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WINTER CURRENTS IN LAKE HURON

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FOREWORD

This report presents the results of an investigation of water flow and temperature structure during winter in Lake Huron. Twenty-one current meter moorings were deployed in the lake in November 1974 and retrieved approximately 6 months later. Collected data were analyzed to determine the character of current flow during conditions of an almost isothermal lake water mass. This study was a cooperative effort of the National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory, the Canada Centre for Inland Waters, and Region V of the Environmental Protection Agency. It was partially supported by the Environmental Protection Agency through an Interagency Agreement and is a contribution to the International Joint Commission Upper Lakes Reference Study. The authors are particularly grateful to Dr. E. B. Bennett of the Canada Centre for Inland Waters for his arrangement for and coordination of Canadian participation in the study and to Mr. R. J. Bowden of the Environmental Protection Agency, Region V, for his generous support of field operations from the *Research Vessel Roger R. Simons*.

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WINTER CURRENTS IN LAKE HURON*

James H. Saylor and Gerald S. Miller

Twenty-one current meter moorings were deployed in Lake Huron during winter 1974-75. The moorings were set in November 1974 and retrieved approximately 6 months later. The stations were configured on a coarse grid to measure the lake-scale circulation during winter. Water temperature was also recorded in nearly all of the 65 current meters deployed. Results reveal a strong cyclonic flow pattern in the Lake Huron Basin persisting throughout the winter. The observed winter circulation was in essence very similar to what is now believed to be the summer circulation of epilimnion water, although the winter currents penetrated to deeper levels in the water column and were more intense. Winter cyclonic flow persisted in a nearly homogeneous water mass, while summer currents exhibited an almost geostrophic balance with observed water density distributions. This suggests that the current field driven by prevailing wind stresses across the lake's water surface may be largely responsible for establishing the horizontal gradients of water density observed in the lake during summer. Analyses of energetic wind stress impulses reveal the prevailing wind directions that drive the dominant circulations. The winter studies permit a description of the annual cycle of horizontal current speed variation with depth in Lake Huron, and in the other Great Lakes as well. The effects of ice cover are examined and the distribution and movement of the ice cover with respect to lake current and temperature fields are discussed.

1. INTRODUCTION

This report presents the results of an investigation of the character of winter current flow in Lake Huron. The investigative effort was undertaken during winter 1974-75 as a part of the International Joint Commission Upper Lakes Reference Study. The current surveys were accomplished through a cooperative effort of the Great Lakes Environmental Research Laboratory (GLERL) of the National Oceanic and Atmospheric Administration, The Canada Centre for Inland Waters (CCIW), and the United States Environmental Protection Agency (EPA), Region V. The study reported here represents the first serious attempt to describe the winter circulation of Lake Huron.

The earliest study of Lake Huron currents was reported by Harrington (1895) Drift bottles were released from cargo ships traversing Lake Huron during the summers of 1892 and 1893. By correlating release and recovery points of the drift bottles, he deduced a prevailing cyclonic flow pattern of Lake Huron surface water. noting especially a persistent southward flow along the entire length of the lake's west coast. Water moving southward along this shore was observed to return northward along the lake's east coast, closing the circulation pattern to form essentially a single cyclonic cell. We shall return to

*GLERL Contribution No. 111.

Harrington's observations later in this report as the winter observations reported here reveal some remarkable comparisons with this early effort to describe currents.

Ayers et al. (1956) performed three multiship synoptic surveys of Lake Huron during the summer of 1954, observing on several Lake Huron cross sections distributions of physical, chemical, and biological properties of the water mass. Using the observed water temperature distributions and a dynamic height method developed for fresh water to compute geostrophic currents, they determined current flows from the water density field for each survey. The current patterns determined were in general more complex than Harrington's results, although there were certain similarities in the reported cyclonic character of the gross circulation.

In the summer of 1966, the Federal Water Pollution Control Administration (FWPCA) performed extensive measurements of currents in Lake Huron by mooring a large number of current meters at numerous open lake locations. Subsequent to this data collection effort, reorganization within the Federal government placed this activity within the EPA. Changing program priorities prevented timely analyses and reporting of these surveys. As part of the International Joint Commission Upper Lakes Reference Study, GLERL undertook analyses of these current data and the results were reported by Sloss and Saylor (1975). This effort was subject to many shortcomings because of inherent instrument limitations in the generation of current meters used in the surveys and the loss of documentation in the interval between data collection and analysis. In spite of these shortcomings, evidence of a general cyclonic lake circulation was revealed to support the nature of the gross summer current patterns reported previously.

All of these previous investigative programs were performed during summer and fall, when the Lake Huron water mass is typically density stratified. Several current meter moorings were set along the west coast of the lake during winter 1965-66 by FWPCA, but the effort was unsatisfactory for determining large-scale characteristics of winter circulation (FWPCA, 1967). With the near absence of any knowledge of winter currents in Lake Huron, the program described in this report was initiated. The winter season is characterized by an almost isothermal water mass in Lake Huron, as is true of the other Great Lakes as well. Circulation during this long season of nearly homogeneous water in the lake basins has received very little attention, primarily because of the difficulties and rigors of working during the severe weather associated with winter on the Great Lakes.

