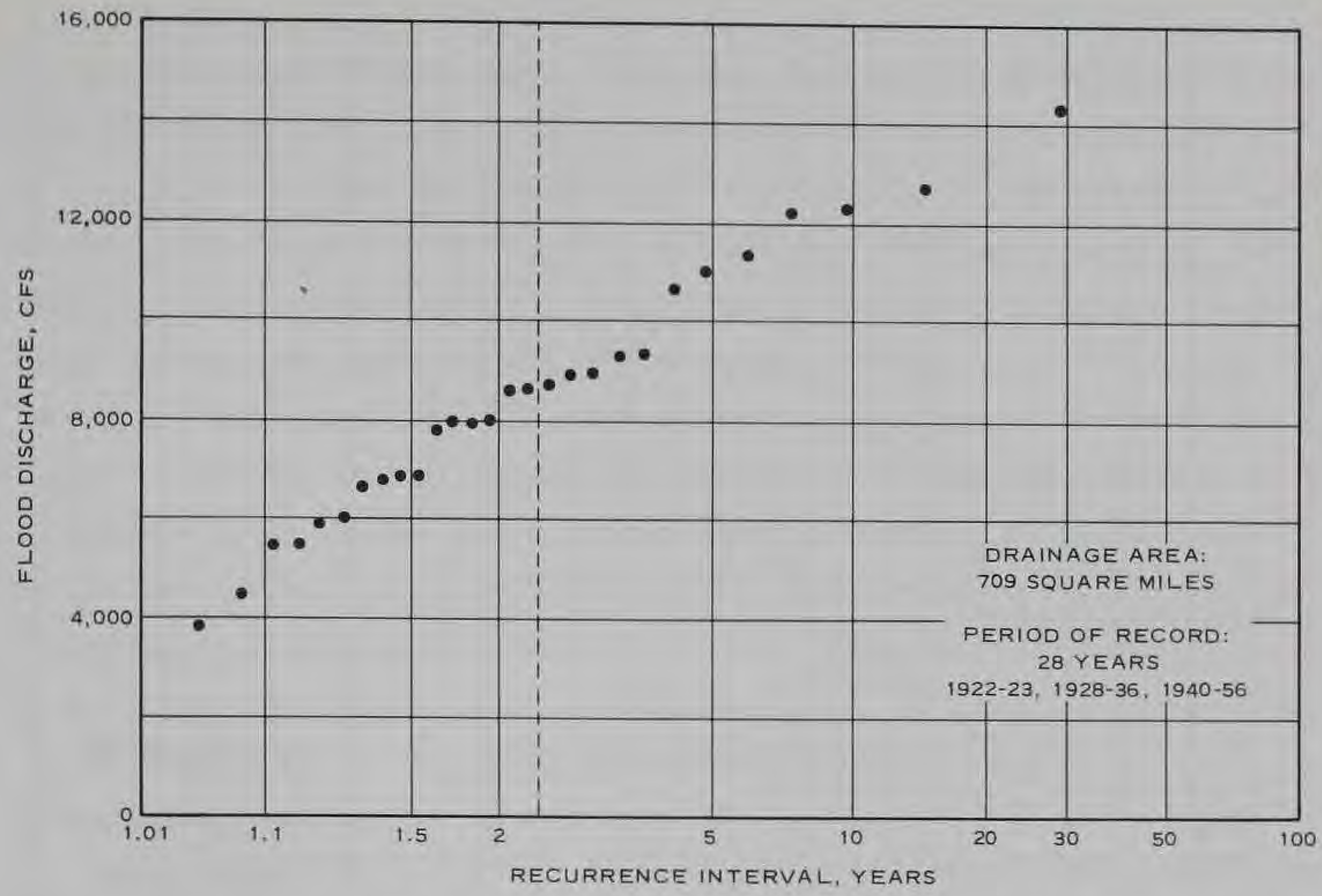


Fig. 5. Flood discharge recurrence interval for the Cuyahoga River at Independence (from reference 6)

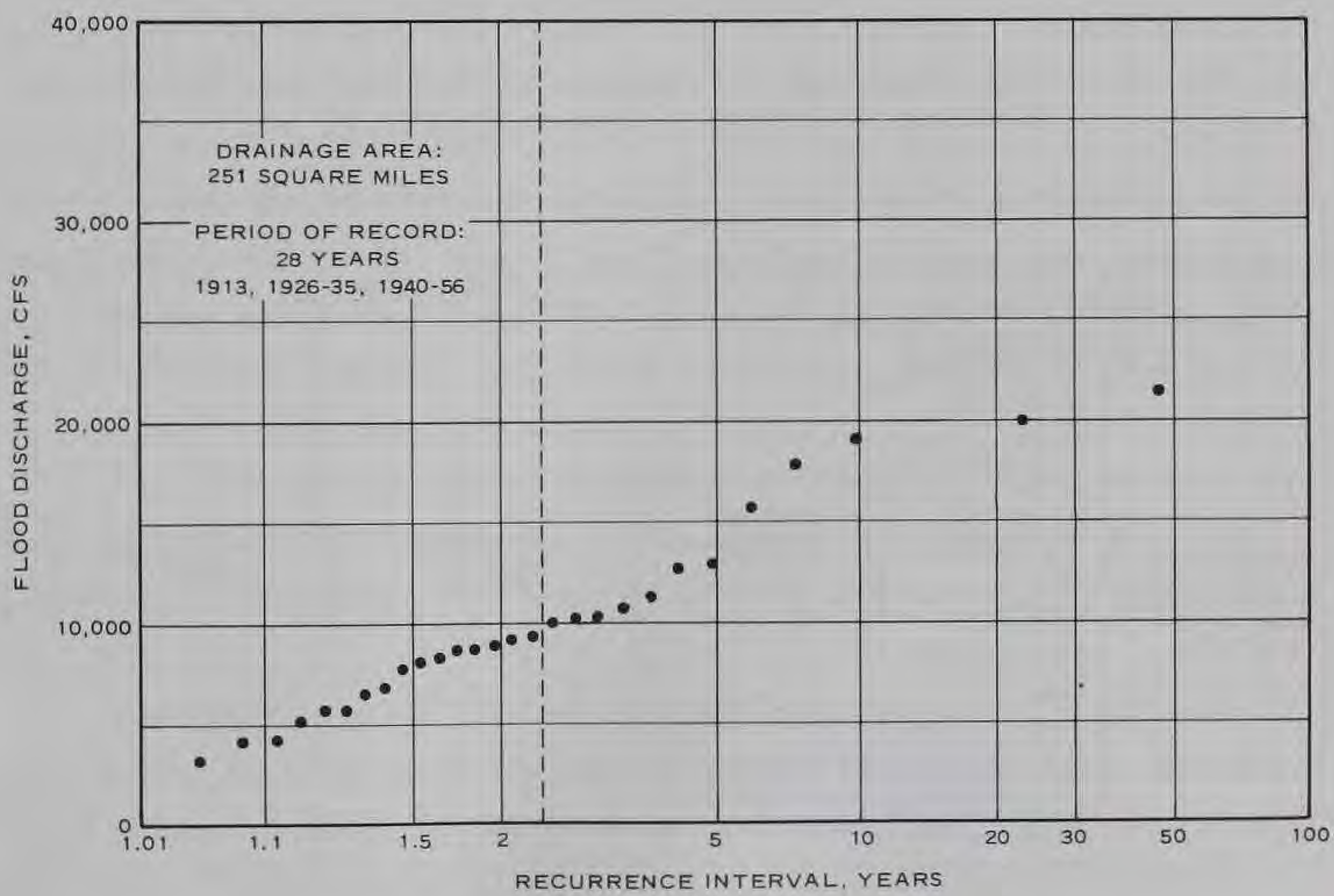


Fig. 6. Flood discharge recurrence interval for the Rocky River at Berea (from reference 6)

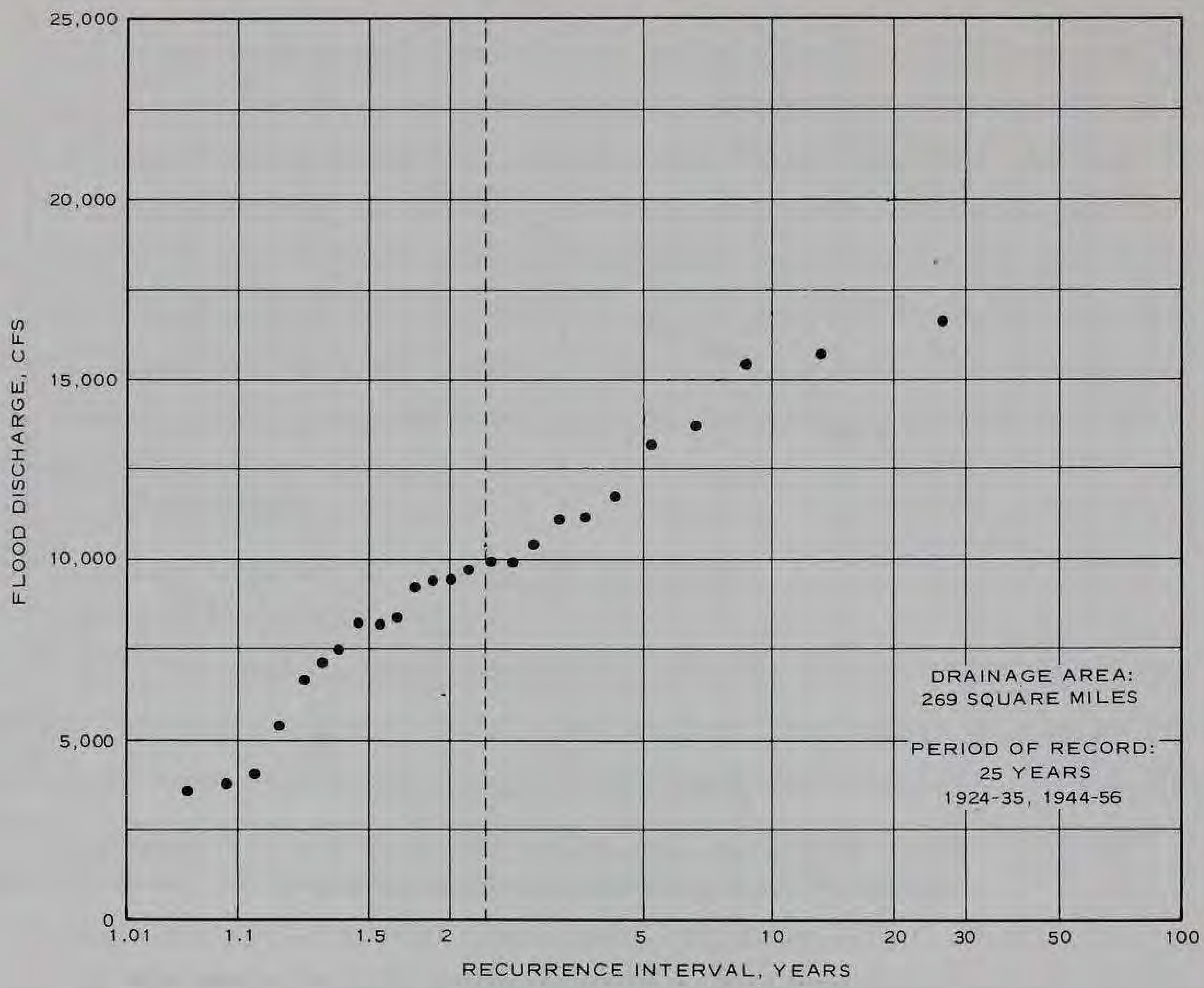


Fig. 7. Flood discharge recurrence interval for the Chagrin River at Willoughby (from reference 6)

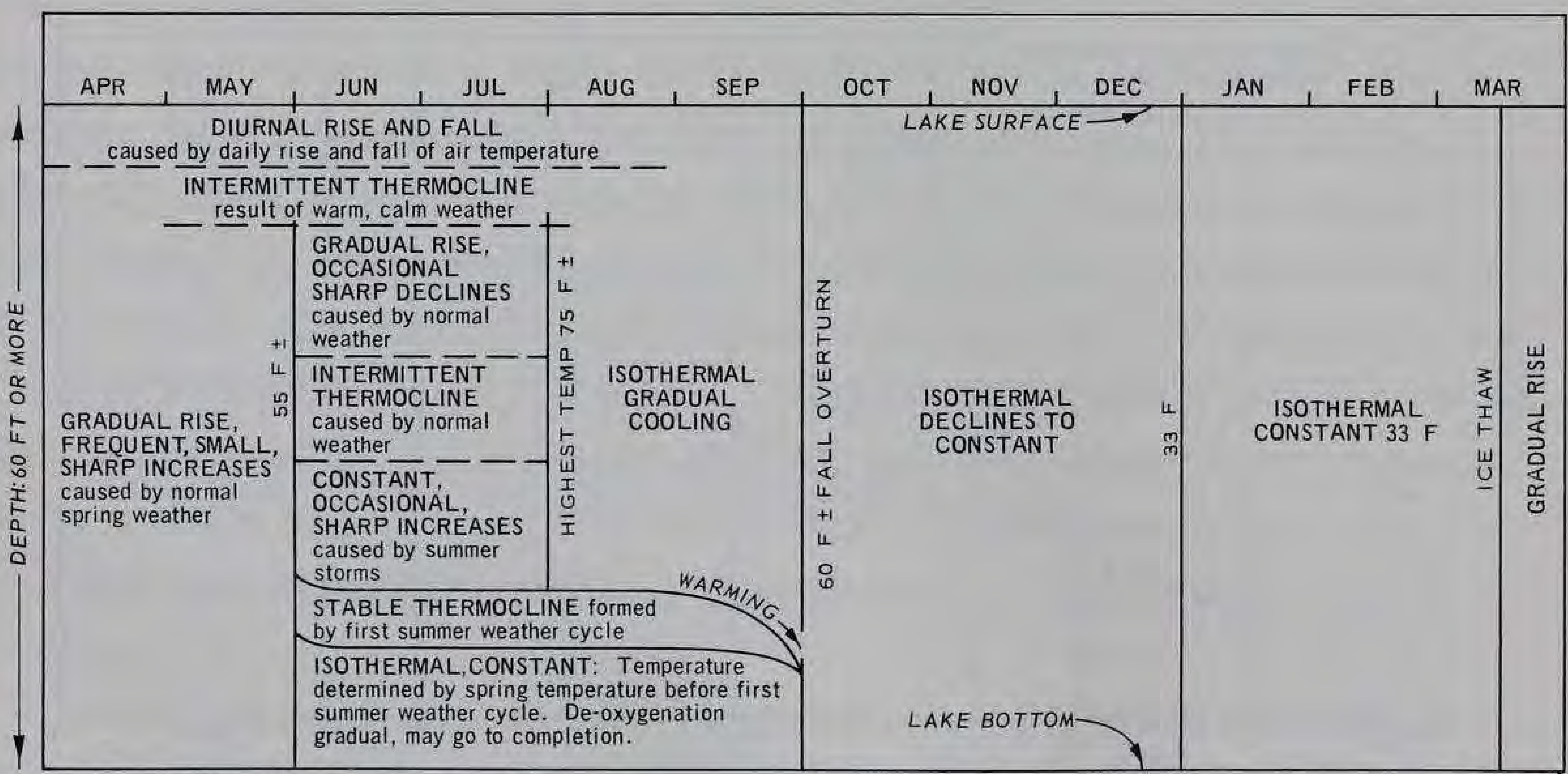


Fig. 8. Annual temperature development of the central basin of Lake Erie (from reference 1)

the central basin of Lake Erie. However, summer storms can create upwelling, downwelling, and internal waves at the thermocline and shift the hypolimnion slope and water mass. The period of the internal waves varies; but a period of about 17 hr, near the inertial period of the lake, is observed most often. Upwelling of hypolimnion waters is observed during the summer along the northern shore.

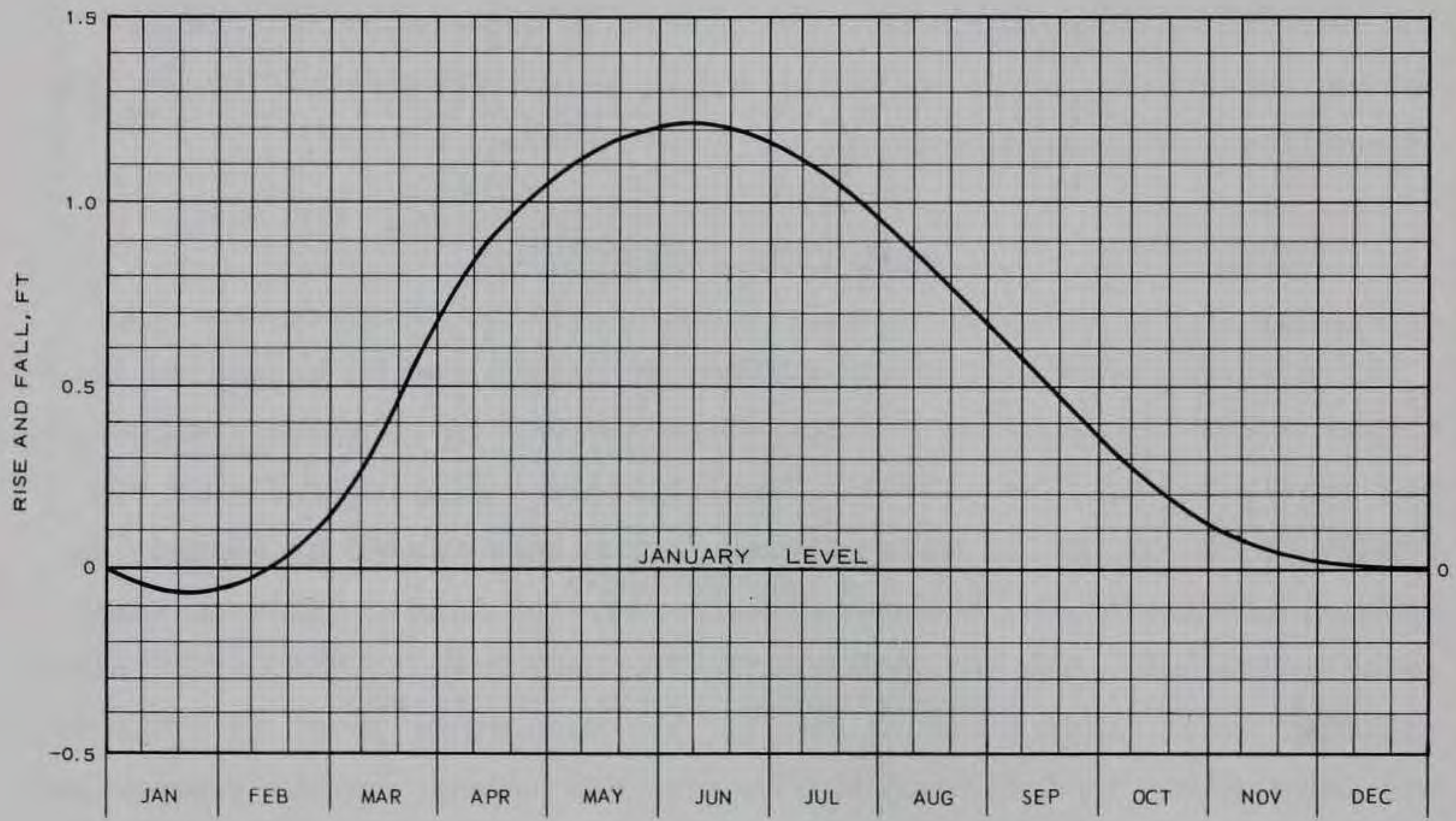
37. The nearshore surface temperatures along the southern shoreline are normally warmer during the spring and summer for several kilometers out into the lake. The effect is especially noticeable during the spring and is probably due to warm tributary inflow and the prevailing southwesterly winds.

Lake Level Fluctuations

38. The Lake Erie water surface variation can be separated into short-period fluctuations and long-term changes in monthly, seasonal, and yearly average lake level. The long-term variation reflects the change in the volume of water stored in the lake caused by changes in inflow, precipitation, and evaporation over the lake. Based on past water level data, the low-water datum for Lake Erie is 568.6 ft (International Great Lakes Datum of 1955). The mean water level is 570.4 ft, and the maximum variation of the highest and lowest monthly average between 1860 and 1951 was 5.17 ft. The monthly average lake levels in the past several years have exceeded the record set between 1860 and 1951, and the maximum recorded difference in monthly lake level averages is increasing.

39. The average annual variation of monthly lake levels is 1.6 ft. The average monthly lake level is usually at a maximum in June and at a minimum in February. The average monthly fluctuation is shown in fig. 9.[8]

40. Short-period changes in lake level occur daily and even hourly, due to wind setup (seiche) and gravitational tides. Gravitational tides, computed for Lake Erie by Endrös[9] and published in 1930, are small. Water level data analyzed by Platzman and Rao[9] show a



NOTE: FROM REPORT BY GREAT LAKES DIVISION ENGINEER DATED JUNE 1952

Fig. 9. Average seasonal fluctuation of Lake Erie (from reference 8)

semidiurnal tidal component of about 0.16 ft at Toledo. This compares closely with the 0.17-ft M2 (semidiurnal tidal component) found by Endrös for Amherstburg, Ontario. Platzman and Rao[9] also found a diurnal component in the water level data, but attributed this to a diurnal component in the atmospheric disturbance forces. In any case, Platzman and Rao state that tidal effects are, at most, an order of magnitude smaller than the effects of wind setup.

41. The seiche oscillations are standing waves which start when the wind subsides and can no longer maintain the wind setup. The phenomenon was first investigated in detail by Platzman and Rao[10] using one-dimensional channel equations. The effect of bottom friction was neglected, but the computed seiche periods were within 4 percent of the observed periods for the first four modes of oscillation. The predicted water surface profile agrees closely with the observed water surface profile for the first mode of oscillation, except at Port Clinton. However, the velocities predicted by the one-dimensional approach are not realistic because of the one-dimensional approximation.

42. A seiche analysis has also been published by Science Engineering Associates (SEA) using the two-dimensional channel equation[11]

$$\frac{\partial}{\partial x}\left(h\,\frac{\partial \eta}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\,\frac{\partial \eta}{\partial y}\right) + \frac{\sigma^2}{g}\,\eta = 0 \qquad (1)$$

where

$$\sigma = \left(\frac{2\Pi}{T}\right)$$

and

- h = local water depth
- η = surface elevation above mean water
- σ = wave frequency
- g = acceleration of gravity
- T = period of oscillation

for a horizontal x,y coordinate system. Friction and the earth's rotation are neglected in both the one- and two-dimensional approaches, but the velocities predicted from the two-dimensional results should be more realistic. Both the observed periods of the first five modes of oscillation and the computed periods using the one-dimensional and two-dimensional equations are shown in table 4.

43. The 20-yr period 1940-1959 was investigated by Irish and Platzman[12] for incidences of extreme wind setup. Seventy-six cases were found in which the Buffalo-minus-Toledo setup exceeded 6 ft. Three cases were also found in which the Toledo water level exceeded the Buffalo level by 6 to 8 ft, although these cases were not included in the analysis. The recurrence interval for wind setup is shown in fig. 10 (from reference 12). Table 5 (from reference 12) is a frequency

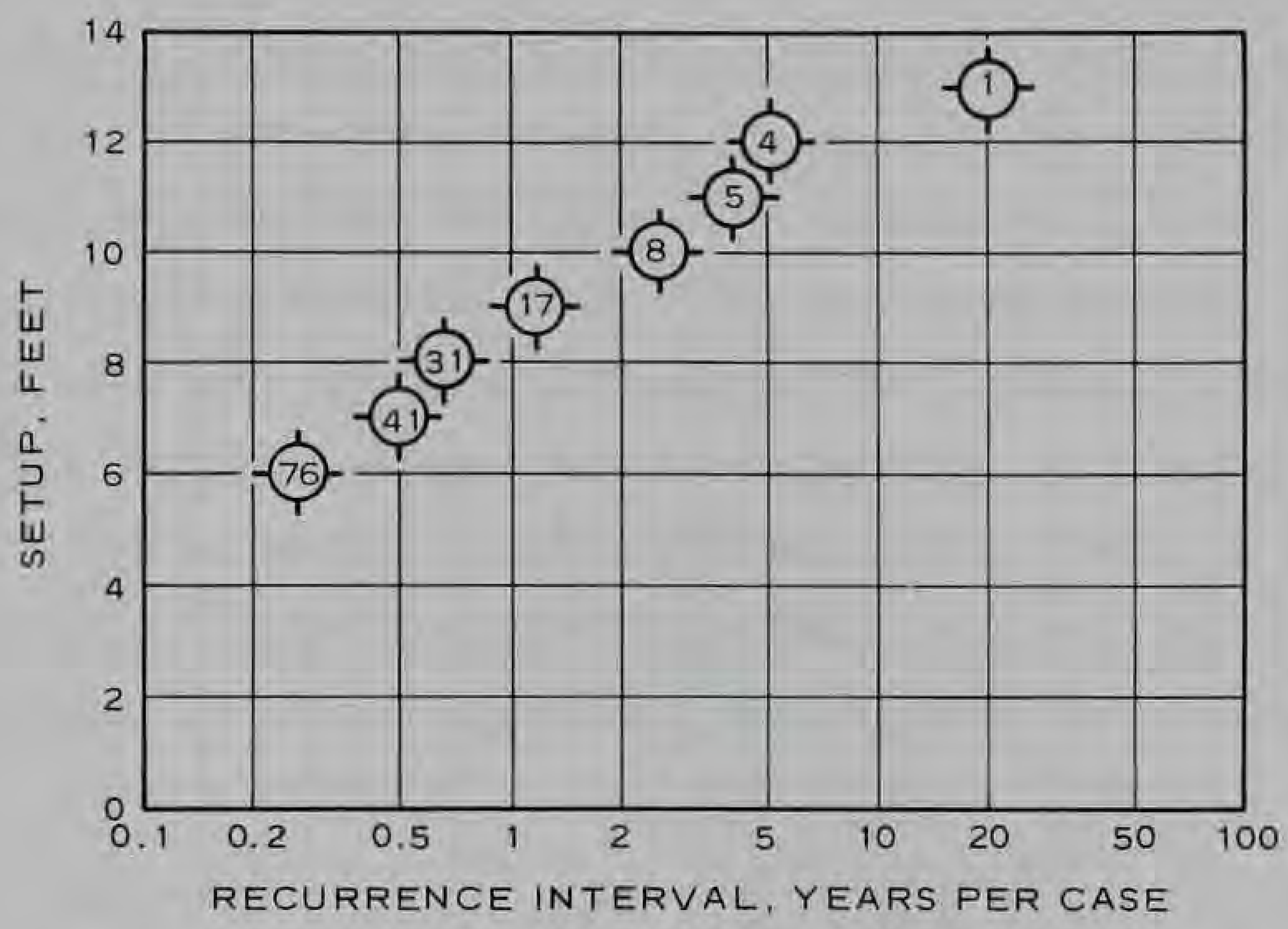


Fig. 10. Recurrence interval for Buffalo-minus-Toledo setup exceeding 6 ft. The circled numbers are the number of cases for which setup exceeded 6, 7, 8, 9, 10, 11, 12, and 13 ft from 1940 to 1959 (from reference 12)

distribution by months of the 76 cases. All cases occurred from September through April with the maximum number occurring in November. Differences in elevation between Buffalo and Toledo as high as 13.9 ft have been observed[13] during seiche oscillations.

44. Cleveland is near the nodal line of the first mode and does not have as large a variation in lake level as Buffalo or Toledo. The water level observed by Platzman and Rao at Cleveland for the first mode

is approximately 40 percent of the setup at Buffalo. However, the predicted levels by Platzman and Rao and SEA indicate that the fluctuation through the first five modes at Cleveland will range from 20 to 55 percent of the maximum seiche amplitude. The maximum amplitude may not occur at the east and west ends of the lake for oscillation modes other than the first mode. The interval in months expected between recurrence of a given short-period rise in the lake level has been analyzed by Saville[8] for Buffalo, Toledo, Gibralter, Put In Bay, and Cleveland. The expected fluctuation for any recurrence interval is lowest for Cleveland[8] as indicated in fig. 11 (from reference 8) with a maximum observed setup of 3.7 ft.[14]

Lake Currents

Types of lake currents

45. Circulation in lakes as large as Lake Erie involves the relatively slow motion of a large mass of water, and many physical forces that can be neglected when considering flow in a river or channel must be considered.[15] The velocity can no longer be considered unidirectional (averaged over the lake width) and is not as strongly dependent on the slope of the water surface. The currents usually have both a horizontal and small vertical component. The mass circulation will be affected by gravitational force, pressure gradients, the deflecting force of the earth's rotation (Coriolis force), and frictional forces. The resultant current at any location in the lake will be due to the wind-driven (drift) currents, seiching, density stratification, and inertial currents. The through-flow current component is too small to be detected away from inflow and discharge points. The wind-driven component (1-3 percent of the wind speed at the surface) will normally be the largest except during periods of relative calm and is the most variable with time. Dr. G. H. Keulegan* has estimated the average

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* G. H. Keulegan, "Patterns of Lake Current Velocities" (unpublished memorandum), Apr 1973.

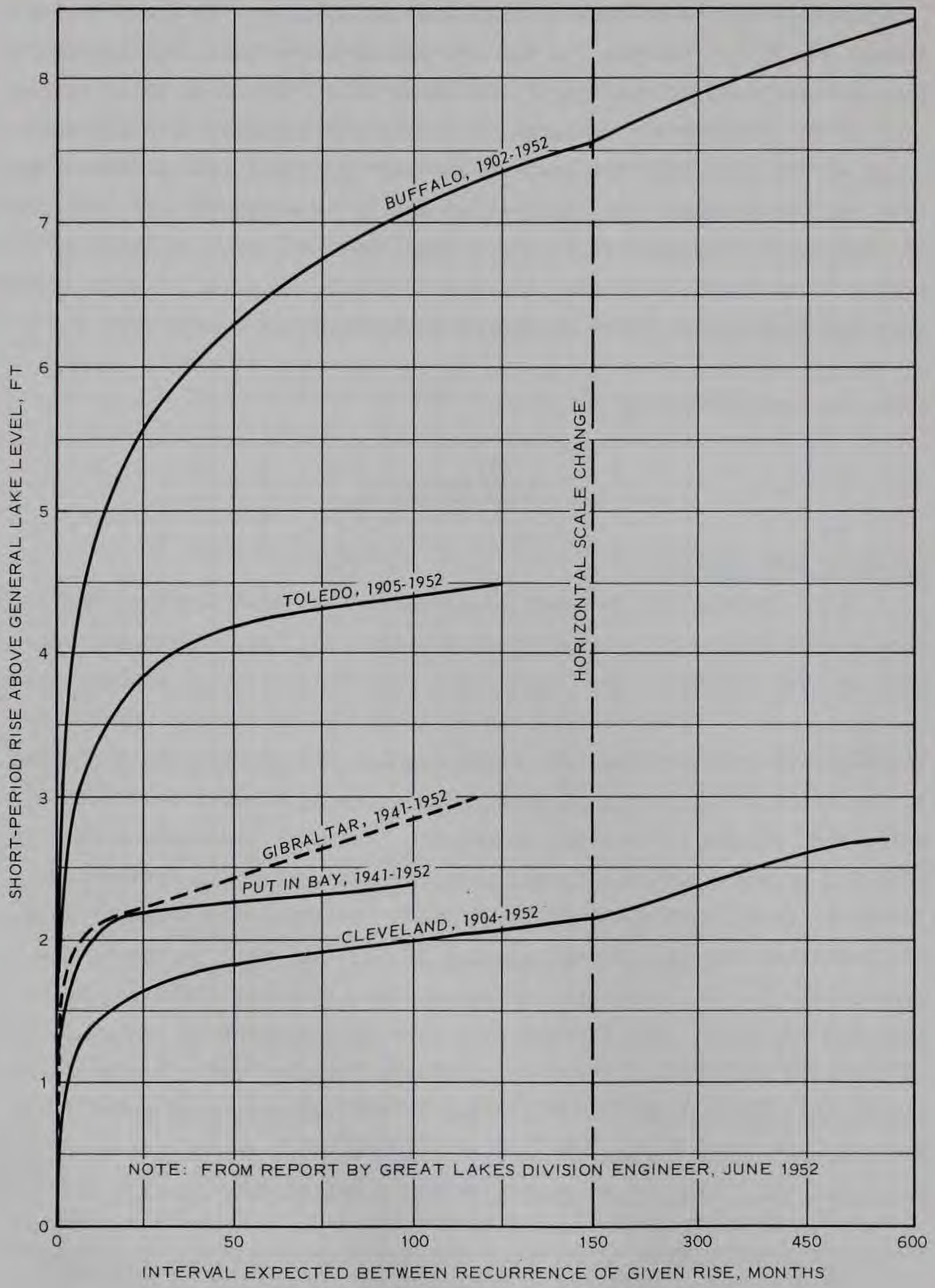

Fig. 11. Frequency of occurrence of short-period fluctuations on Lake Erie (from reference 8)

wind-driven current to be 11 percent of the surface current velocity. Waves are also generated by the wind, but net mass transport by wind waves is relatively small. Longshore currents inside the breaker zone are formed by the waves, particularly when the wave crest is not parallel to the shoreline. These currents can be of the same magnitude as the longshore currents outside the breaker zone,[16] but the net mass transport is rarely significant due to the shallowness of the water inside the breaker zone.

46. Seiche currents decay with time due to frictional effects but rarely disappear entirely. The maximum seiche currents occur normal to nodal lines or in constrictions such as the inter-island region between the central and western basins. In a study of ship damage at Conneaut Harbor in 1958,[13] seiche velocities outside the harbor of up to 1 fps were predicted for the first mode. SEA in its two-dimensional seiche analysis[11] shows maximum seiche currents (first mode) at Cleveland of approximately 0.08 fps for each foot of maximum surface displacement (amplitude) at Toledo.

47. Density currents normally occur when the water flowing into the lake is at a different density from the surrounding water. Temperature changes are the primary cause of the density gradients although dissolved or suspended solids may affect the stratification near tributary streams and at municipal or industrial outfalls.[17] Lake turnover in the spring and fall is the result of small-density currents due to density changes from gain or loss of heat at the surface.[1]

48. Inertial currents occur when the acceleration of the water is balanced by the Coriolis acceleration and the current changes direction, resulting in a circular current pattern. Lake Erie has an inertial period of 17.6 to 18.1. The inertial effect or right-hand acceleration of lake currents has been observed by Verber[17] in Lake Michigan. When the Coriolis acceleration is balanced by the pressure gradient, unidirectional flow can occur. Observations by Verber indicate that unidirectional flow is found more frequently in the winter than in the summer. Unidirectional flow was always observed by Verber within five-eighths mile of the shoreline or in constricted channels; however,

Verber concluded that local boundary conditions affected the flow in these regions.

49. Inflow to Lake Erie from the Detroit River is the only inflow of sufficient size to affect the lake current patterns away from the tributary mouth. Even the Detroit inflow is difficult to detect 8 miles from the mouth.[18]

50. The currents in a lake as large as Lake Erie also vary in magnitude and direction with depth. The surface currents are generated by the wind and are directed to the right of the wind. Mass transport due to the velocities in the surface layer can be much larger than the lake outflow, and a return-flow current must be formed. Due to the shallowness of Lake Erie, the return-flow velocities, although smaller than the surface velocities, are easily detected.

51. In the summer, the thermocline suppresses transfer of momentum into the hypolimnion, and the return flow is above the thermocline. Small currents are induced in the hypolimnion by the return flow but are normally of an order of magnitude less than currents in the epilimnion.[7] In a seiche oscillation, the slope of the thermocline is opposite to that of the lake surface and is larger in amplitude. The thermocline can even intersect the lake surface, exposing hypolimnion water. This upwelling of the hypolimnion water is a well-known feature of Lake Erie during the summer and usually occurs near the north shore east of Pelee Point.[7]

52. Lake currents in the nearshore boundary layer are strongly affected by the shoreline and bottom topography. The currents are generally parallel to the shoreline and have no return flow at the lower depths. The currents are also influenced in the spring and summer by temperature changes and lake stratification. As the lake warms in the spring, the water temperature near the shore rises above the temperature for maximum density (4 C) while the central lake water remains below 4 C. In extreme cases, a total change in surface water temperature of 5 to 7 C can occur within approximately 325 ft horizontally.[19] The phenomenon is known as a thermal bar, and the density of the bar inhibits the offshore flow of warm nearshore water. Lakes which form a

thermal bar in spring will also form a bar in fall as the lake cools. Due to the nearly uniform depth and temperature of the central basin in Lake Erie, the bar, if formed, will probably move rapidly offshore.[19]

53. Currents behind the thermal bar can be rapid and are known as coastal jets. A longshore current component of 1.2 fps has been observed in Lake Ontario, and these rapid currents have been correlated with antecedent winds over the lake.[20] However, the coastal jet has not been observed in Lake Erie, and some investigators doubt the formation of a coastal jet near Cleveland.*

54. In summary, lake currents are highly variable with time and are strongly influenced by the wind field. In the nearshore region, the currents are influenced by the nearshore boundary layer. Thermal stratification changes the circulation pattern in both the central lake and nearshore region. Correlation of offshore lake currents between two stations is difficult, even with stations located one-half mile apart and using 4-hr averages.[21]

Observed current patterns in the central basin

55. The mass circulation patterns in Lake Erie prior to the 1960's were investigated using drift cards, drift bottles, and shallow drogues. Only one study covered the circulation in the entire lake; the others concentrated principally on the western basin. The studies do not agree with one another and should be used with caution. The methods used in these studies to detect circulation patterns respond only to the surface currents which are highly dependent on the wind field. A review of these early studies may be found in references 22 and 23.

56. The Ohio Department of Natural Resources[22] conducted a water sampling survey of the western basin in June 1963, and additional measurements were made in May 1964. The wind speed over the basin was at a maximum of 10 mph and generally less than 5 mph. Turbidity, hydrogen ion concentration (pH), and conductivity were determined at

* R. A. Sweeney, personal communication, Sep 1973.

approximately 300 stations. Bathythermograph recordings were made at 76 stations. The authors concluded from the data that the major portion of the Detroit River discharge flows southward, perhaps as far as the Ohio shore, and that some water from the main channel and east side of the Detroit River flows eastward along the southern shore. Flow into the central basin was mainly through Pelee Passage with some return flow through the southern island region. The lake level changed approximately 0.25 ft at Sandusky the day of the survey, but had been relatively constant the previous day. This small fluctuation indicates that seiche currents and wind-driven currents should be small. The Detroit River inflow is the controlling effect on the observed circulation pattern, and the observed pattern should not be expected when other factors affect the currents.

57. The Federal Water Pollution Control Administration (FWPCA) conducted a current metering program in the central basin in 1964 and 1965 and reviewed the existing drifter data. The dominant surface circulation pattern in the central basin inferred from the data is shown in fig. 12 (from reference 1). The major central basin surface circulation pattern shown in the figure is the eastward flow of the surface water and a current along the southern shore. The Canadian Inland Waters Branch of the Department of Energy, Mines and Resources[23] has also published an average surface circulation pattern for the central basin indicating the eastward surface flow and the current along the southern shore. The main disagreement between the two flow patterns was along the northern shore of the central basin. Several of the conclusions of the Canadian study are quoted as follows:

- a. "Surface currents are typically erratic in time. Among other factors this variability is correlated with antecedent and actual winds."
- b. "The surface circulation derives a certain degree of permanence from the prevailing direction of the surface wind over the lake. The orientation of the basin with its longitudinal axis essentially parallel to the prevailing southwest winds, makes this effect especially important."
- c. "The resultant surface drift may be four times as rapid as the drift at intermediate depths."