The bathymetry of Lake Huron is shown in Figure 1. Also shown in the figure are locations of the 21 current meter moorings placed in the lake during the winter of 1974-75. Comparison of the bottom topography with station configuration gives some idea of the plan of study, which we will discuss in more detail later in this report. The geology of the region played an important role in shaping the Lake Huron Basin. The north shore of the lake, along the North Channel and northeastern shore of Georgian Bay, is on the edge of the Precambrian Canadian Shield. The lake basin otherwise was carved out of the Paleozoic

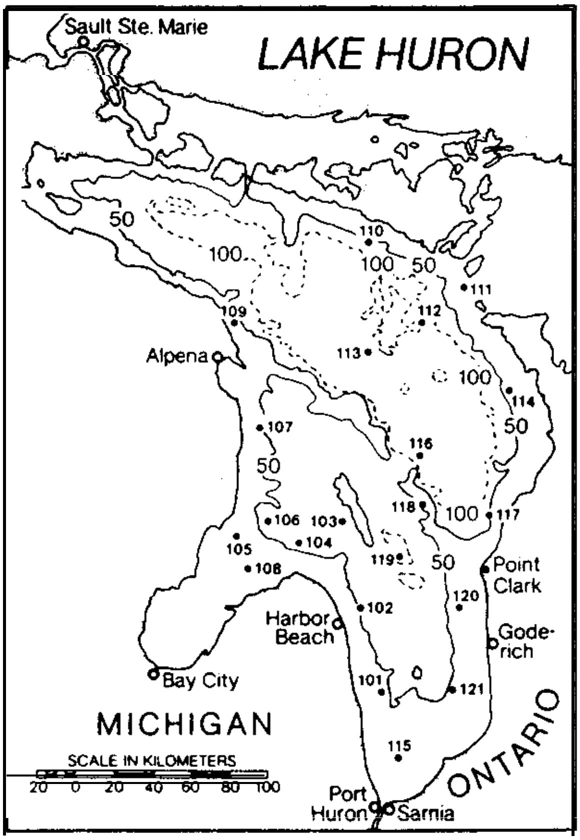


Figure 1. Location map showing current meter mooring sites and Lake Huron bathymetry. Only the 50 and 100 m contours are shown as the bottom in the deep northeastern basin is very irregular, exceeding depths of 150 m in over 30 percent of its area.

rock province of the region (Hough, 1958). Resistant formations within the Paleozoic province may be correlated with the major bathymetric features of the lake bottom. Niagara Dolomite is the hard, erosion-resistant formation that forms the Lake Huron shoreline for a distance of nearly 60 km east of the Straits of Mackinac. It continues southeastward to form the southern and southwestern shores of the chain of islands separating Lake Huron from Georgian Bay and the Bruce Peninsula. Along the Michigan shore, resistant formations of the Rogers City and Traverse Group formed lake shores and headlands from Thunder Bay at Alpena, Mich., northward to Presque Isle, Mich. From Thunder Bay southeastward, the underwater extensions of these resistant formations formed the most important bathymetric feature of the lake basin, a ridge that extends across the lake to Clark Point on the Canadian shoreline nearly 15 km southwest of Kincardine, Ont. This ridge is a very prominent feature of basin topography and it rises to within 11 m of the lake surface near the middle of the lake at Six Fathom Bank. The northeastern face of the ridge is very steep as the lake bottom descends to depths exceeding 200 m, while the ridge itself is generally 30 to 60 m deep. Southwest of the ridge the lake bottom descends more gradually to depths of 70 to 100 m. Thus, the southeastward trending ridge separates the lake into two distinct basins.

I" this report we will present evidence that there is in fact a prevailing and dominant patter" of water current flow in Lake Huron during winter. seasonal and monthly current roses of water transport will be presented, and the response of the lake to episodes of strong and steady wind stress will be examined. The winter Studies make possible a description of the annual kinetic energy cycle of the Lake Huron water mass.

2. METHOD

Twenty-one current meter moorings were Set in Lake Huron during the latter half of November 1974. Each mooring consisted of a string of current meters suspended on a taut line beneath a subsurface float. Current meters were planned for placement at uniform depths of 15, 25, and 50 m below the water surface and at 2 m above the bottom; actual depths of the current meters deployed varied only slightly from the planned depths. Most of the moorings were Set in water about 50 m deep and included three current meters. Three moorings were Set in much deeper water and included the full complement of four current meters. Current meter depths on each mooring and the length of record obtained from each meter are summarized in Figure 2. Moorings numbered 114 and 117 were not recovered in the spring of 1975, having been lost in regions of large surface wave stress during winter storms.

Twelve moorings were deployed by CCIW from the *Canada Survey Ship Limnos*. Current meters on these moorings were a mix of Plessey model M021's and Geodyne model 850's. All of the current meters had a" integral temperature recorder. The remaining nine moorings were deployed from the EPA *Research Vessel Roger R. Simons* and included a mix of AMF vector averaging current meters and Geodyne model A-100's. Only the AMF meters had a" integral temperature recorder on these moorings. All of the winter moorings included an acoustic release just above each mooring's sinker for recovery in the spring of 1975 and a ground line of several hundred meters of polypropelene for recovery with a grapnel in the event of release failure.