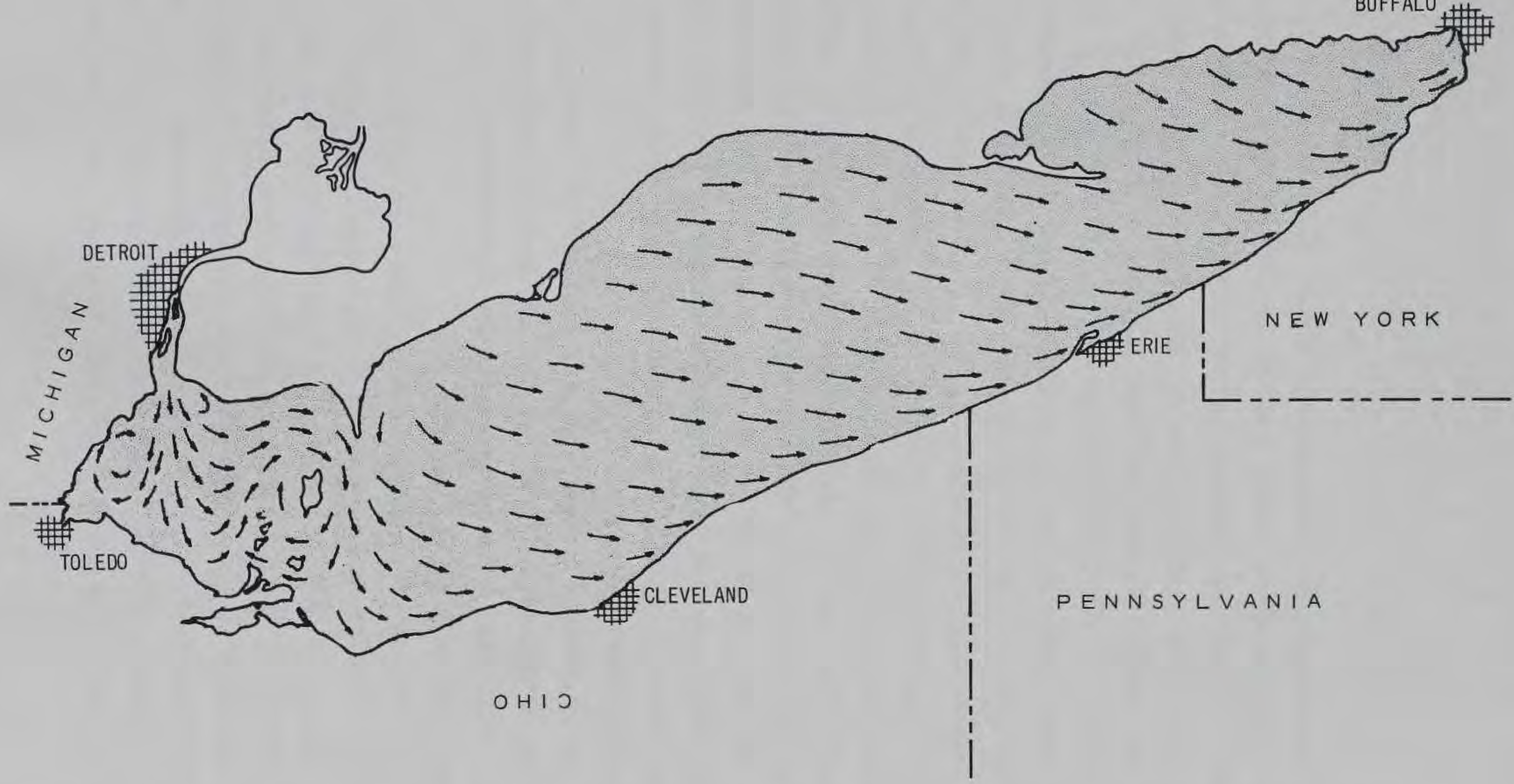

Fig. 12. Dominant summer surface flow pattern in Lake Erie, direction only (from reference 1)

d. "While nearly all of the experimental evidence is relevant to summer conditions, it is unlikely that the surface pattern or circulation is altered appreciably with season. The prevalence of north and northwest winds during winter months is expected to cause the surface currents to run in a more southerly direction in winter."

58. Currents at the intermediate depth, 33 to 50 ft, were also considered in the Canadian study, and the current pattern inferred from the FWPCA 1964-1965 current data is shown in fig. 13 (from reference 23). The current along the southern shore is again shown at this depth.

59. The 1964-1965 study by FWPCA included a study of the circulation within 8 in. of the lake bottom using seabed drifters.[24] Bottom current patterns inferred from the drifter returns in the Canadian study are shown in fig. 14 (from reference 23). FWPCA and the Canada Centre for Inland Waters conducted a joint study of the central basin again in July and August 1970. The net bottom (hypolimnion) currents observed during the period are shown in fig. 15 (from reference 23). The observed currents are in agreement with the circulation pattern shown in fig. 14, even though this pattern was not recorded in the 8-in. zone, and indicate a dominant bottom flow toward the Canadian shore. Currents were also measured in the epilimnion during the 1970 study, and the measured currents reflect the anticyclonic gyre shown in fig. 13 for the intermediate depth regime.

60. The observed currents indicate that the net average surface current is approximately 0.33 fps and the net average bottom velocity is approximately 0.02 fps. The currents can be considerably larger and have been measured as high as 3.23 fps.[7]

61. The only observed FWPCA current data near the Cleveland Harbor are from four stations, E-23 to E-26, operated as a part of the 1964-1965 program. All stations were in operation from mid-June to mid-July 1965, and two of the four were in operation from 8 Aug to 17 Sep 1965. The locations of these four stations and several stations more remote from Cleveland are shown in fig. 16 (from reference 1). Summaries of the observed current data for the four stations and for sta E-4, which operated during the entire 1964-1965 program, were provided by the

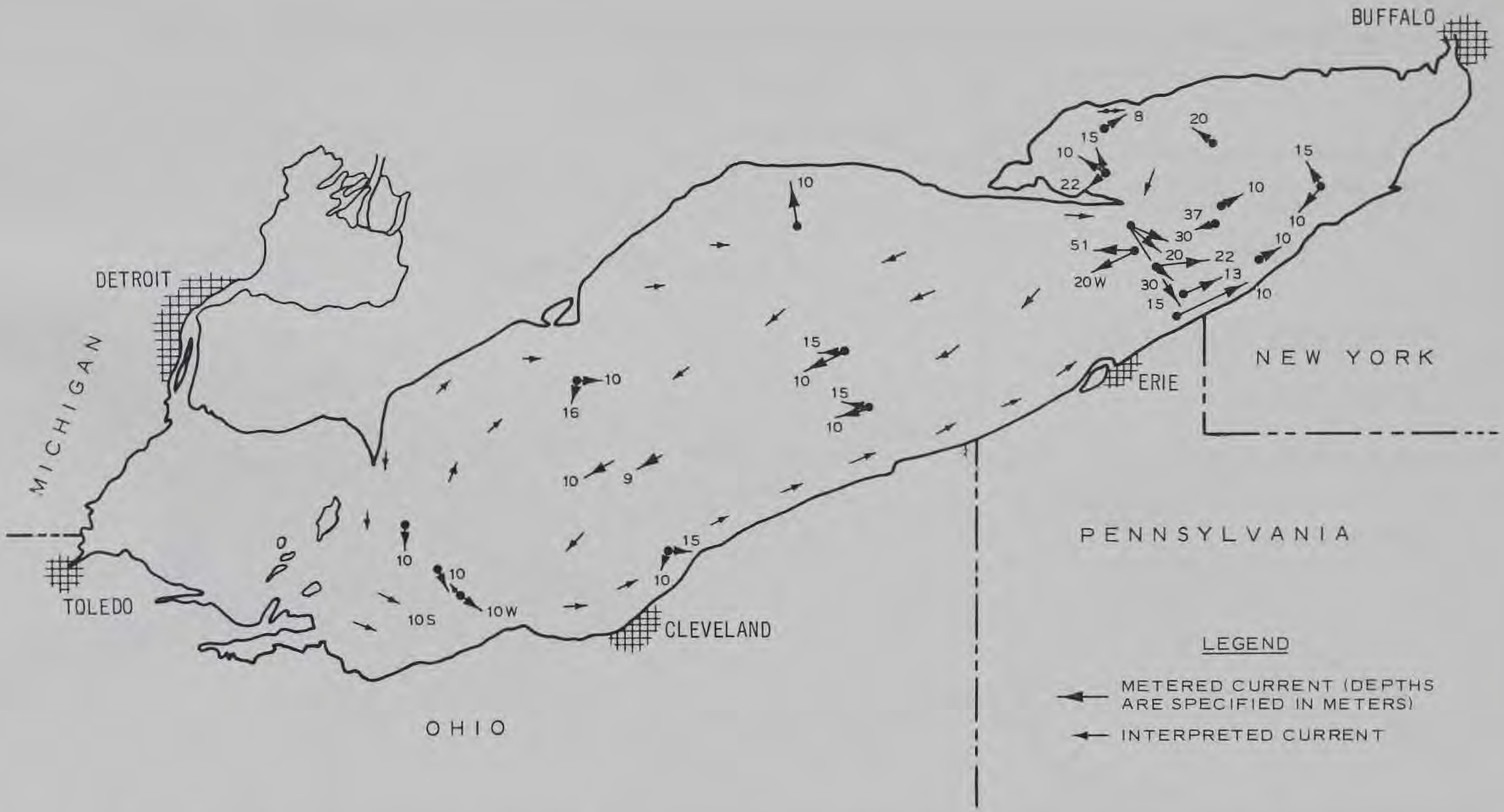

Fig. 13. The permanent circulation at intermediate depth in the central and eastern basins of Lake Erie (from Hamblin[23])

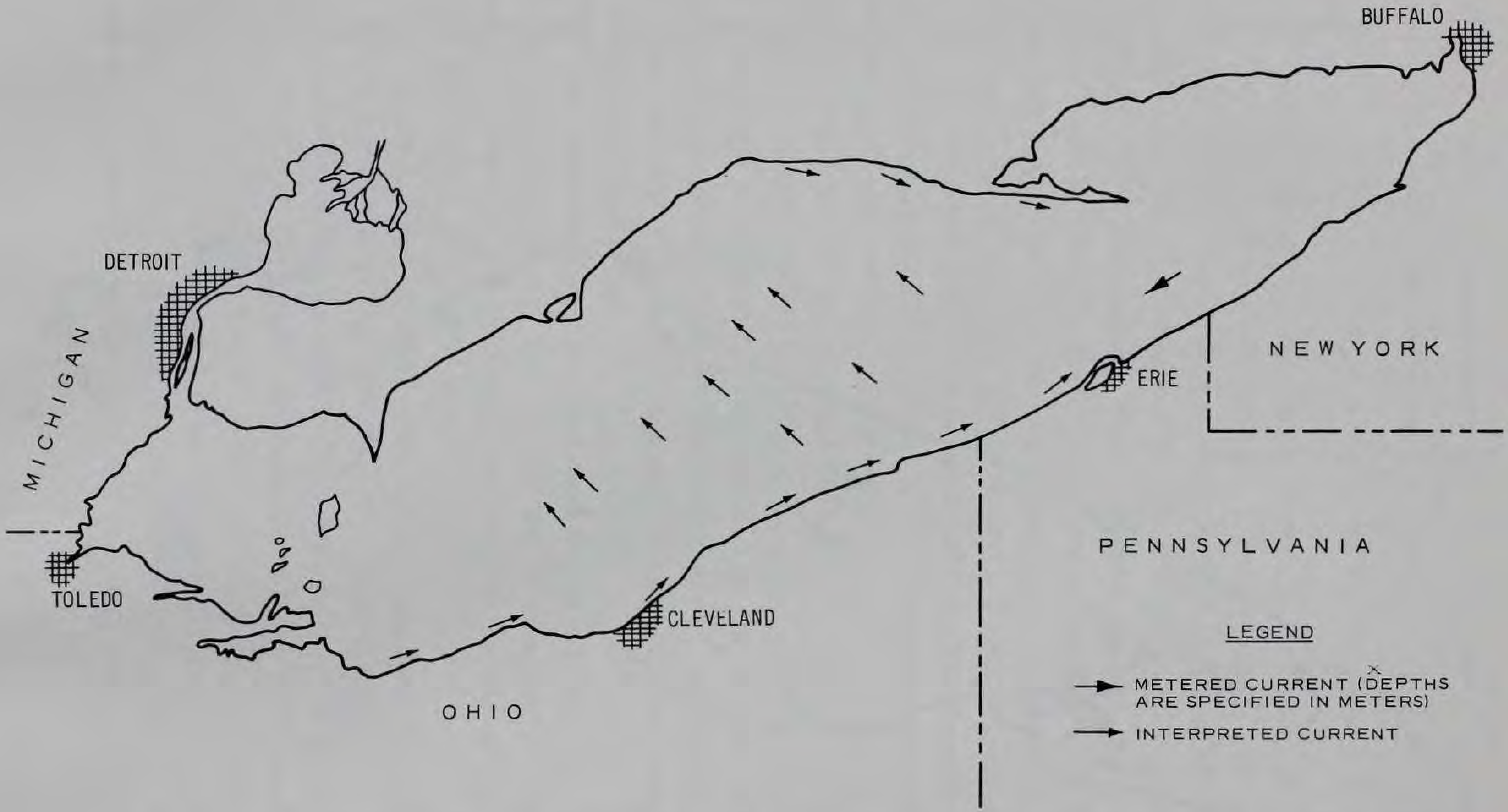

Fig. 14. The permanent bottom currents in the central basin of Lake Erie (from Hamblin[23])

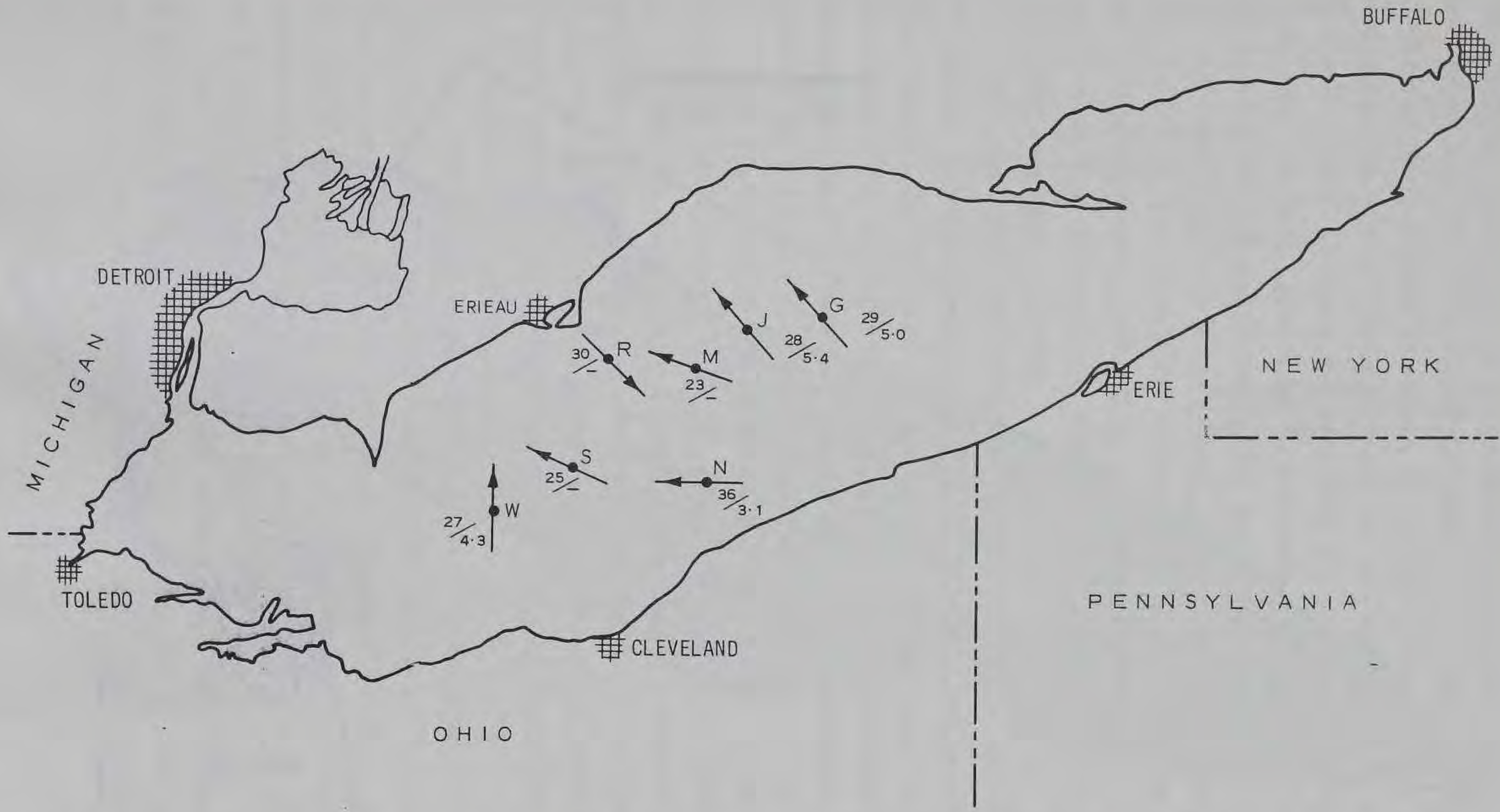

Fig. 15. Hypolimnion currents during the period 14 Jul-3 Sep 1970. The arrows represent the dominant direction toward which the currents were moving. The number to the left of the slash represents the percent of frequency of occurrence of all currents within 30 deg of either side of the dominant direction. The number after the slash is the average speed in cm/sec of the currents associated with the dominant direction (from Hamblin[23])

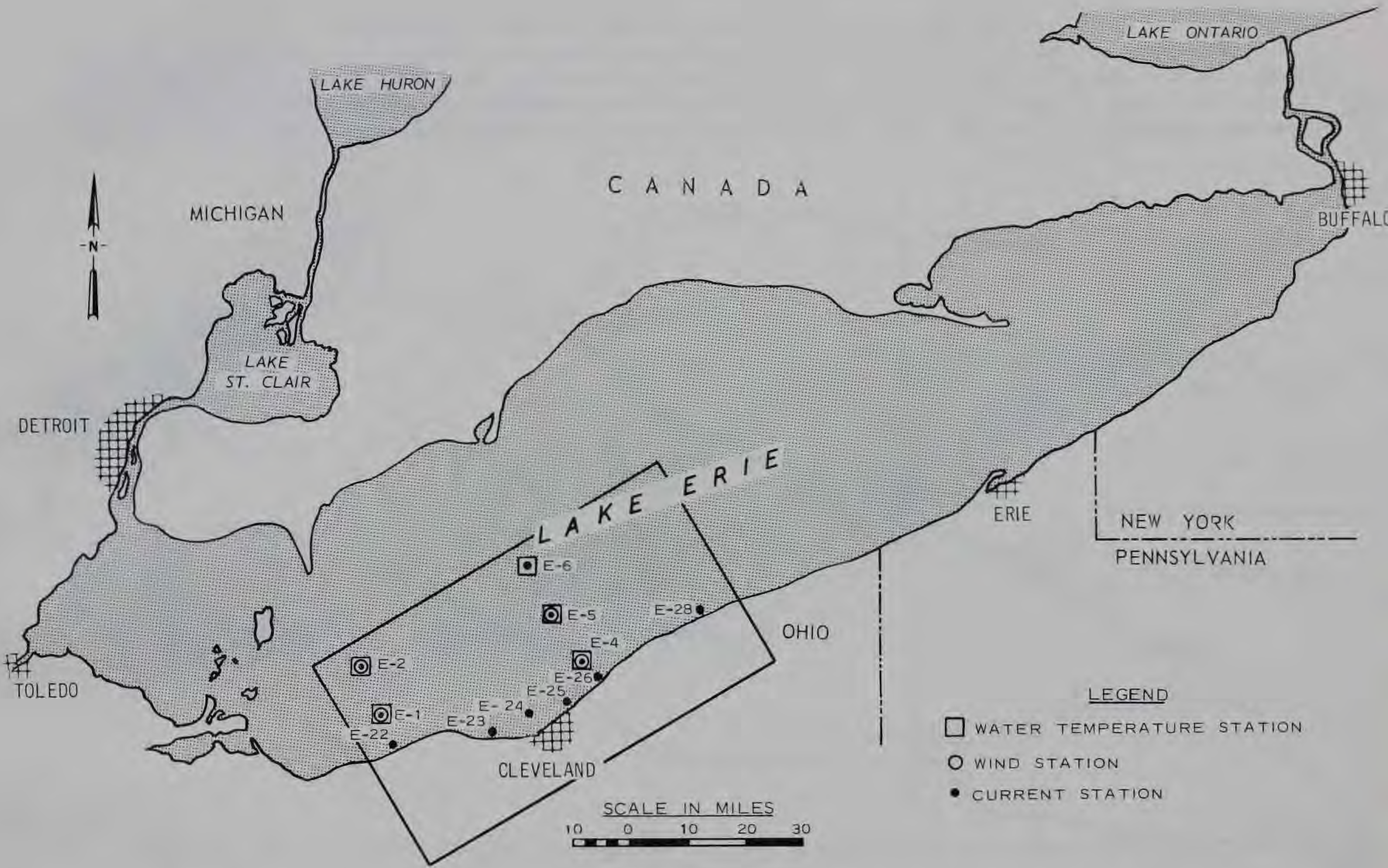

Fig. 16. Current, water temperature, and wind measurement stations in Lake Erie, near Cleveland, Ohio, 1964-1965 (from reference 1)

Ohio District Office of the Environmental Protection Agency (EPA). A few segments of the data appeared erratic (i.e., having a large number of current observations in excess of 1.5 fps) and were not used in developing the current direction and current speed distributions shown in figs. 17-34. Although the mass flow distributions for the four stations, E-23 to E-26, generally do not cover the same time intervals, are developed from relatively short time intervals, are at varying depths, and show some flow in all directions, they do indicate a predominant flow in one or two directions approximately parallel to the shoreline with the exception of E-24. Only one of the four stations, E-24, has usable data available for two depths, but the data for each depth do not cover the same time interval.

62. Mass flow distributions for sta E-4 at 10- and 15-m depths for August 1964 are shown in fig. 27. A flow distribution similar to those for sta E-23 to E-26 is observed at the two depths but with less pronounced flow approximately parallel to shore, particularly at the 15-m depth. Possibly the decrease in the predominant flow is due to the location of E-4 farther offshore than E-23 to E-26.

63. Mass flow and current speed distributions at sta E-4, 15-m depth, for fall, winter, and spring are shown in figs. 29-34. Again the predominant flow is approximately parallel to the shoreline with a considerable increase in the southwest flow at the 15-m depth during winter and spring. All the speed range distributions indicate that velocities are usually less than 12 cm/sec and that velocities in excess of 30 cm/sec occur infrequently.

64. Current observations[14] from July to December 1972 near Perry, Ohio, at stations located 1000 and 3500 ft offshore showed a bimodal flow approximately parallel to shore. The observed speed exceeded 0.5 fps during approximately 2 percent of the observation period. The current measurements were taken at a depth of about 18 ft on the 1000-ft tower and at 17 and 21 ft on the 3500-ft tower.

65. For the three principal tributaries (the Cuyahoga, Rocky, and Chagrin Rivers) in the Cleveland area, no observed current measurements were found in the literature. However, a water quality survey was

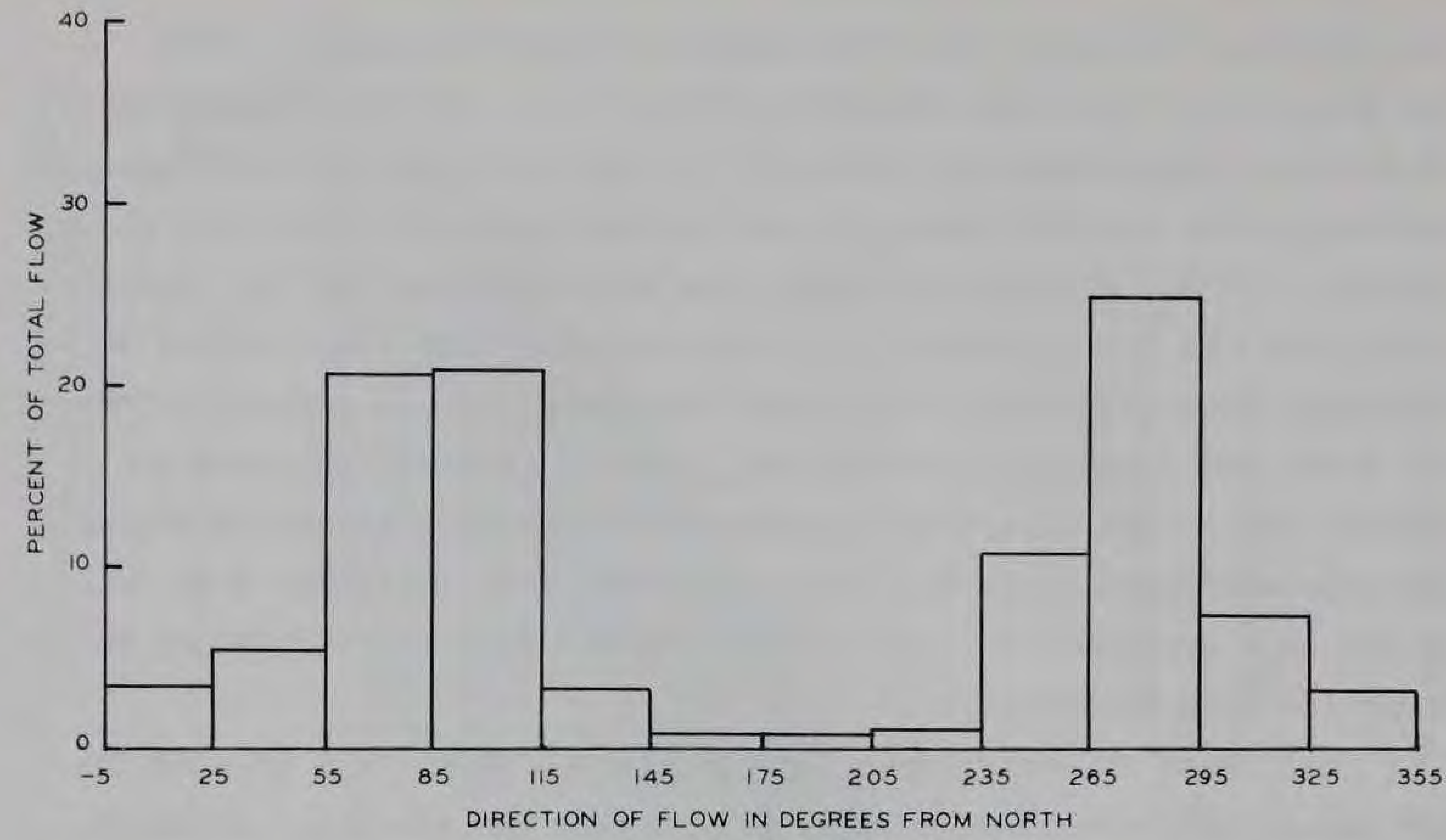

Fig. 17. Mass flow direction distribution at sta E-23, 5-m depth, for 18,874 observations during June and July 1965

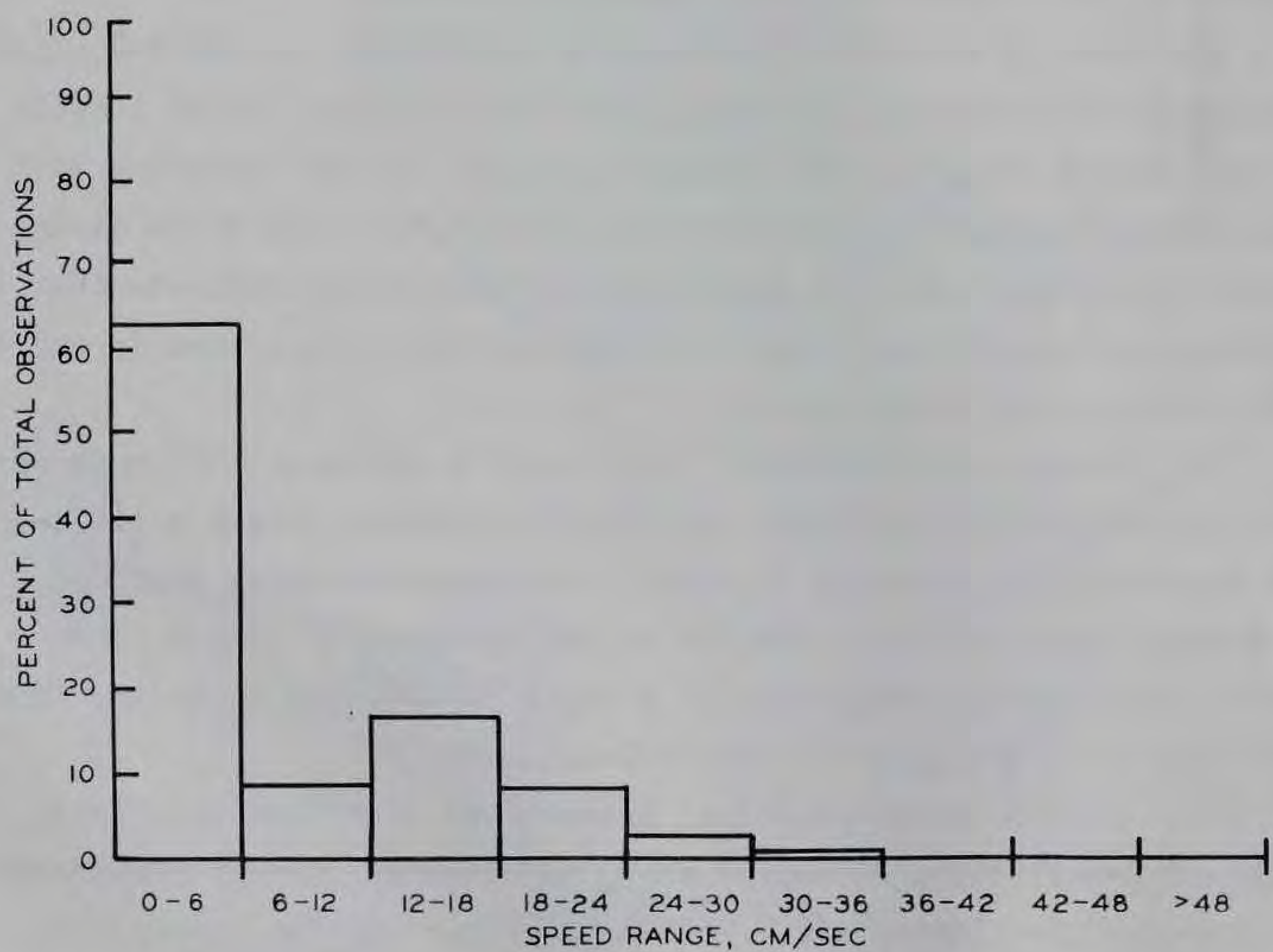

Fig. 18. Current speed distribution at sta E-23, 5-m depth, for 18,874 observations during June and July 1965

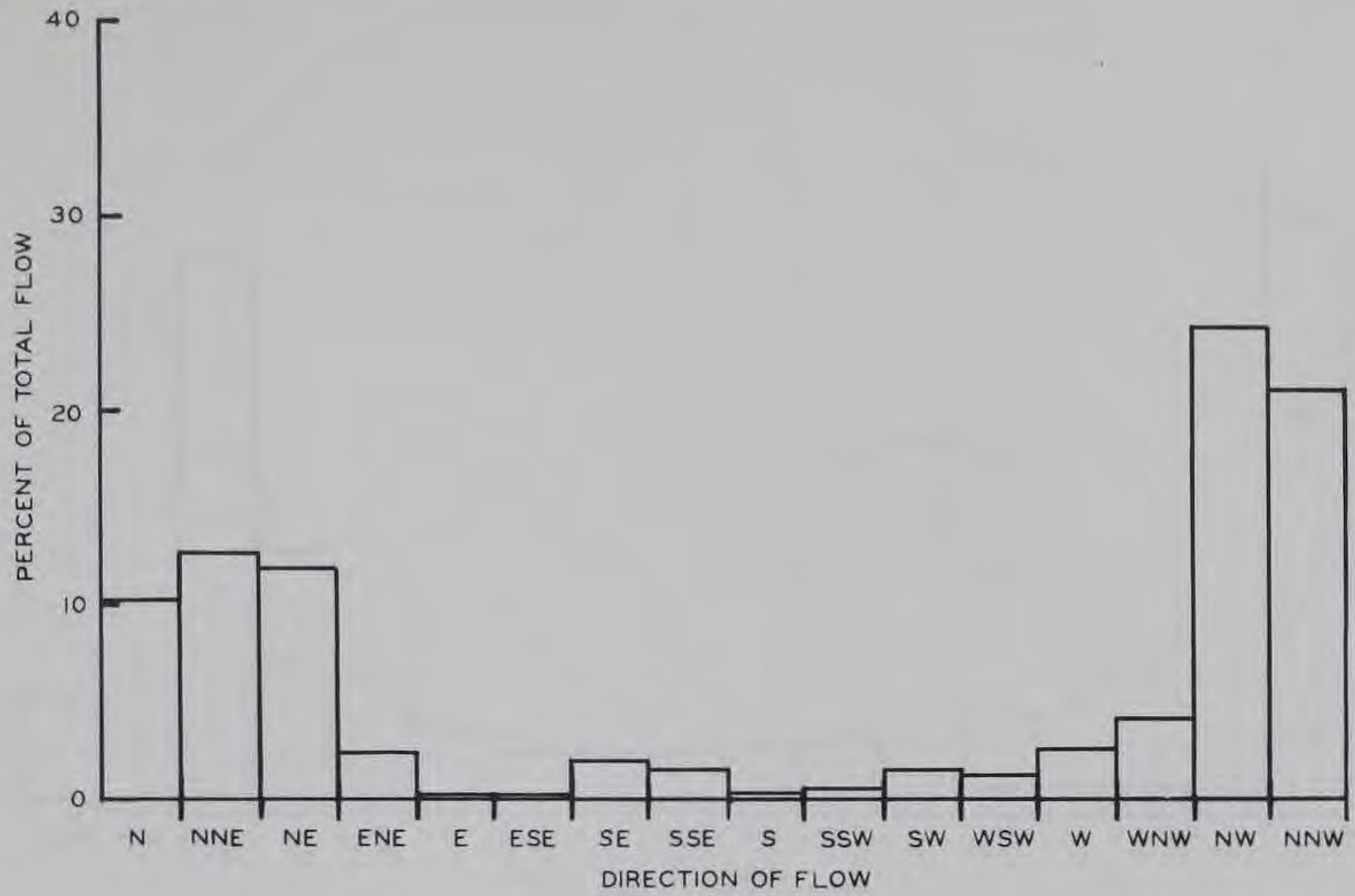

Fig. 19. Mass flow direction distribution at sta E-24, 10-m depth, for 1046 observations during August 1965

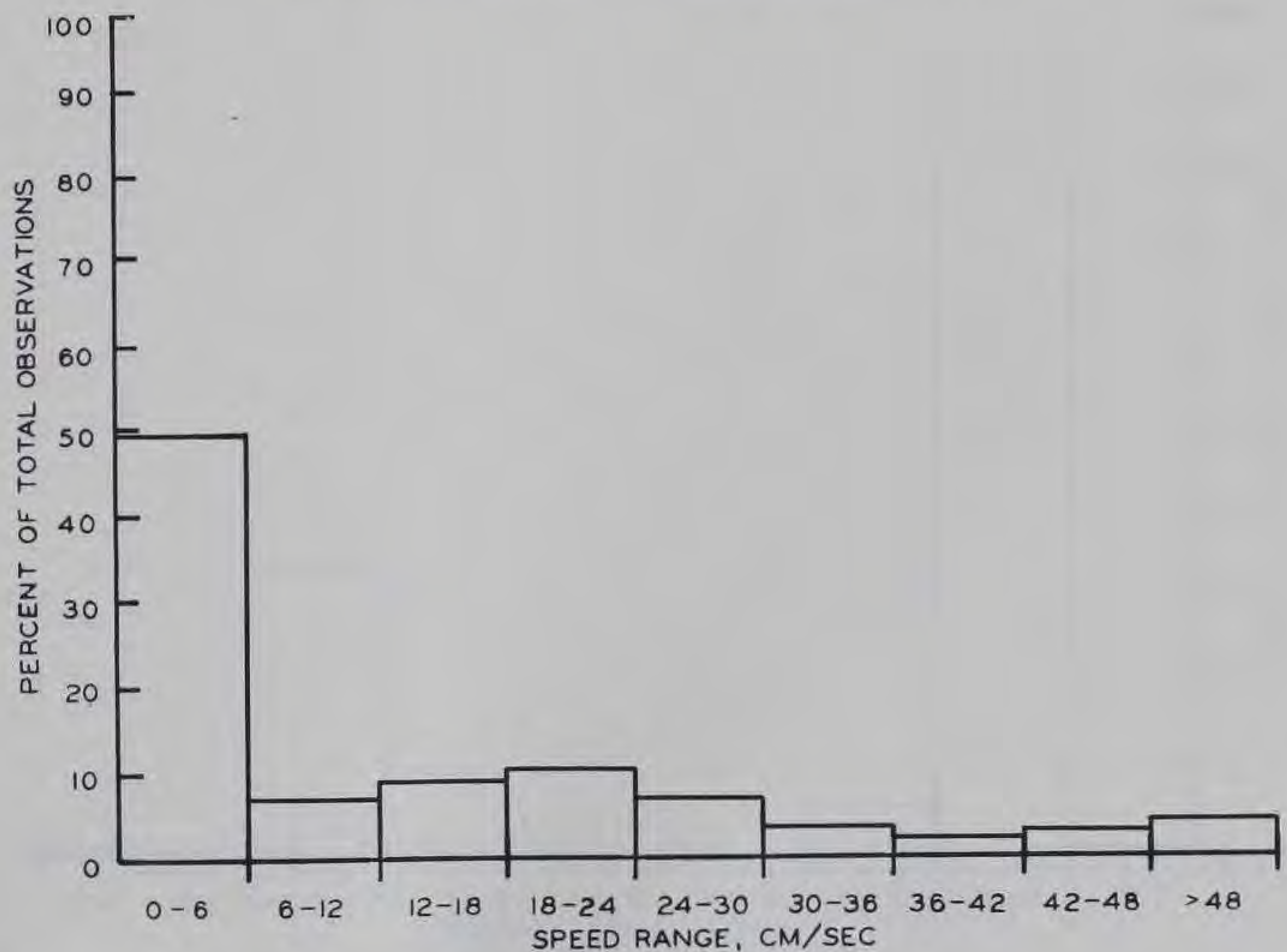

Fig. 20. Current speed distribution at sta E-24, 10-m depth, for 1046 observations during August 1965