No other measurements were attempted during the course of the winter current meter deployments. It was felt that existing meteorological stations around the perimeter of the lake were sufficient for adequate description of wind and air temperature fields influencing Lake Huron. Many of the current meter stations were placed fairly close to shore (10 to 20 km) St a water depth of about 50 m. The placement of current meters "ear the lake boundaries was based on considerations of the present knowledge of lake circulations during the density stratified season as all of the lakes have revealed that the strongest and most persistent currents are observed within the first 20 km or thereabouts lakeward of the coasts. Flow in the coastal strips in long-term averages is essentially parallel with the bathymetric contours and during summer these regions are characterized by strong, though variable, horizontal density gradients. I" retrospect, the placement of current meters "ear the lake boundaries was a good choice as the results presented herein will illustrate. Other areas of current meter concentrations included the mouth of Saginaw Bay and the southeastern section of the ridge separating the lake into two distinct basins.

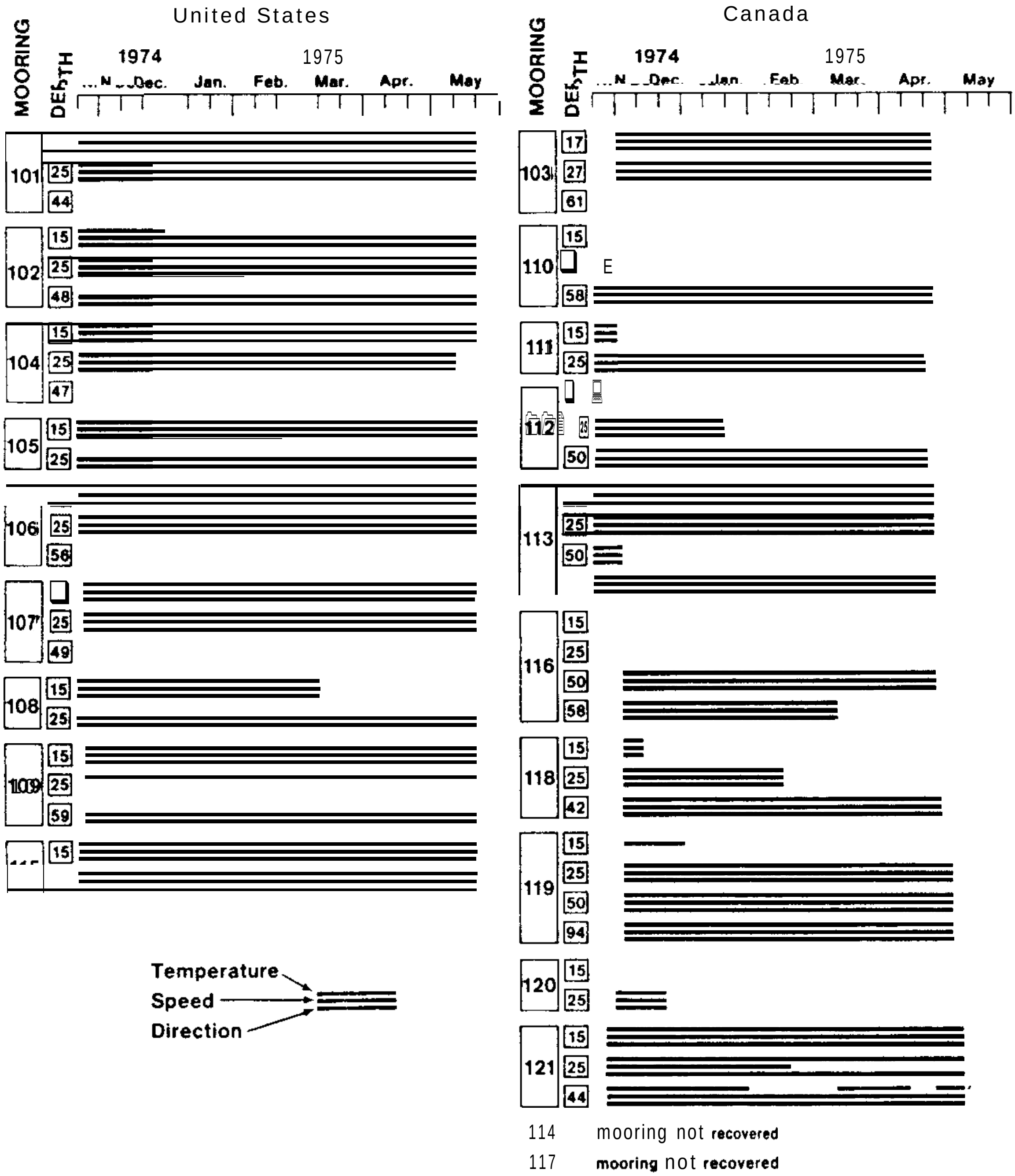


Figure 2. Summary of data returned from each current meter deployed in Lake Huron during winter 1974-75.