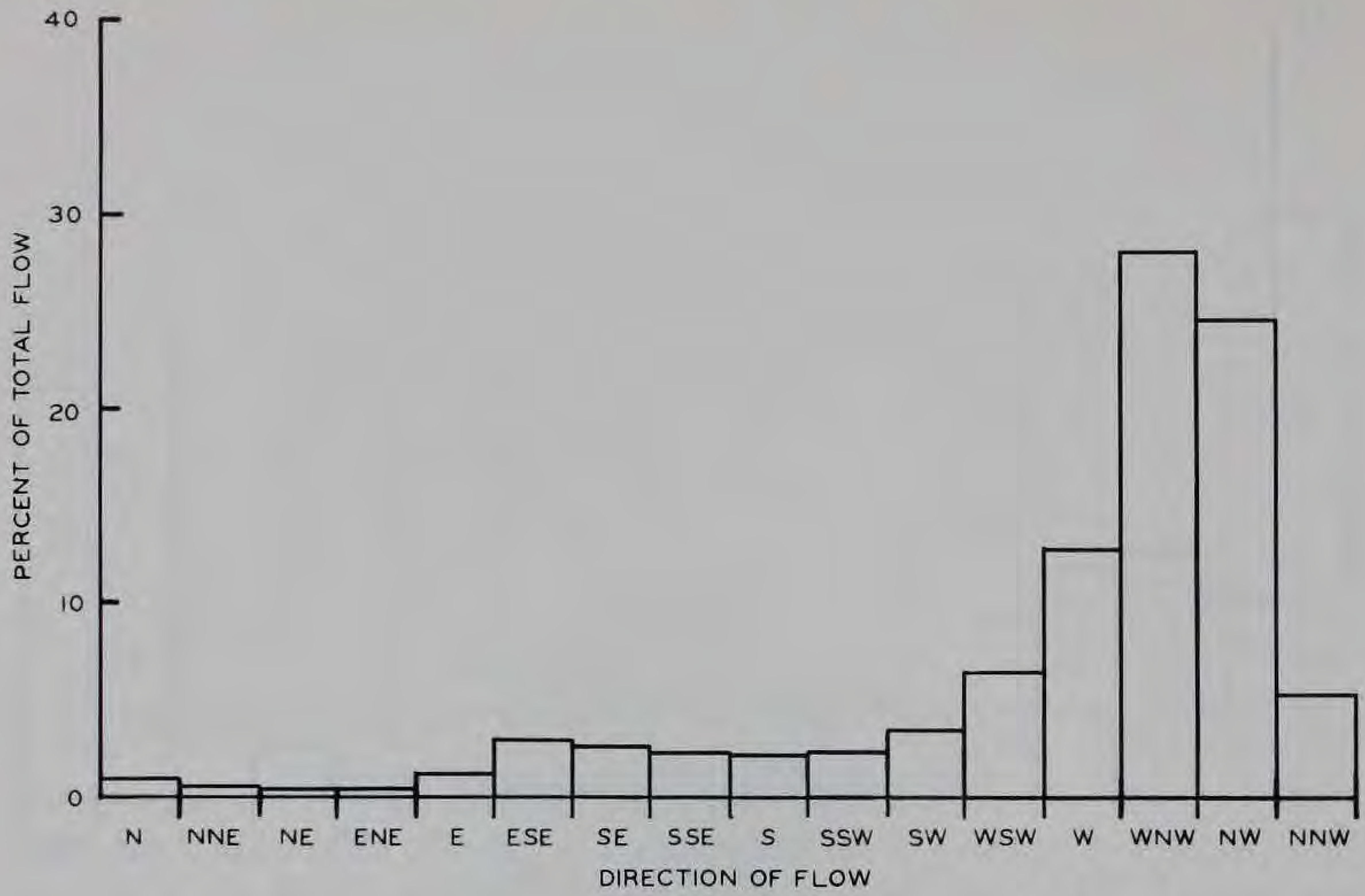

Fig. 21. Mass flow direction distribution at sta E-24, 15-m depth, for 3329 observations during September 1965

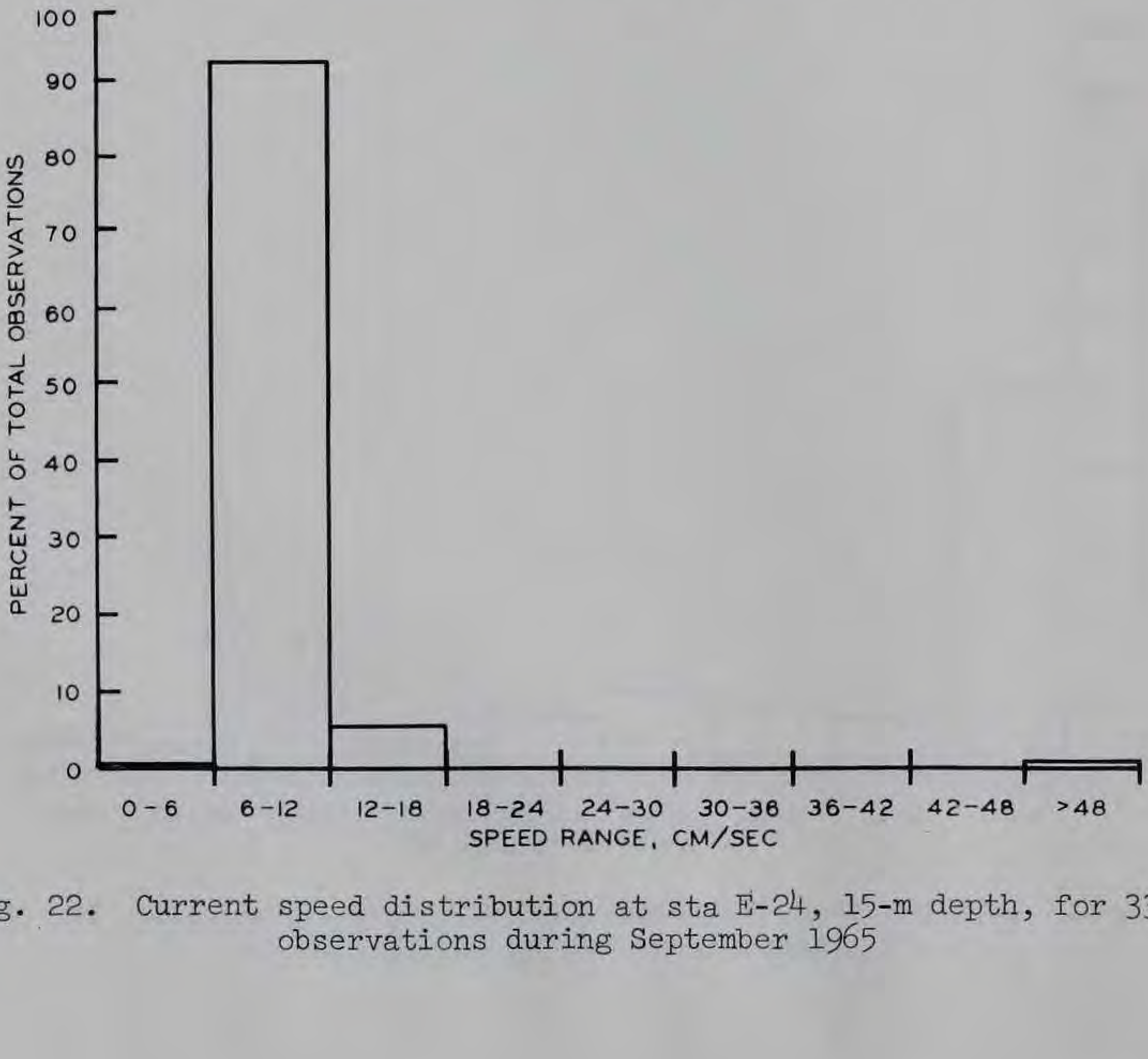

Fig. 22. Current speed distribution at sta E-24, 15-m depth, for 3329 observations during September 1965

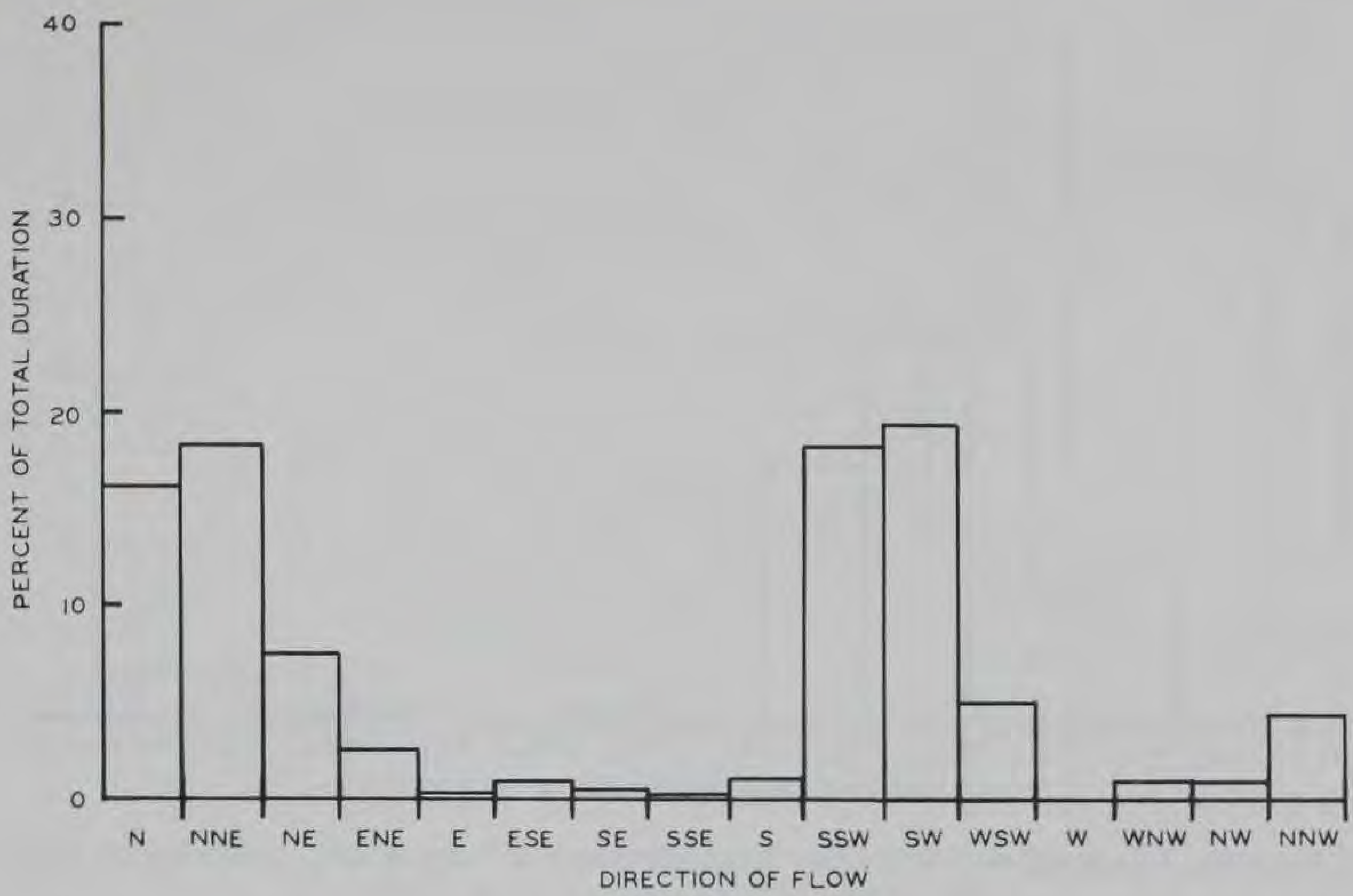

Fig. 23. Mass flow direction distribution at sta E-25, 5-m depth, for 398 observations during August 1965

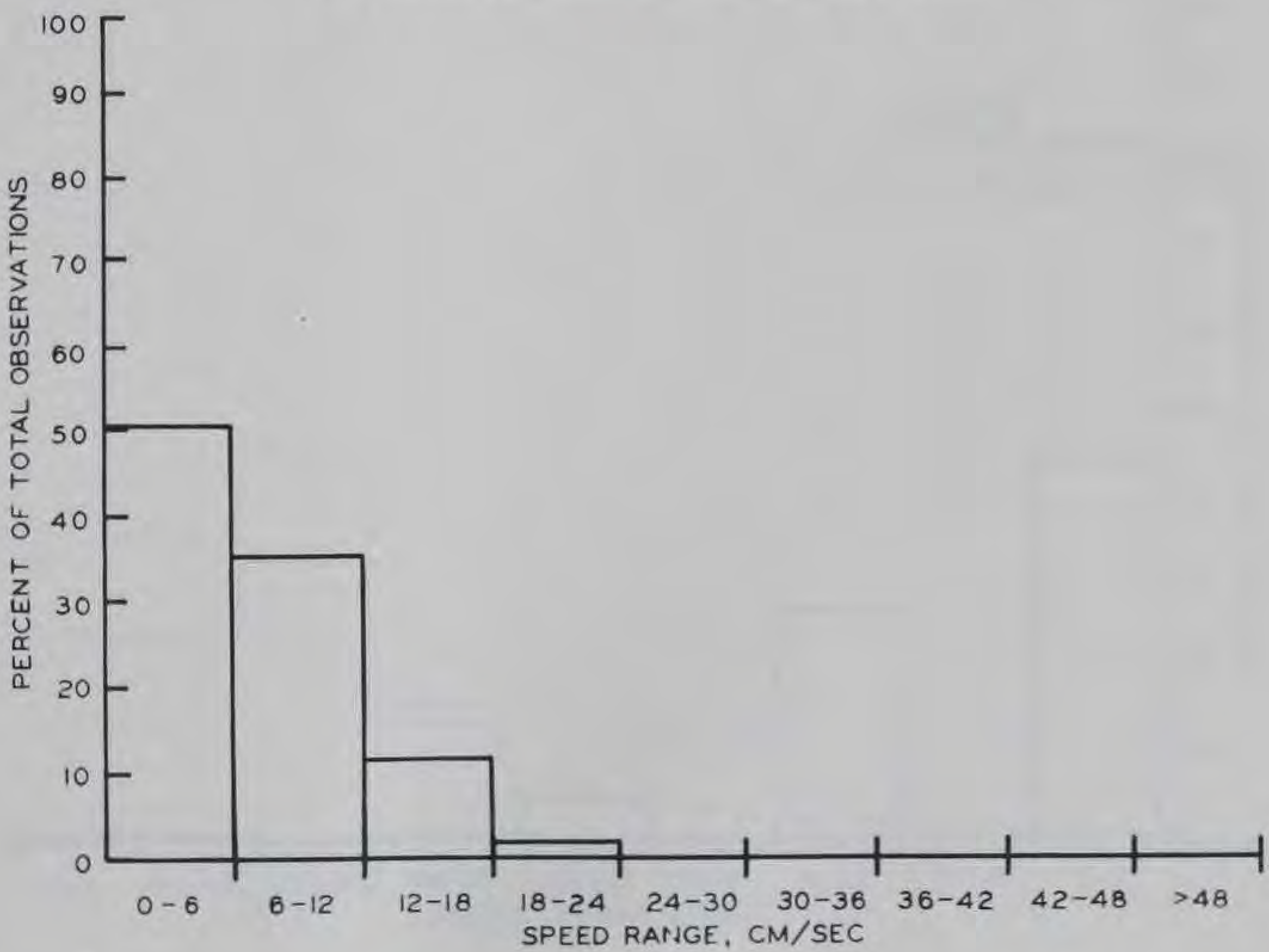

Fig. 24. Current speed distribution at sta E-25, 5-m depth, for 398 observations during August 1965

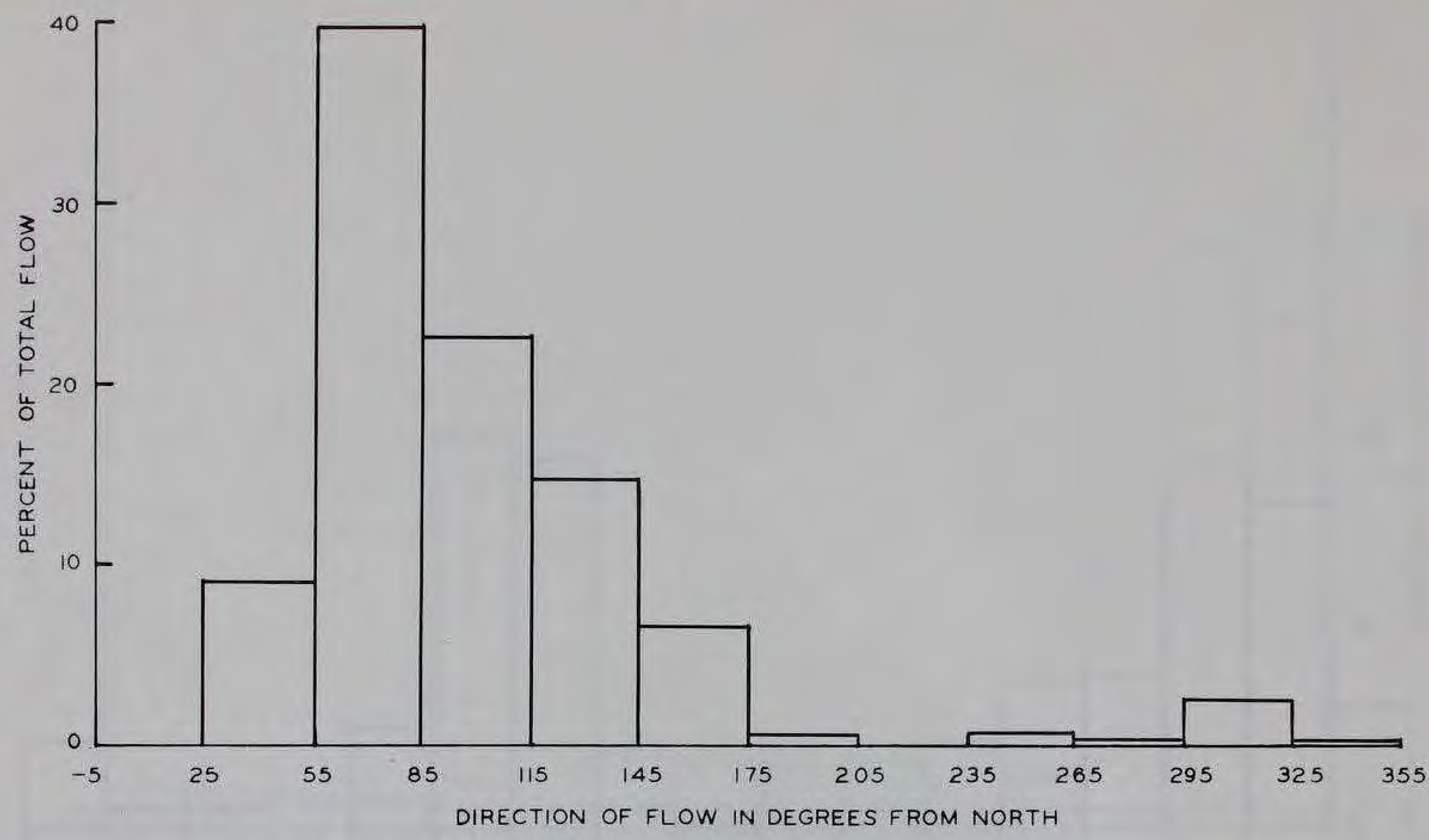

Fig. 25. Mass flow direction distribution at sta E-26, 5-m depth, for 202 observations during June 1965

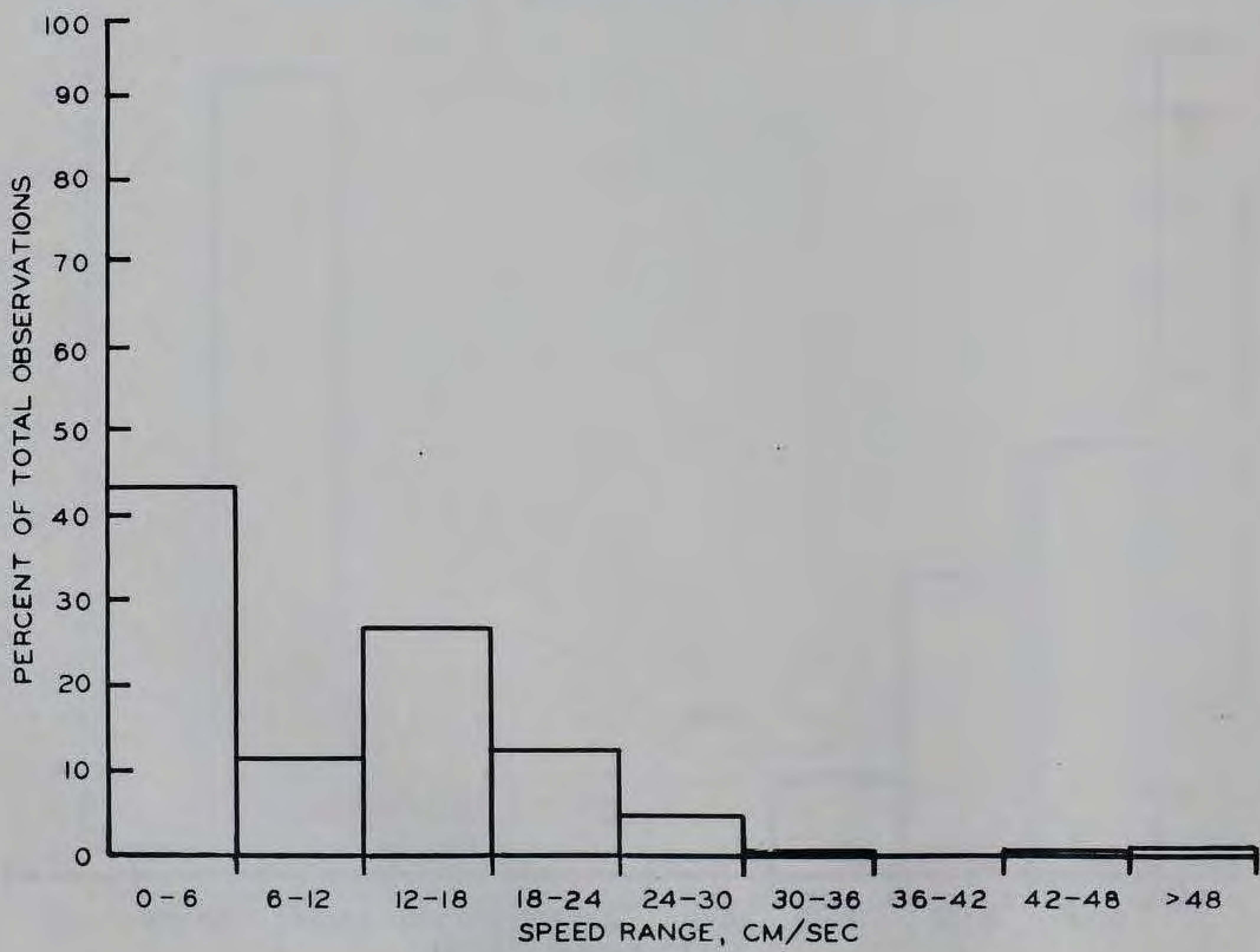

Fig. 26. Current speed distribution at sta E-26, 5-m depth, for 202 observations during June 1965

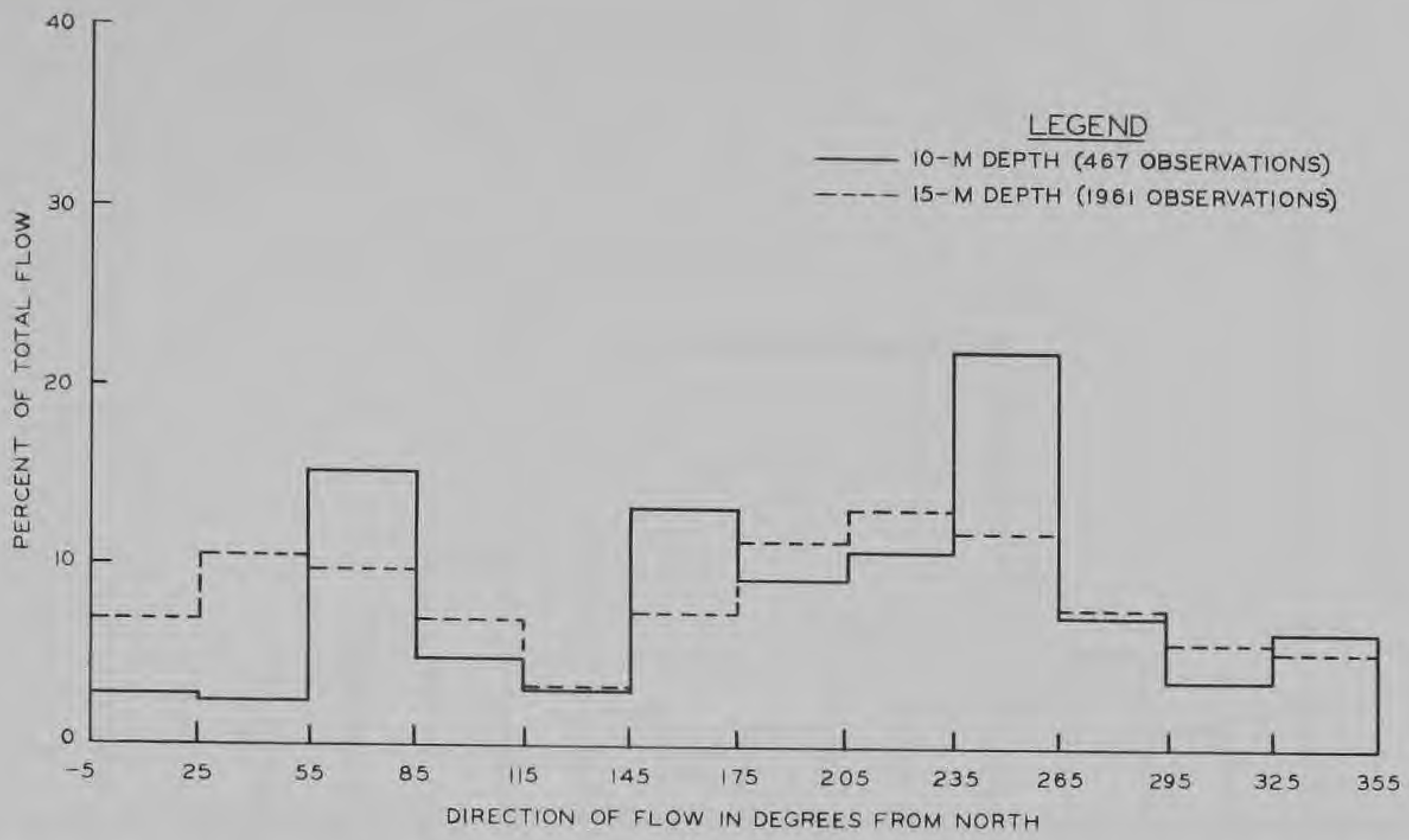

Fig. 27. Mass flow direction distribution at sta E-4 during August 1964

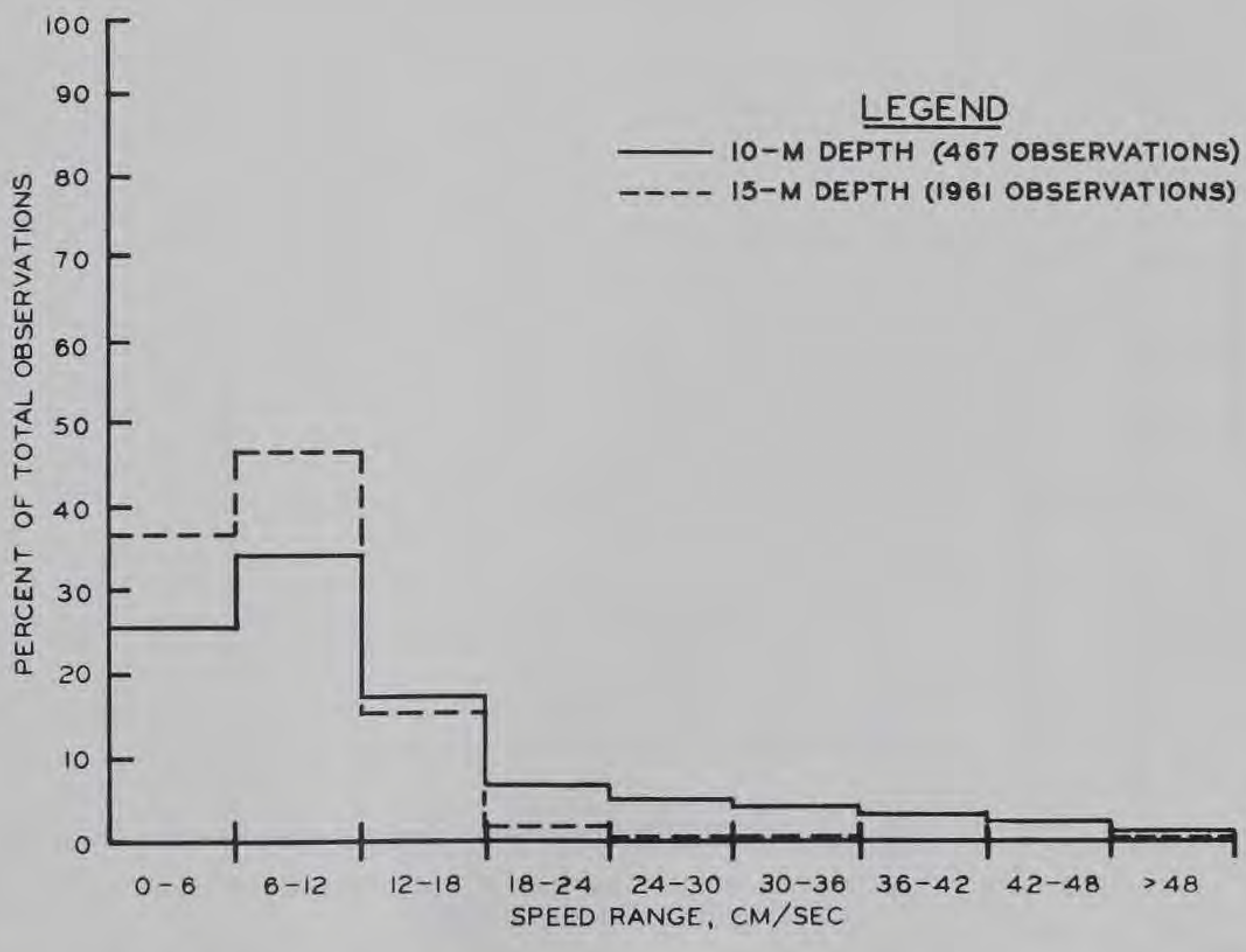

Fig. 28. Current speed distribution at sta E-4 during August 1964

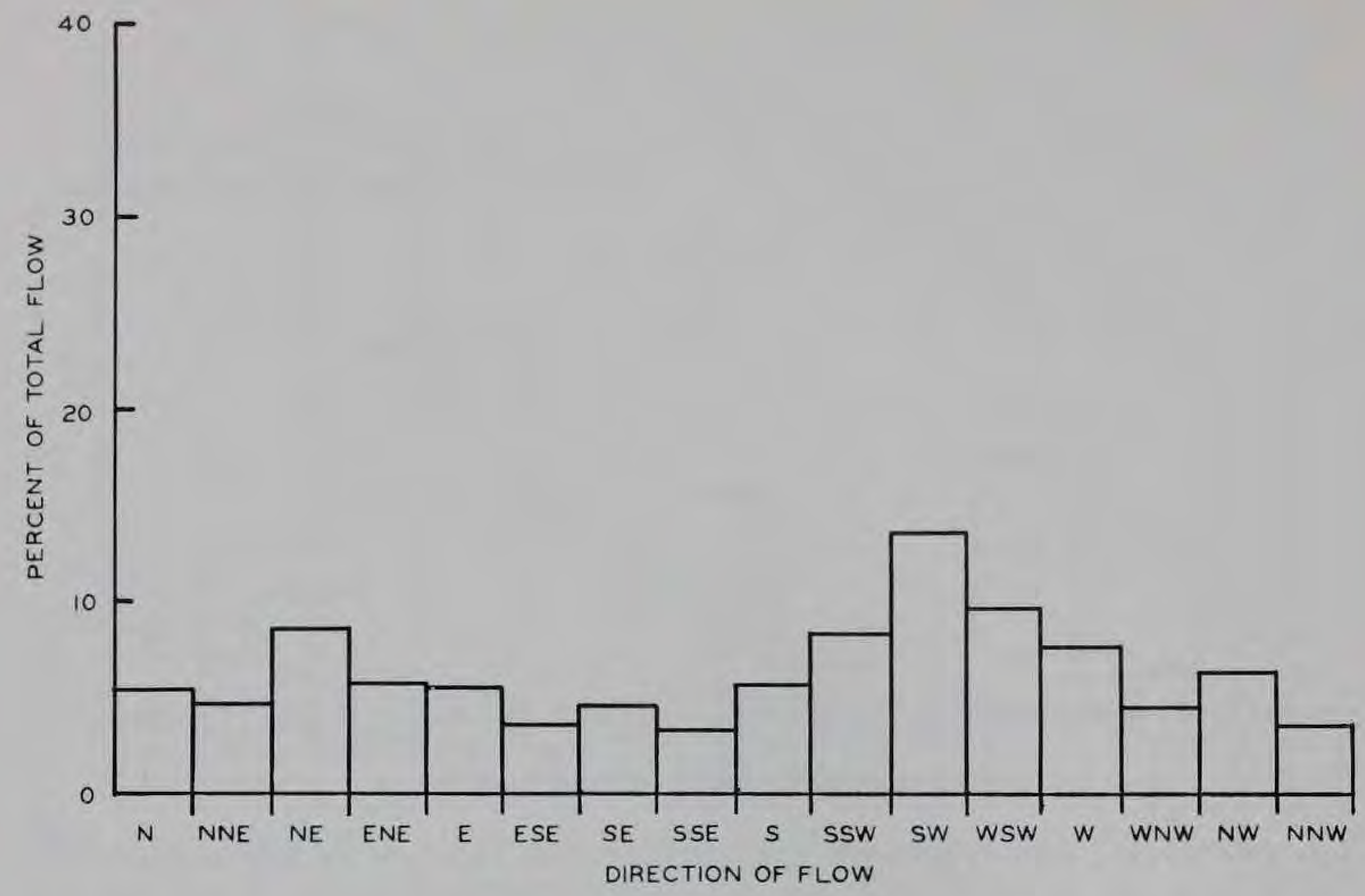

Fig. 29. Mass flow direction distribution at sta E-4, 15-m depth, for 4758 observations during August-October 1964

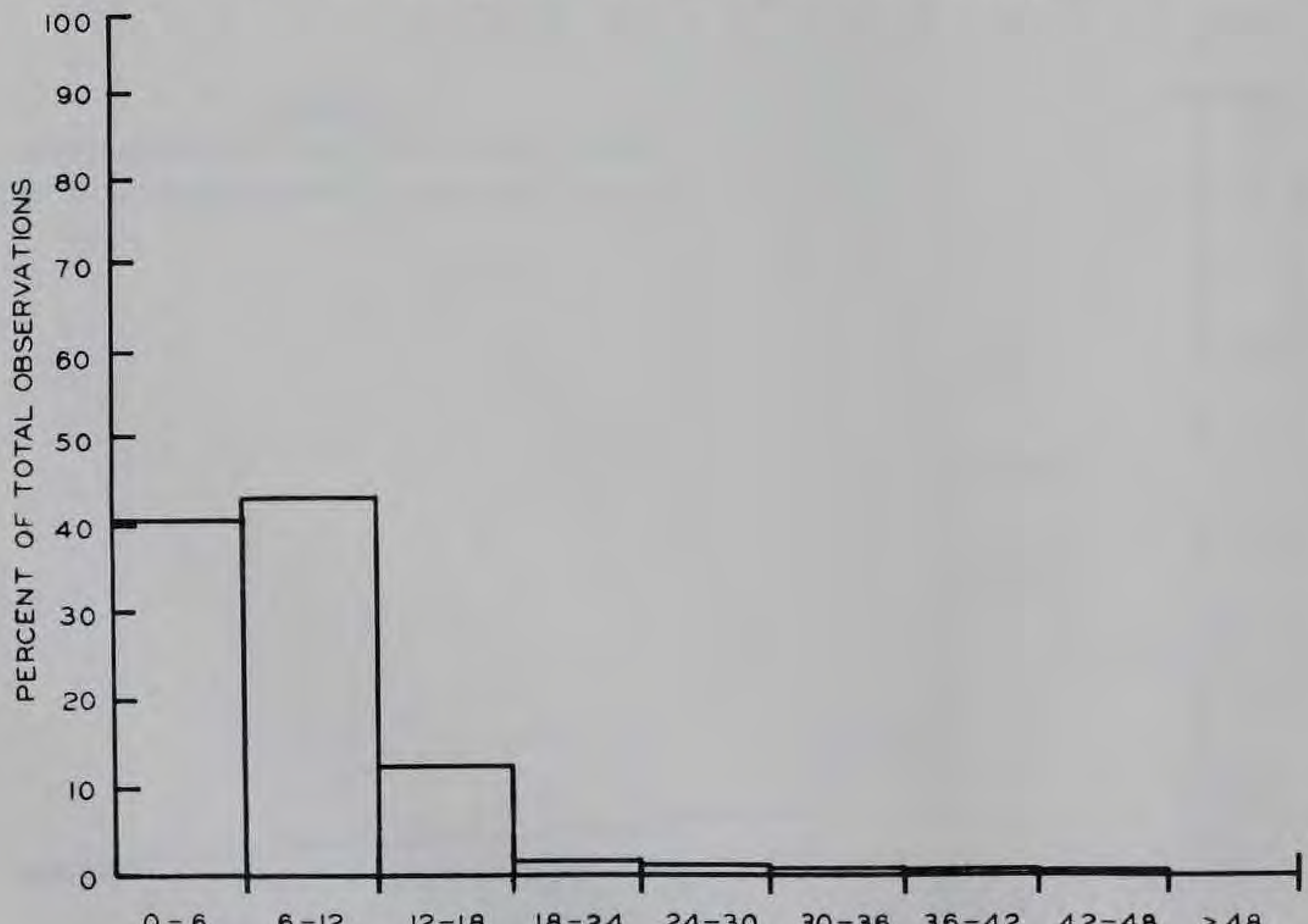

Fig. 30. Current speed distribution at sta E-4, 15-m depth, for 4758 observations during August-October 1964

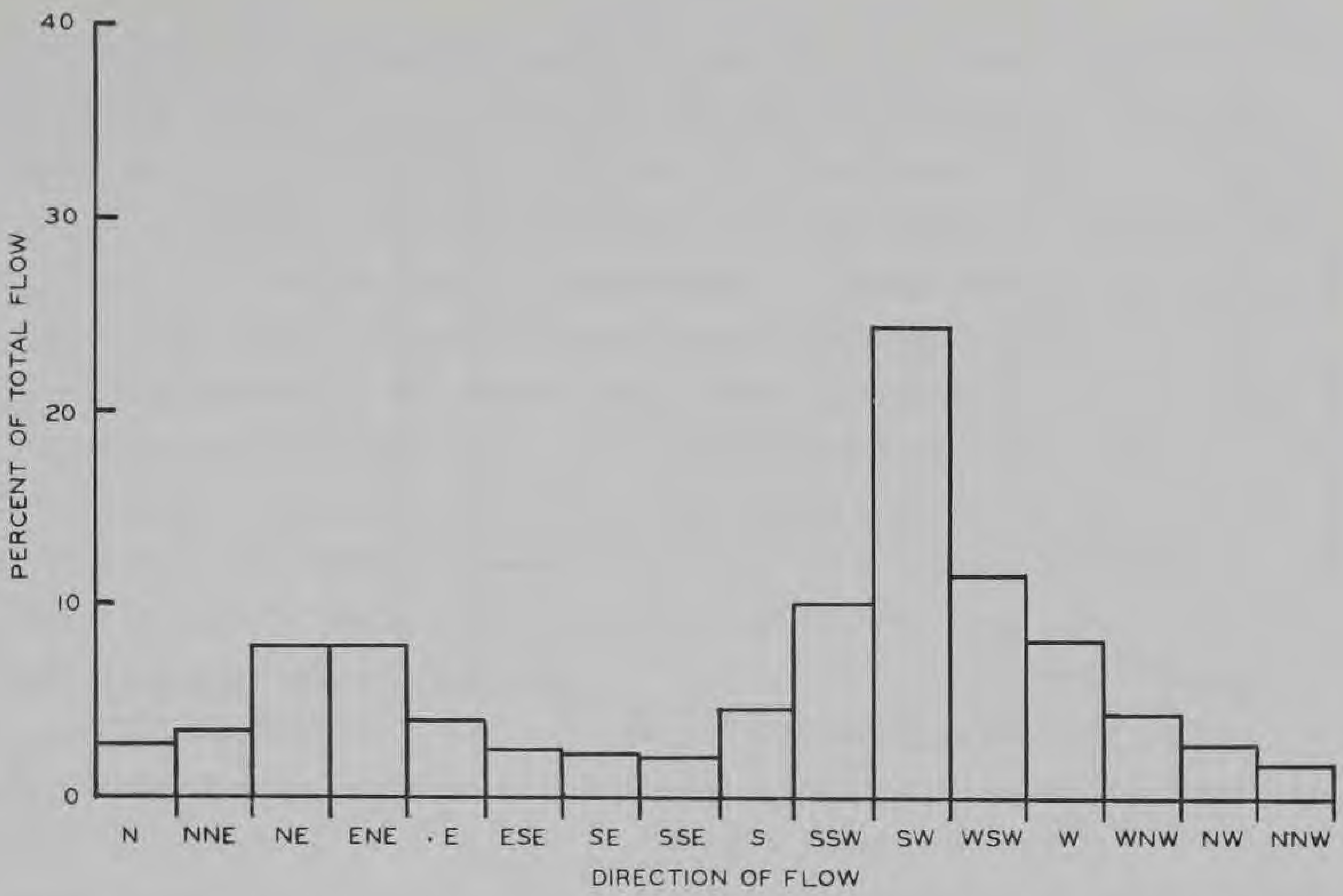

Fig. 31. Mass flow direction distribution at sta E-4, 15-m depth, for 7035 observations during November 1964-March 1965