3. RESULTS

3.1 The Character of the Wind Field

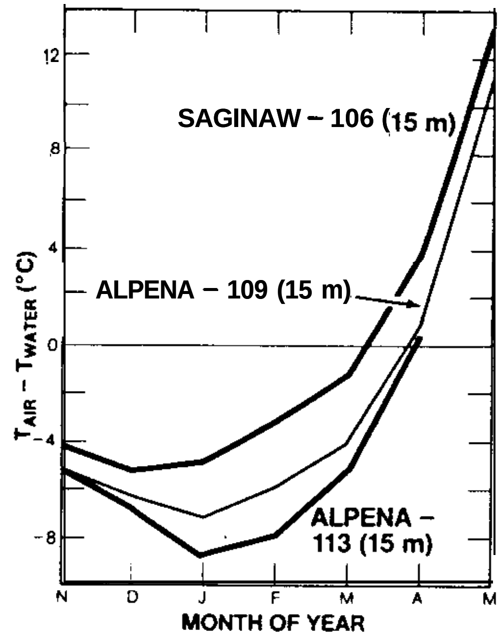
Great Lakes weather is characterized by high-pressure systems with associated fair skies interrupted every 3 to 4 days by the passage of synoptic-scale low-pressure storm systems. Air masses determining Great Lakes weather are of Pacific origin about 30 percent of the time during summer and 75 percent of the time during winter. Gulf of Mexico air masses constitute 10 to 40 percent of the summer weather, but seldom penetrate as far north as the upper lakes in winter (Phillips and McCulloch, 1972). Arctic air outbreaks during winter are common over the basin.

The Great Lakes act as a vast reservoir for the storage of heat energy and its subsequent exchange with the atmosphere. During fall and winter, intense heat and momentum transfers occur and the Great Lakes' interaction with, and influence on, synoptic and mesoscale weather are greatest. Cold, dry Arctic air moving across the warm water of the Lakes triggers numerous phenomena such as increased cloudiness, convective precipitation, increased down-wind air temperature, and intensification of low-pressure systems due to large inputs of heat and moisture.

Air mass modification occurs rapidly. Phillips (1972) found that during cold air outbreaks over Lake Ontario more than half the total temperature modification occurs over the first 3 km of water. The degree of modification is a function of the initial air-water temperature difference and the length of time the air is over the water. Phillips's results also show that, in the lowest 15 ❑ , the maximum modification usually does not exceed 55 percent of the total possible modification. (Total modification is when the air warms to the same temperature as the water.) A mesoscale consequence of the addition of heat energy and moisture is the creation of a local system with cyclonic vorticity, a low-pressure trough that in terms of pressure translates into a deficit of up to 6 mb over the lake area (Petterssen and Calabrese, 1959).

With upward heat flux, a high intensity of turbulence in the atmospheric boundary layer is produced by buoyancy. This increased vertical exchange of momentum during winter results in increased wind speeds in the surface layer and, presumably, a decrease of speed in the upper layers. It has been established that overwater wind speed is indeed a function of the difference between land air temperature and water temperature, which is a measure of the atmosphere's stability. For example, with the water 8°C warmer than the air temperature, Richards et al. (1966) found that the overwater wind speed over the lower Great Lakes was about twice that of the upwind land station. The mean monthly thermal stability values ($T_{air} - T_{water}$) using Alpena and Saginaw, Mich., air temperatures and 15 m water temperatures from nearby moorings show the characteristic pattern (Fig. 3). Very unstable conditions exist from November through March, implying that for this period the wind speeds over Lake Huron are probably about twice those recorded at nearby land stations. During April the air becomes increasingly warmer and hence is neutral to slightly stable, while conditions during May are extremely stable.

Figure 3. Comparison of air temperature measurements at meteorological stations near the west coast of Lake Huron and water temperatures at 15 m depth at nearby current meter moorings during winter 1974-75.



During April and May the cold water rapidly cools the air above by conduction and a cold dome of extremely stable air extends 100 m to occasionally 1500 m above the lake surface (Lyons, 1970). The conduction inversion that develops is generally less than 100 m deep and strengths of 25°C/100 m have been reported (Bellaire, 1965). The cold air dome and inversion effectively shield the lake from surrounding atmospheric influences. Vertical exchange of momentum is drastically reduced with the results that cumulus clouds are absent over the water due to subsidence, thunderstorms are suppressed, and most important for this study, wind speed and consequently waves and currents are dramatically reduced. This mesoscale anticyclone appears to be a separate feature of each of the Great Lakes (Strong, 1972) and is more pronounced over large, deep lakes like Lake Huron.

Wind data from five stations, Alpena and Saginaw, Mich., and Goderich, Bruce Ontario Hydro, and Southampton, Ont., were used to define the wind field over the lake. The mean monthly wind speeds for November 1974 through May 1975 show that speeds at most stations peaked in January, dropped off slightly through April, then decreased markedly in May (Fig. 4). The decrease in May was due to the cold air over the lake, which spilled over the nearshore land area, and the general decrease in the synoptic pressure gradients. Note that Saginaw, farthest from the lake and probably out of the cold air influence, experienced a lesser speed decrease.

Wind run roses for the five recording stations, expressed as a percentage of the total wind flow past each anemometer during the analysis interval, are shown on all subsequent 15 m current maps. The wind roses are displayed according to meteorological convention, i.e., the direction is that from which the

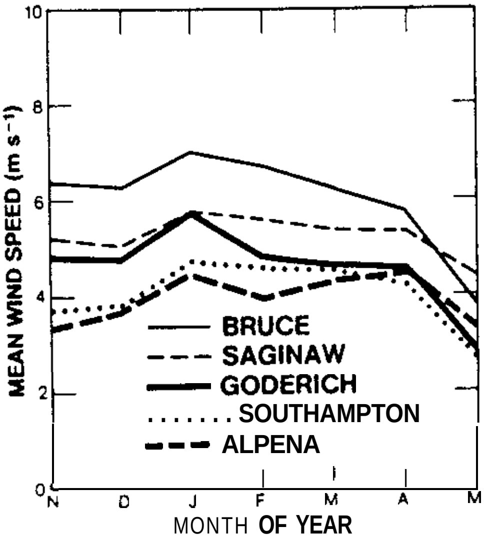


Figure 4. Monthly mean wind speeds measured at five meteorological stations about the perimeter of Lake Huron.

wind blows. The prevailing directions, southwest through northwest, and mean scalar speeds for the period of about 4 m s^{-1}, indicate that the November 1974 through May 1975 wind regime was near "normal." No attempt has been made to adjust the measured land winds to simulate overwater conditions. It must be kept in mind that instrument location and exposure can cause variations in the measured winds and that overwater winds are dependent on thermal stability as described by Richards et al. (1966) and others.

3.2 Water Temperature Structure

A comprehensive study describing water temperatures in the Great Lakes was published by Millar (1952). who constructed monthly temperature charts for each of the lakes during 1935 to 1941 using temperature data from ships' intakes. Data from the navigation months were extrapolated to obtain means for the winter months. Measurements of winter temperatures were limited to the surface layer using the airborne radiation thermometer (ART) technique (Richards et al., 1969). Satellites also provided infrared data. However, both methods are limited to cloudless days and measure only surface temperature. Temperature data obtained during the 1974-75 Lake Huron winter study provided the first continuous large-scale synoptic picture of winter temperatures in Lake Huron.

During the period of study, the winter temperature structure was essentially isothermal at all stations (Fig. 5), indicating that mixing was taking place throughout the water column. Though the shallowest depth at which water temperature measurements were taken was at 15 m, bathythermograph results from Lake Michigan show that the water temperature in winter is uniform from the surface to at least 120 m (FWPCA, 1967). There are periods during calm, cold conditions when a shallow reverse thermocline forms, but such stratification is readily destroyed by wind and turbulence. A winter thermocline of unspecified magnitude at a depth of about 180 m was observed in Lake Michigan, with indications of large-amplitude internal waves on the thermocline (FWPCA, 1967).

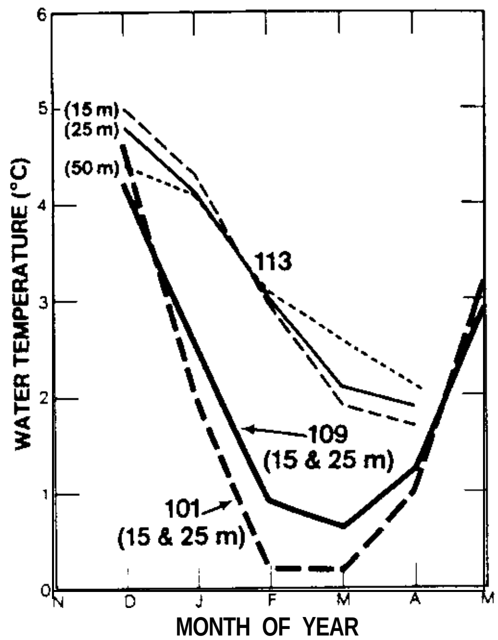


Figure 5. Monthly mean water temperatures from Lake Huron's deep northeastern basin (mooring 113), the northern part of the lake off Alpena, Mich. (mooring 109), and the southern end (mooring 101).

In Lake Huron a temperature difference of up to 0.8°C was observed between 25 and 136 m depths in the deep northeastern basin in March, but it is doubtful that this weak temperature gradient would result in significant internal wave development.

Some spatial characteristics of the observed Lake Huron winter temperature field are shown in Figure 5. The nearshore areas (moorings 101 and 109) cooled rapidly, with the minimum temperature of 0.2°C first occurring in middle-to-late February, while the northeastern basin did not reach its minimum of 1.5°C until early April. The monthly cooling rate in the northern basin was about 1°C per month from December through March, while the rate was 1.6°C per month in the southern basin. The largest horizontal temperature gradient was in February, when the nearshore areas had cooled to near zero and the mid-lake region was still about 3°C. It was also the month with the coldest air temperatures and maximum ice cover. Figure 6 shows the isotherm pattern for the upper 15 m. Lack of data in the eastern part of the lake required some suppositions (given as dashed lines). Other winter months showed basically the same isotherm pattern, although the horizontal gradient was less, and were similar to ART results (Richards et al., 1969).