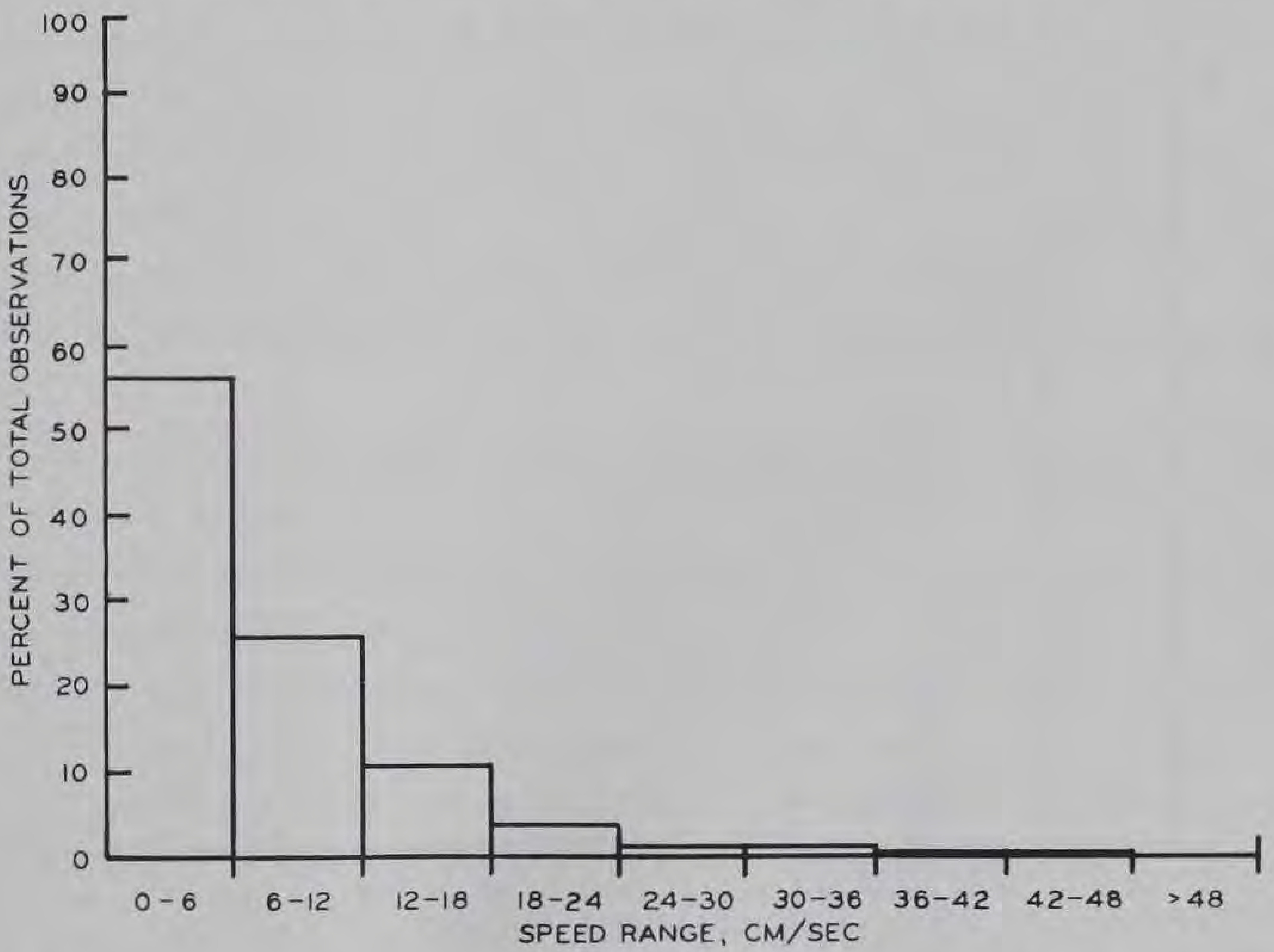

Fig. 32. Current speed distribution at sta E-4, 15-m depth, for 7035 observations during November 1964-March 1965

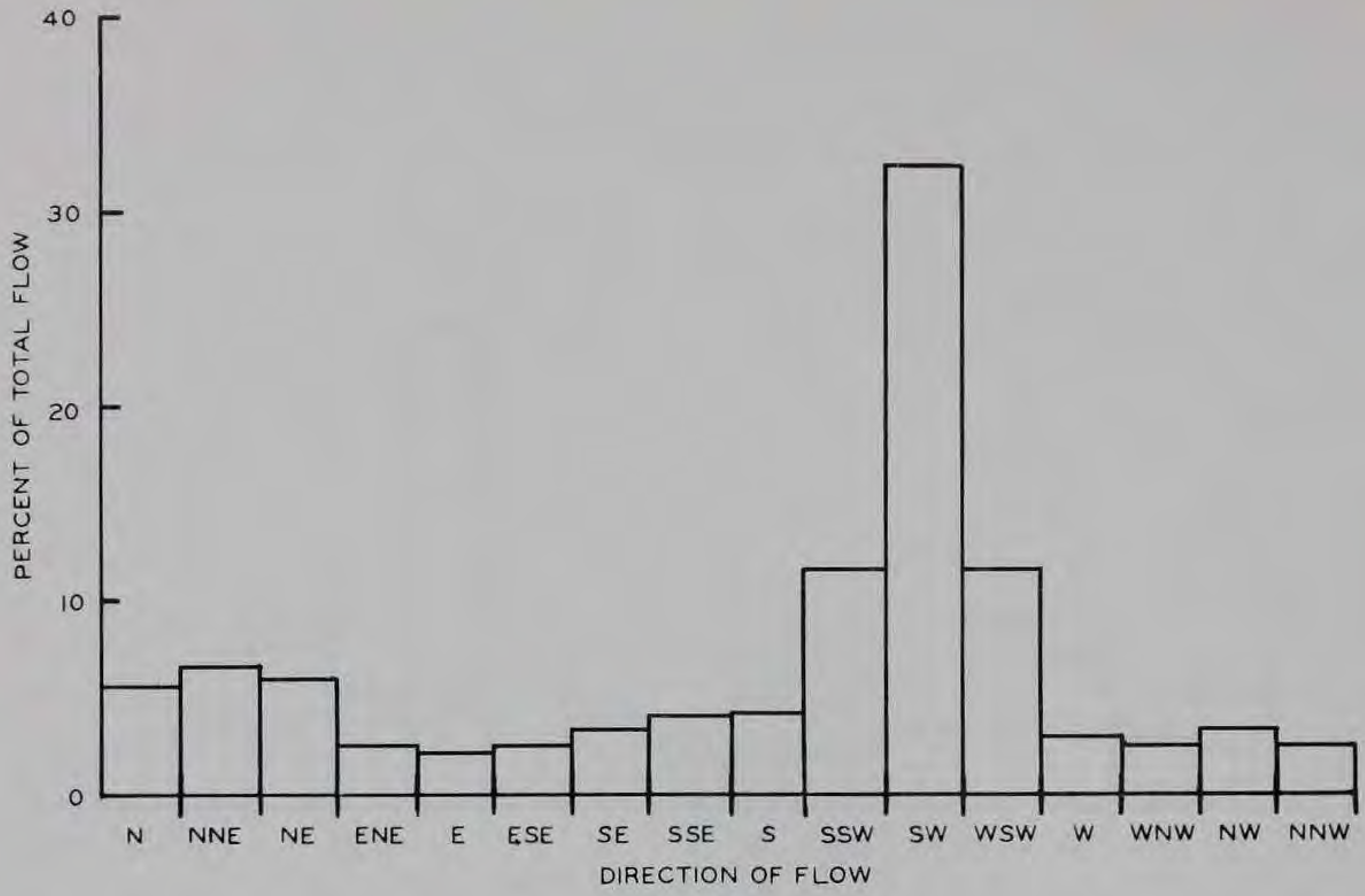

Fig. 33. Mass flow direction distribution at sta E-4, 15-m depth, for 3439 observations during April-June 1965

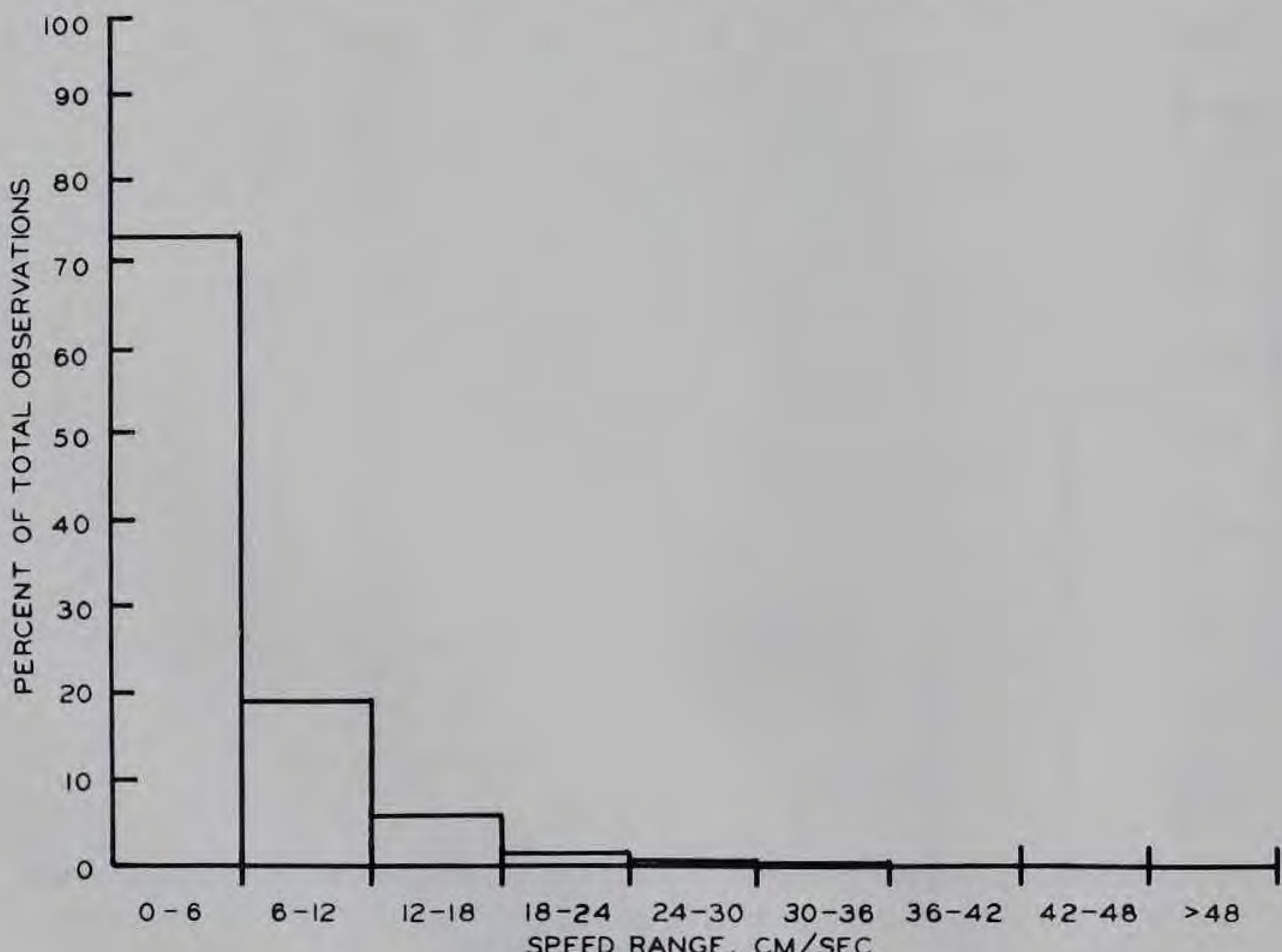

Fig. 34. Current speed distribution at sta E-4, 15-m depth, for 3439 observations during April-June 1965

conducted in the navigable channel of the Cuyahoga River by the U. S. Geological Survey[25] in cooperation with the Ohio Department of Natural Resources. This survey indicates that the heat load, which is contributed by industrial and municipal waste outfalls along the channel, has a significant effect on the river discharge. During the two days of the survey, the upper navigation channel was approximately 25-30 F warmer than the river water at Independence River Gage Station. Thus, the lake water underran the river water and intruded into the lower navigation channel. The study concluded that seiche, wind, and probably fluctuations in streamflow and lake levels affect both the extent of the intrusion and the degree of stratification of the river water.

Analytical circulation studies

66. Analytical investigations of wind-driven currents in the Great Lakes have all been published within the past 10 yr and have been based on potential flow theory. In recent years, Csanady[26,27,28] obtained exact solutions for a circular basin of constant depth or "model Great Lake." Gedney and Lick[29] have shown that, for well-mixed, constant density conditions and a constant wind velocity, the predicted steady-state circulation pattern from the wind stress is affected by the bottom topography and boundary geometry. The results predicted by Gedney and Lick for Lake Erie compare reasonably well with the FWPCA data for several cases when the wind was fairly steady for several days. Gedney and Lick's approach can be used to predict the variation with depth of current velocity and direction, but does not include the advective terms.

67. A numerical model using a vertically averaged velocity has been applied to Lake Ontario by Paskausky[30] and Simons.[31] The model is time-dependent and includes both the advective horizontal eddy viscosity terms and bottom friction. The results by Simons suggest that the bottom friction has a small effect on the circulation pattern but that changes in horizontal eddy diffusion are significant. The vertically averaged velocities are not indicative of the actual velocities but are representative of the net mass transport. The predicted circulation pattern is for the open lake and does not apply in the coastal boundary

layer. Mass circulation in the Great Lakes has been investigated by others, but the above-mentioned numerical methods are representative of the approaches used for well-mixed, constant density conditions.

68. The numerical models are for well-mixed, constant density conditions and would not be expected to apply to the lake stratification which occurs in the summer. The well-mixed, constant density models can be used in Lake Erie during the spring, fall, and winter due to the shallowness of the lake and the gradual formation of the thermocline. Ice cover can also be included in the well-mixed, constant density analysis.[32]

69. No analytical or numerical methods for predicting summer circulation are currently available for a lake with a variable bottom topography and shoreline. The summer thermocline alters the circulation pattern significantly, and the hypolimnion currents are normally of an order of magnitude less than the epilimnion. However, as noted in the previous section, the average summer mass circulation at the surface and intermediate depths does not seem significantly different from those for other periods of the year.

70. A numerical model for the time-dependent, three-dimensional, variable density, variable temperature flow of a rectangular jet horizontally entering a basin of semi-infinite extent has been developed by Paul and Lick.[33] The effects of variable inlet velocity and temperature profiles, surface heat transfer, coupling between momentum and energy transfer, and a finite bottom depth are included in the model. The model has not been extended to include ambient lake stratification, variable bottom topography, and crosscurrents representative of stratified summer conditions; but it should be possible to include these parameters in the model.[33] An extension and application of this model to summer circulation with river inflow for Lake Erie is presently being carried out by Gedney and Lick.*

71. A three-dimensional model recently formulated by Leendertse[34] has potential for treating the stratified or variable density problem.

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* W. Lick, personal communication, March 1974.

Unfortunately, the model formulates the density variation in terms of salinity and is thus applicable to estuaries rather than freshwater lakes. In addition, the model in its variable density mode has been applied only to a very few simple geometries. In the only application reported for a real lake geometry, the density is considered as a constant. Leendertse suggests that this model can be extended to provide a density variation with temperature; however, this requires introducing the energy equation with its associated boundary conditions into the system of governing equations. Considerable development will be required before such an extension of the model can be applied to real lake geometries.

72. A more extensive discussion of the analytical and numerical models, their assumptions, limitations, and general applicability to lake hydrodynamic phenomena will be included in task d of the model feasibility analysis.

Wave Statistics

73. A wave hindcast for Cleveland was published by the Beach Erosion Control Board in 1953[8] using 3 yr of recorded wind data (1948-1950). The hindcast is for deepwater conditions only (water depth greater than one-half the wave length). The hindcast method developed by Sverdrup, Munk, and Arthur was used without the revisions suggested by Bretschneider, and the report states that the predicted wave periods may be expected to be slightly low.

74. The U. S. Army Corps of Engineers, North Central Division (NCD), also made a hindcast using 5 yr of recorded wind data (1948-1952). The monthly and annual summaries of wave period direction, duration, and height were not published, but the frequency of occurrence of the actual (not significant) wave height was shown.[35] For both the full year and the ice-free period, wave frequencies were derived by NCB for Cleveland. For instance, NCD calculated that a 12.4-ft wave would occur once in 10 yr versus a 15.4-ft wave predicted in reference 8. The difference in predicted wave height is attributed to the longer period of

recorded wind data used in the second hindcast. This difference is quite important in the design of slope protection since the weight of the armor unit varies with the cube of the design wave height. International Weather Consultants[36] has prepared a design wave analysis for NCB using an envelope enclosing the winds from the 10 worst storms of record from the northeast, north, northwest, and west. This procedure gives a conservative combination of maximum speed and longest duration of the wind; however, the calculated design wave is based on an artificial storm.

75. Wave hindcasts have been made for other harbors on Lake Erie, and one hindcast[37] has been compared with observed wave data. The data were taken at Port Burwell, Ontario, over a 3-yr period, and the results of the comparison show that the observed and predicted periods agree reasonably well. The observed significant wave height did vary up to approximately 50 percent from the predicted wave height for waves over 3 ft. Most predicted wave heights were smaller than the observed height but did fall within a band ranging from two-thirds of the predicted height to the predicted height.

Shore Erosion

76. Erosion along the Lake Erie shoreline is a continuing process and is most severe during periods of high lake levels. The faces of the bluffs are subject to erosion by sheet and concentrated runoff of surface water, freezing and thawing, subsurface moisture, ice, and most important, wave action. The waves can attack the toe of the clay bluff sections directly when lake levels are high. Slope failure of the bluff results after the waves undermine the bluff and the shear strength of the bluff is reduced by the high lake level. The shoreline east and west of Cleveland is described in the section on lake shore characteristics.

77. Littoral currents near Cleveland flow generally from west to east with temporary reversals of direction due to northerly and northeasterly winds. The predominant current direction has resulted in accretion of sand west of the city of Cleveland's small craft

breakwater. The breakwater traps sand moving eastward, and during the period 1926-1947, an average annual accretion of 6400 cu yd occurred. The relatively low accretion rate suggests that much of the eroded material is transported offshore.[38] Just east of Bratenahl, a sewage disposal plant operated by Cleveland is protected by a breakwater, and sand has accumulated immediately adjacent to the west side of the plant. However, erosion problems are serious on either side of the plant. The next section of major accretion is the west side of the Cleveland Electric Illuminating Company power plant intake breakwater at Chagrin River. In 1964, a shore erosion survey by R. P. Hartley for the Ohio Department of Natural Resources, Division of Shore Erosion, found a loss of beach sand apparent for at least 2 miles east of the breakwater.[39] The survey concluded that serious erosion areas exist near all major shoreline structures, in part due to trapping of littoral transport and dredging of navigation channels.