The winter thermal structure is established and maintained through the interaction of several processes. The coldest air temperatures are associated with westerly and northwesterly winds and so the greatest heat flux takes place within the first 10-20 km lakeward from the west shore. When the shallow nearshore water cools to near zero, ice formation retards wind generated mixing, prevents conductive heat flux with the air, and reduces radiational heating. A winter thermal bar, a sharply defined boundary between the near-zero inshore water and 2°C offshore water, was observed about 16 km offshore in Lake Michigan from bathythermograph surveys (FWPCA, 1967). Although bathythermograph surveys

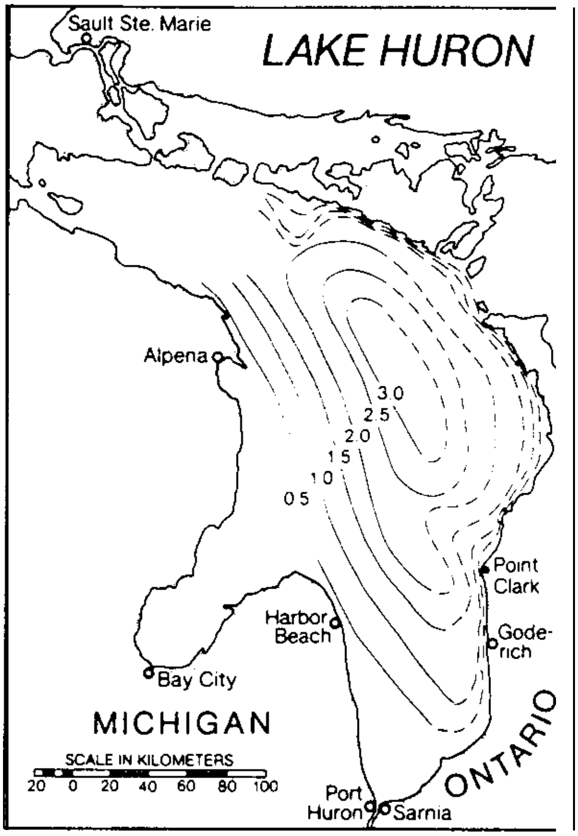


Figure 6. Monthly mean water temperatures (°C) at 15 m depth during February 1975 in Lake Huron. Distributions in the eastern parts of the lake are assumed, but ice was present along the east coast, indicating the presence of near 0°C water.

were not performed during the Lake Huron winter study, the monthly temperatures from inshore and midlake locations and the extent of the ice formation suggests that a winter thermal bar probably exists in Lake Huron also, at least around the northern basin. The sharpness of the thermal discontinuity and its effectiveness in inhibiting mixing between the two water masses needs further clarification.

The shallower southern basin cools most rapidly through conduction and convection and the mid-lake ridge inhibits subsurface water movement between the two basins. A comparison of temperatures to the north, south, and on the ridge (moorings 116, 119, and 118, respectively, in Fig. 7) shows that the northern basin was cooler until mid-January and thereafter warmer through April. The temperature difference reached a maximum of 1.6°C in March. During January and February the ridge temperature (at mooring 118) was colder than either basin, which is consistent with previous data observed in this area. Individual ART surveys in winter and spring showed the isotherms following the general isobaths of the ridge; transparency measurements showed a tongue of more turbid water extending northwestward into the lake (Ayers et al., 1956), and satellite imagery showed turbid plumes meandering lakeward in the ridge area, with the water over the ridge warmer than either basin during the summer warming period (Strong, 1974). Apparently a part of the northward flow along the eastern shore is deflected lakeward by the ridge, resulting in more turbid water over the ridge and cooler or warmer temperatures, depending on the season.

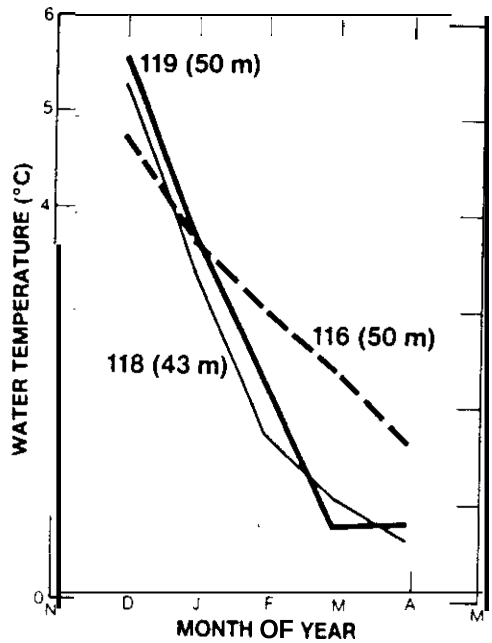


Figure 7. Water temperature distribution across the mid-lake ridge. Mooring 116 was just north of the ridge in the southern part of the deep northeastern basin, mooring 118 was on the ridge, and mooring 119 was just south of the ridge in the southern basin.

3.3 Seasonal and Monthly Current Patterns

Currents observed during the winter surveys are summarized as monthly and seasonal current roses in Appendix A. The current roses present the distribution of current run, expressed as a percentage of the total water transport past each current meter suspended in the water column, in a fashion analogous to our presentation of wind statistics. The current roses are draw" to show the percentage of flow past each meter toward each octant in the oceanographic preference, while the wind run roses retain their usual presentation in the direction from which the wind is blowing. There are, of course, many alternative techniques for the presentation of flow statistics. The choice made here has the advantage that it is easily interpreted visually to give patterns of dominant water transport in addition to some indication of the variability of current flow. The disadvantage of this sort of presentation is the absence of a suitable display of the lake-scale distribution of current speeds. To display representative current speeds for lake currents, we will include several charts of resultant current vectors.

3.3.1 November 1974

The winter current studies started in November and current patterns presented represent only the latter third of the month. Figures A.1a-d, show the current and wind roses for this period. Each level of observation is show" on a separate chart and it should be noted that several current meters used at the 25 m level were just 2 m off the bottom (those at the mouth of Saginaw Bay and at the extreme southern end of the lake), as were many of the current meters shown at the 50 m level about the perimeter of the lake and on the mid-lake ridge. I" general, current meters at the 25 and 50 m levels showed flow characteristics very similar to shallower current meters on the same mooring for the duration of the winter season. Therefore, current meters near the bottom at 25 and 50 m were usually still very much within the upper level flow regime during winter in Lake Huron and are presented as such. Bottom currents at 2 m off the lake floor are shown only in much deeper water.

November winds prevailed from the southwest quadrant at meteorological stations in the southern half of the Lake Huron basin, while Alpena recorded a higher percentage of wind from the north-northwest. Lake water temperatures were nearly uniform throughout the upper SO m, averaging a little less than 6°C in the northern half of the lake and just over 7°C in the southern half of the lake. Along the Michigan coast a dominant southward flow characterized the circulation. This steady southward flow ran parallel to the bathymetry and was present from surface to bottom with unchanging steadiness. Not all of the current meter moorings were deployed in the eastern part of the lake, but reporting stations showed a return northward flow along the east coast closing the circulation to form one large cyclonic cell. The pattern of flow was especially steady and persistent about the perimeter of the lake, with only mooring 113 in the center of Lake Huron's northern reaches showing much variability. Here the resultant flow was northward at all levels. East-southeastward flow at the 50 m level at mooring 112 persisted for the entire winter season. Mooring 112 was placed on a ridge-like structure protruding eastward into the lake basin from the vicinity of Cove Island. The lake bottom is deeper both north and south of the station, and the 50 m level flow was nearly parallel with the local bathymetry.

The coherent pattern of lake-scale circulation illuminated by the November data is unusual in comparison with earlier reported surveys of currents in Lake Huron during summer (cf., Sloss and Saylor, 1975). The consistent pattern of lake-scale flow, as observed especially along the western coast of the lake, is attributed to the improved instrumentation used in the surveys and not to any fundamental changes in the character of Lake Huron currents.

3.3.2 December 1974

December winds were predominantly southwesterly over the entire lake basin (Fig. A.2a). Water temperature was nearly isothermal throughout the lake, averaging just over 4°C. Currents observed during December are shown in Figures A.2a-d. Southward flow along the west coast of Lake Huron south of Alpena continued to be the dominant feature of lake circulation. Return flow along the eastern shore was not as persistent as observed in November, although the eastern shore current meters and most of the mid-lake stations exhibited a general northerly drift. Mooring 118 on the mid-lake ridge showed northwesterly flow at both 25 and 50 m, while at mooring 119 south of the ridge the flow below 50 m was northerly. North of the ridge the current meters at 50 m and near the bottom at mooring 116 exhibited southeasterly flow, a pattern that persisted throughout the winter.

At the mouth of Saginaw Bay, current meters at 15 and 25 m depth indicated a clockwise flow pattern. This is consistent with the work of Danek and Saylor (1976), who found that a clockwise eddy occupied the outer reaches of the bay during southwest wind conditions, with the core of southerly flow along the west coast of Lake Huron pushed lakeward. On the other hand, northeasterly wind caused a part of the Lake Huron flow to sweep in a counterclockwise loop through the outer reaches of the bay, exiting the bay in eastward flow just north of the Michigan thumb.

3.3.3 January 1975

Southwesterly wind flow in January (Fig. A.3a) was similar to the wind distribution observed in December, although the mean wind speed was greater, as January recorded the highest mean wind speed during the 1974-75 winter season. Cooling of the lake's water mass resulted in nearshore water temperatures averaging about 2°C, while over the deep northeastern basin water temperature averaged a little less than 4°C. Current flow during the month is summarized in Figures A.3a-d. The circulation was essentially unchanged from December. Southward flow along the east coast of Lake Huron continued to be the dominant feature in the lake. Flow along the mid-lake ridge retained the characteristics observed the previous month, with northwestward movement on the ridge itself and a southeastward return in deeper water to the north along the southern margin of the deep northeastern basin. The clockwise eddy at the mouth of Saginaw Bay intensified from the December pattern, and the southerly coastal flow migrated lakeward far enough for mooring 106 to be influenced by this localized cell of circulation.

3.3.4 February 1975

In February, winds shifted to a more westerly direction with more episodes of wind with a northerly component. Continued cooling of lake water near the coasts caused water at nearly 0°C to encircle a warmer core of denser water centered over the deep northeastern lake basin. Currents, shown in Figures A.4 a-d, were strongly cyclonic. Currents along the Michigan coast were almost exclusively southward, and northward return flow along the Ontario coast was very steady in the southern basin. Flow through the outer reaches of Saginaw Bay was in one large counterclockwise loop.

We note that with the westerly wind of February, flow at mooring 118 on the mid-lake ridge lost its strong northwestward character, changing to southeastward flow at 25 m and bimodal at 50 m. The flow remained nearly parallel with the bathymetry, though, as it did throughout the season. North of the ridge, mooring 116 continued to record southeastward flow at deeper levels in the northeastern basin of the lake. South of the ridge, southeastward flow at 25 m at mooring 119 was accompanied by more northward flow components deeper in the water column.