78. West of Cleveland, the shale bluff sections recede at a slower rate than the clay bluffs. The predominant direction of littoral transport west of Avon Point changes to an east-to-west pattern, resulting in accretion of beaches on the east edge of large structures at Beaver Creek, Vermilion, Huron, and Sandusky. At Lorain, just west of Avon Point, the direction of the longshore transport is difficult to establish, but the accretion patterns do indicate a westward transport.[39] The westward transport does not indicate that the predominant currents along the shore west of Avon Point flow to the west but does indicate that storms from the northeast produce more severe shore erosion and a larger sand transport. This effect is probably due to the decreased fetch in the northwesterly direction. At Cleveland the sand load in the Cuyahoga River has little effect on the longshore transport due to the deposition of the sand in the river navigation channel and inside the present harbor breakwater.

79. The erosion rate varies along the shoreline but has been observed at up to 5 ft per year west of Chagrin River[40] and up to 6 ft per year at Perry Township.[4] Local slope failures can exceed these rates. The average recession rate is 2 to 4 ft per year and can be as

low as 1 ft per year at the shale bluffs near Lakewood.[41]

80. The effects of ice formation on the shoreline have been reviewed by NCB,[38] and the District has concluded that the net effect is beneficial. Ice builds up 12 to 15 ft above lake level on the bluffs and shore structures and protects them from wave attack. Ice can also eliminate the wave attack during periods when the lake is iced over, usually in mid-winter. Storms can break up the ice field; and when this occurs, battering by ice blocks may damage light structures.

Environmental Changes

81. Numerous investigations of the chemical, biological, and microbiological conditions in Lake Erie have been made, and a bibliography of these efforts has been compiled by the Center for Lake Erie Area Research.[42] Comprehensive surveys were conducted in 1963-1964 and 1967-1968 by FWPCA. The two surveys were not made at the same stations, and the 1963-1964 survey included data from nearshore stations that were affected by tributary inflow. The changes in water chemistry in the central basin are shown in table 6 (from reference 43). This table shows that all the observed chemical constituents have increased from 1963-1964 to 1967-1968 in the central basin except the chlorides, silica, and nitrate nitrogen. The increases may be more pronounced than indicated due to the tributary influence on data from the 1963-1964 survey. The significance of the water quality parameters in table 6 is summarized in reference 1.

82. NCB conducted a dredged material disposal study in the Great Lakes from 1966 to 1969 and distributed a summary report[44] in 1969. The Cleveland Harbor was one of the pilot study sites for a diked dredge-fill disposal program and a study of the effect of dredged material on water quality. The Cuyahoga River, outer harbor, and dumping grounds were sampled during the study by the FWPCA Program Office in Cleveland, and ranges of the values for some of the chemical and microbiological constituents in the river and outer harbor are shown in table 7 (from reference 44). The data for the central lake in the report are essentially the same as the 1964 data for the central lake in table 6. As

stated in the study report, the Cuyahoga River at Cleveland has been appreciably degraded by heavy waste loads from combined sewer overflows, wastewater treatment plant effluent and bypass discharge, and direct industrial waste discharge. In the navigation channel maintained by NCB, the iron and other metal ions form precipitates with the dissolved solids with 96 percent of the iron, 86 percent of the phosphates, and 44 percent of the total solids settling out. Below the Cleveland south sewage treatment plant, FWPCA found that the average value for the 5-day BOD was 8.9 mg/ℓ (and that the phenols averaged 58.0 mg/ℓ) (maximum 175 mg/ℓ) during 1964. The average daily loads in lb/day in the channel during the same year for several water quality parameters were as follows (from reference 45):

BOD	80,000
Phosphates	3,500
Ammonia nitrogen	42,500
Nitrate nitrogen	9,100
Phenols	104

As shown by the ranges in tables 6 and 7, the actual concentration of a water constituent can vary over a wide range and is influenced by many factors. In the river, the streamflow has a direct effect on the concentration.

83. Pollution abatement programs have been initiated by both the cities and industries along the Cuyahoga, and those efforts are not reflected in the FWPCA data.

Conclusions

84. The review of available data by WES indicates several areas in which sufficient data were not found to define properly the wave regime, mass circulation, and shoreline erosion of Lake Erie. A limited summary of water quality data is presented for Lake Erie near Cleveland and for the Cuyahoga River; however, the most recent data presented are from the 1967-1968 EPA study.

85. General mass circulation patterns in Lake Erie on a seasonal

or annual basis have been inferred from existing lake mass circulation studies, but current observations at any point near Cleveland may vary extensively from an inferred seasonal or annual average. Observed long-term current data from stations near Cleveland, discussed in paragraphs 61-63, are limited to a few months during the summer of 1965, and no reported observations were found inside the existing commercial harbor. Additional hydraulic and meteorological data from the commercial harbor and central basin near Cleveland are needed in order to obtain (a) an estimate of the current speed and directional distributions at the jet-port site and at several nearby stations for an ice-free year, (b) data for a verification of well-mixed, constant density and baroclinic analytical circulation models, (c) data for a verification of any necessary hydraulic models, and (d) an estimate of the thermal structure near the shoreline and jetport site during the summer months.

86. Data on the extent of discharge in Lake Erie, discharge rates, flow recurrence intervals, and water quality for the tributaries of interest in the vicinity of Cleveland are limited. Average discharge rates and flow recurrence intervals for Rocky Creek, Cuyahoga River, and Chagrin River are available (paragraph 33); however, no flow data were found for Euclid Creek and Doan Brook. No water quality data are found in the literature for any of the tributaries near Cleveland except the Cuyahoga River, and only limited data were available from the 1967-1968 EPA study. At times, the discharge plume of the Cuyahoga River can, when the river water is discolored by suspended sediments, be observed visually. The extent of such discharge into the lake could be obtained from photographs; however, no long-term photographic data are available for such analyses. Also, no synoptic velocity data in the rivers and in the lake near the mouth of the rivers were found in the literature. Thus, the discharge plumes into the lake of the tributaries of interest, in particular the Cuyahoga River, are not well defined. In addition, lake water may intrude into the major tributaries near Cleveland, especially the Cuyahoga River, but consideration of the stratification and flow regime in the navigable channels of the tributaries is beyond the scope of the present investigation.

87. Review of the analytical mass circulation models presently available indicates that numerical models[29] of well-mixed, constant density wind-driven circulation for shallow lakes can be used to predict wind-driven circulation near the jetport. Such models have recently been extended[46] to include time-dependent wind stress and horizontal diffusion. In addition, the nonlinear advective terms can be added to these models, but such terms are not expected to be important except relatively near a boundary.

88. An analytical model capable of describing the baroclinic (stratified) mass circulation in a lake with a variable shoreline, bottom topography, and river outflow is not presently available. Since Lake Erie is normally stratified from June through October, a baroclinic model is necessary to describe adequately mass circulation during the summer months. Since the Cuyahoga River inflow may also underrun or overflow lake water if the river and lake water are not at the same temperature, a baroclinic model will be necessary to describe the outflow of the Cuyahoga in the harbor and central basin for these cases.

89. Baroclinic models for wind-driven lake circulation with river outflow are in the process of being developed (e.g., Dr. W. Lick at Case Western Reserve University), and these models, when completed, should adequately describe lake circulation, including the harbor, near Cleveland. However, specific applications of such models must await further model development and verification.

90. Tidal effects in Lake Erie can be neglected (paragraph 40), but as found by Irish and Platzman (paragraph 43), the variation in lake level between Toledo and Buffalo due to seiching exceeded 6 ft 79 times in the 20-yr period from 1940 to 1959. On the average, approximately four seiches exceeding 6 ft will occur every year.

91. Analytical seiche period and lake level data available in the literature are sufficient for Lake Erie without the jetport, but the frequency of seiching above 6 ft indicates that the effect of the jetport on seiche periods, currents, and water levels should be investigated.

92. The published wave hindcasts for Cleveland are in significant

disagreement (paragraphs 73 and 74), and the need for a hindcast over a longer period of record is evident in order to select design waves. In 1973 the lake exceeded the previous record monthly high lake level. Thus, the data in the lake level section will need to be revised to include recent lake level data.

93. As indicated in paragraph 74, erosion of the bluffs near Cleveland occurs primarily as the result of wave action on the bluffs, particularly during periods of high lake level. The average percentage of sand available for beach replenishment from the bluffs has been determined by NCB for various sections of the shoreline; however, only limited long-term estimates of the littoral transport rates along the shoreline were found. Profiles taken perpendicular to the shoreline by NCB[47] indicate that the lake bottom depth out beyond the 18-ft contour is decreasing and that bluff erosion is a probable source of the accretion. The absence of clay in the beaches along the shoreline near Cleveland indicates that the bluff clay is taken offshore in suspension before deposition and may be a source of the accretion beyond the 18-ft depth contour.

94. In summary, the major areas of deficient data are long-term and synoptic current measurements near Cleveland in the lake, commercial harbor, and tributaries, and quantitative littoral transport rates that can be related to the wave regime. Monthly and annual lake level data and recurrence intervals also need updating. Although another area of deficiency is wave data, a new wave hindcast by A. H. Glenn & Associates utilizing a 10-yr period of wind records has been completed[48] and will be used in addition to the existing wave data.

95. This summary of data relative to the hydraulics of Lake Erie near Cleveland presents results of the WES review of existing literature and information available from individuals through 1973. The review will be updated continually during the entire WES investigation, and additional data available before completion of the investigation will be included in the final report of the model feasibility investigation or (depending on the quantity involved) published as an appendix to this report.

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Table 1

Physical Characteristics of Lake Erie Basin

(from Reference 2)

Characteristic	Western Basin	Central Basin	Eastern Basin	Entire Basin
Volume				
cubic feet × 10^{12}	0.8	10.6	5.4	16.8
percent	5	63	32	100
Area				
square feet × 10^{10}	3.5	17.4	6.7	27.6
percent	13	63	24	100
Depth, feet				
Mean*	24.2	60.7	79.9	60.7
Maximum	48	84	210	210
Dimensions, miles				
Length (maximum)	50	132	85	241
Width (maximum)	40	57	42	57
Width (mean)	25	47	28	41

* Mean depths are based on International Great Lakes Datum of 568.6 ft.

Table 2

Meteorological Data for Cleveland, Ohio

(Taken Over a Period of 29 yr)

(from Reference 5)

Month	Normal Daily Temperature, °F Maximum	Normal Daily Temperature, °F Minimum	Average Monthly Precipitation in.
January	35.4	21.3	2.67
February	36.1	20.8	2.33
March	43.9	26.3	3.13
April	57.3	36.7	3.41
May	68.9	47.0	3.52
June	78.3	57.2	3.43
July	82.4	61.3	3.31
August	80.8	60.0	3.28
September	74.5	53.8	2.90
October	63.4	43.4	2.42
November	48.8	33.7	2.61
December	37.0	24.0	2.34
Yearly Average	58.9	40.5	Yearly Total 35.35

Table 3

Percent of Time Discharge Indicated Was Equalled or Exceeded

Period	Discharge	5	10	15	20	25	30	40	50	60	70	75	80	85	90	95
		Percent of Time Discharge Indicated Was Equalled or Exceeded														
		Cuyahoga River at Independence														
1922, 1928-35, 1941-65	cfs	2860	1900	1470	1200	980	800	545	400	305	248	225	205	184	166	143
	cfs/square mile	4.05	2.69	2.08	1.70	1.39	1.13	0.771	0.566	0.431	0.351	0.318	0.290	0.260	0.235	0.202
1956-60	cfs	3250	2400	1820	1520	1300	1130	890	700	550	435	385	345	305	258	220
	cfs/square mile	4.60	3.39	2.57	2.15	1.84	1.60	1.26	0.990	0.778	0.615	0.545	0.488	0.431	0.365	0.311
1961-65	cfs	2420	1600	1160	880	670	520	385	290	237	208	201	198	195	188	175
	cfs/square mile	3.42	2.26	1.64	1.24	0.948	0.736	0.545	0.410	0.335	0.294	0.284	0.280	0.276	0.266	0.249
Adjusted to 1931-60	cfs	2800	1980	1480	1160	930	750	500	375	298	240	216	195	173	153	132
	cfs/square mile	3.96	2.80	2.09	1.64	1.32	1.06	0.707	0.530	0.421	0.339	0.306	0.276	0.245	0.216	0.187
		Rocky River near Berea														
1922-35, 1944-65	cfs	1120	560	335	267	182	140	83.0	50.0	32.0	20.0	15.4	11.8	8.80	6.40	3.90
	cfs/square mile	4.19	2.10	1.33	0.925	0.682	0.524	0.311	0.187	0.120	0.075	0.058	0.044	0.033	0.024	0.015
1956-60	cfs	1280	675	440	315	246	198	131	90.0	60.0	39.5	32.0	25.5	19.2	14.0	9.30
	cfs/square mile	4.79	2.53	1.65	1.13	0.921	0.742	0.491	0.337	0.225	0.148	0.120	0.096	0.072	0.052	0.035
1961-65	cfs	830	450	272	180	126	84.0	58.0	39.0	26.0	17.2	13.7	11.0	9.00	7.30	5.55
	cfs/square mile	3.11	1.69	1.02	0.674	0.472	0.315	0.217	0.146	0.097	0.064	0.051	0.041	0.034	0.027	0.021
Adjusted to 1931-60	cfs	1060	570	360	255	184	138	85.5	55.0	36.0	23.6	18.2	14.1	10.3	7.50	5.00
	cfs/square mile	3.97	2.13	1.35	0.955	0.689	0.517	0.320	0.206	0.135	0.088	0.068	0.053	0.039	0.028	0.019
		Chagrin River at Willoughby														
1926-35, 1940-65	cfs	1220	700	500	380	300	240	167	122	88.0	63.0	53.0	44.5	37.5	32.8	27.0
	cfs/square mile	4.96	2.85	2.03	1.54	1.22	0.976	0.679	0.496	0.358	0.256	0.215	0.181	0.152	0.133	0.110
1956-60	cfs	1340	830	610	470	372	305	221	168	129	99.0	86.0	73.5	61.5	49.5	36.0
	cfs/square mile	5.45	3.37	2.48	1.91	1.51	1.24	0.898	0.683	0.524	0.402	0.350	0.299	0.250	0.201	0.145
1961-65	cfs	1070	630	425	300	237	190	134	98.0	74.0	56.0	48.5	42.5	37.5	32.8	28.0
	cfs/square mile	4.35	2.56	1.73	1.22	0.963	0.772	0.545	0.398	0.301	0.228	0.197	0.173	0.152	0.133	0.114
Adjusted to 1931-60	cfs	1220	700	490	365	290	240	167	122	92.0	66.0	55.5	47.5	39.0	32.8	26.5
	cfs/square mile	4.95	2.85	1.99	1.48	1.18	0.976	0.679	0.496	0.374	0.268	0.226	0.193	0.159	0.133	0.103

Table 4

Computed and Observed Seiche Oscillation

Periods for the First Five Modes

Mode	Periods, hr: Computed: Platzman & Rao	Periods, hr: Computed: SEA	Periods, hr: Observed
1	14.08	14.37	14.38
2	8.92	8.41	9.14
3	5.70	5.53	5.93
4	4.11	4.03	4.15
5	3.69	3.62	--

Table 5

Frequency Distribution of the 76 Cases in Which the

Buffalo-Minus-Toledo Setup Exceeded 6 Ft

During the 20-Yr Period 1940-1959

(Based upon Hourly Scaled Values)

(from Reference 12)

Setup ft	Frequency Distributions for the Following Months*: Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	Total	Cumulative Total
6-7	0	3	9	9	7	1	4	2	35	76
7-8	0	0	5	2	3	0	0	0	10	41
8-9	0	1	7	0	4	1	1	0	14	31
9-10	2	0	3	1	0	0	3	0	9	17
10-11	0	0	0	0	1	1	1	0	3	8
11-12	0	0	1	0	0	0	0	0	1	5
12-13	0	0	1	1	0	0	1	0	3	4
13-14	0	0	0	0	1	0	0	0	1	1
Total	2	4	26	13	16	3	10	2	76	--

* There were no cases for the months May, June, July, and August.

Table 6

Water Chemistry Comparisons for the Central Basin of Lake Erie

(from Reference 43)

Constituents	1963-1964 Max	1963-1964 Min	1963-1964 Avg	1967-1968 Max	1967-1968 Min	1967-1968 Avg	Change %
Conductivity, µmho/cm	353	260	300	330	283	312	+3.7
Dissolved solids, mg/ℓ	239	137	178	283	147	196	+10.1
Total solids, mg/ℓ	218	159	185	307	153	202	+9.2
Chlorides, mg/ℓ	46	19	24	29	19	23	-4.2
Silica, mg/ℓ	9.6	0.2	0.68	0.98	0.15	0.37	-45.6
Soluble phosphorus, mg/ℓ	0.07	0.00	0.01	0.03	0.00	0.02	+100.00
Total phosphorus, mg/ℓ	--	--	--	0.05	0.01	0.02	--
Total nitrogen, mg/ℓ	1.30	0.07	0.43	0.98	0.28	0.47	+9.3
Organic nitrogen, mg/ℓ	--	--	0.25	0.78	0.12	0.32	+28.0
Ammonia nitrogen, mg/ℓ	0.39	0.00	0.09	0.21	0.02	0.10	+9.0
Nitrate nitrogen, mg/ℓ	0.84	0.00	0.09	0.43	0.00	0.05	-44.4
Chemical oxygen demand, mg/ℓ	16.0	3.1	7.1	11.9	5.2	8.6	21.1
5-day biochemical oxygen demand, mg/ℓ	--	--	--	2.7	0.0	1.0	--
Alkalinity, mg/ℓ $CaCO_3$	130	71	97	102	92	96	-1.0
Oxidation reduction potential, mv	--	--	--	612	354	470	--
Hydrogen ion concentration (pH)				8.9	7.7	8.4	--

Table 7

Concentration Ranges of Water Constituents

Cuyahoga River

(from Reference 44)

Constituent	River	Outer Harbor
Total phosphorus, mg/ℓ	0.17-1.53	0.08-0.55
Soluble phosphorus, mg/ℓ	0.05-0.30	0.03-0.16
Organic nitrogen, mg/ℓ	0.28-2.88	0.22-1.93
Ammonia nitrogen, mg/ℓ	2.60-4.36	0.36-2.42
Nitrate nitrogen, mg/ℓ	0.73-1.45	0.43-1.50
Chloride, mg/ℓ	83-294	32-90
Phenol, μg/ℓ	6-747	1-86
Total solids, mg/ℓ	403-936	219-585
Dissolved solids, mg/ℓ	339-828	173-428
Conductivity, μmho/cm	620-1,320	260-620
Coliforms/100 mg	9,000-1,000,000	1,400-58,000

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13. ABSTRACT

This report presents the scope of the U. S. Army Engineer Waterways Experiment Station's (WES) investigation of the proposed Lake Erie International Jetport and summarizes the data obtained from the literature and private individuals. This report is the first of a series published under the general title "Lake Erie International Jetport Model Feasibility Investigation." The objectives of the investigation, Part I, include a review of the literature concerning wave activity (wind waves, seiches, and tides) and mass circulation in Lake Erie, preliminary design of necessary hydraulic models, and preliminary application of analytical and/or numerical models to seiching and mass circulation. In order to accomplish the objectives, the investigation is separated into five tasks: (a) review of the literature, (b) seiche analysis, (c) wave refraction and diffraction analyses, (d) mass circulation analysis, and (e) preliminary model design. Existing lake geology, climate, bottom and shoreline characteristics, water balance, water temperature, lake levels, lake currents, wave regime, shore erosion, and water quality data in the central basin of Lake Erie near Cleveland, Ohio, are summarized in Part II. Mass flow direction and current speed distributions from 1964-1965 Federal Water Pollution Control Administration (now part of the Environmental Protection Agency) current observations at stations near Cleveland are presented. Areas of insufficient information found in the literature survey include synoptic and long-term mass circulation data, wind-generated wave hindcast, lake level data, and longshore sediment transport rates.

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