3.3.5 March 1975

The water temperature patterns of February continued into March, as cold, near 0°C water surrounded slightly warmer water centered over the deep northeastern basin. This warmer water had cooled somewhat from February, however, and averaged about 2°C for the month. Wind over the Lake Huron basin prevailed from the northwesterly quadrant (Fig. A.5a). Currents observed during March are shown in Figures A.5a-d. Flow throughout the lake basin was very strongly cyclonic, almost exclusively southward along the west shore, and northward along the southeast shore. Flow toward the southeast along the mid-lake ridge at 50 m (mooring 118) conformed with bathymetric constraints and was similar to the February currents. Southeastward flow at mooring 112 at 50 m still persisted as it had all winter, while mooring 110 at 50 m was now dominantly southeastward also.

3.3.6 April 1975

April winds were northwesterly, very similar to the wind distribution observed in March. Currents during April (Figs. A.6a-d) were very similar to those during March, characterized by very steady southward flow along the west shore of the lake and northward return flow along the east shore south of Clark Point. A steady counterclockwise flushing of Lake Huron water through the outer reaches of Saginaw Bay was also prominent. The start of spring warming near the coasts of the lake established an almost isothermal lake during April, with monthly averaged water temperatures varying no more than 1°C throughout the basin.

3.3.7 May 1975

The Canadian current meters were removed in early May, while the United States meters were removed in late May. Therefore only the west shore of the lake is covered in Figures A.7a-c, but data from these meters show a remarkable change in the character of Lake Huron current flow. As noted earlier, intense atmospheric stability over the cold lake surface in May was associated with reduced wind speeds at stations along the perimeter of the lake. This sheltering of the lake surface from strong wind stress resulted in a catastrophic decrease in the kinetic energy of the water mass and, inferred from the observed current patterns, the loss of an organized pattern of current flow in the lake. The southward flow along the lake's west coast, as observed in all earlier months, was absent although a counterclockwise flow through the outer parts of Saginaw Bay was still apparent. The warming of nearshore water that started in April continued through May so that at the time of current meter removal, shorebound water as warm as 8° to 10°C had reached offshore to the 15 m level at several of the current meter stations. The neat-shore warming and concomitant establishment of significant horizontal temperature gradients does not in itself, however, prove the existence of characteristic circulation patterns in the absence of significant wind stress.

3.3.8 Winter Circulation

Wind and current roses for the entire winter season are shown in Figures A.8a-d. Only those meters operating a significant part of the season are included. The patterns show that there was clearly a dominant, or characteristic, current flow during the 1974-75 winter season in Lake Huron. Southward flow along the lake's west coast was very steady and extended from Alpena to the southernmost end of the lake. The mouth of Saginaw Bay exhibited two patterns of circulation, either a counterclockwise loop of Lake Huron water flowing through the outer bay during northerly wind, or a clockwise eddy in the outer bay during southwesterly wind. Return northward flow along the east coast of the lake was not as clearly defined except in the region south of Clark Point. Unfortunately, many of the current meters in the important coastal zone in the northeastern part of the lake failed to return useable current records.

To indicate current speeds associated with the winter circulation, resultant current vectors for the season are shown in Figure 8. The highest current speeds wet-e observed close to the coast, with speeds decreasing toward the center of the basin. The strongest resultant currents were associated with the southward flow along the lake's west coast, with the remainder of the lake exhibiting a less intense northerly drift forming one large cyclonic cell of circulation. Flow along the mid-lake ridge was usually parallel with the bathymetry, either northwesterly or southeasterly, although the vector resultant current was northward. Just north of the ridge, currents at deeper levels at mooring 116 were southeasterly along the southern flank of the deep northeastern lake basin.

Mooring 111 between Georgian Bay and Lake Huron has not been discussed in connection with lake circulation as it was placed in a north-to-south trending channel separated from the lake by intervening shallower depths. The resultant current vector for the season indicates an inflow of water to Georgian Bay at the 25 m level, however, which was probably balanced by a return flow to Lake Huron at deeper depths as reported during summer (Sloss and Saylor, 1975). The 50 m level at mooring 109 was also poorly exposed and probably exhibited local effects not closely tuned to whole lake patterns because of the shoal water that protruded eastward in the lake just north of North Point at Alpena. (Depths shallower that 10 m occur south-southeast of this mooring.)

To get an idea of the volume of water transported about the lake by the resultant circulation, we computed the south-southeastward volume transport across the section of the lake between moorings 103 and 104, just east of Saginaw Bay. The lake bottom between these two stations is flat, with an average depth of about 50 m. We know the velocity distribution in the upper 25 m and could reasonably assume a conservative velocity profile as linearly decreasing from the 25 m level to no flow at the lake bottom. The resulting volume flux was about 40,000 m^3/s, or roughly eight times the long-term average discharge of the St. Clair River. Throughout the survey interval (about 180 days), this meant that about 625 km^3 of water was transported southward through the section. This is nearly one-fifth of the total water volume of Lake Huron (3,500 km^3). Most of this water must have returned northward in the eastern parts of the lake basin. This implies that the bulk of the lake's water mass

Figure 8. vector resultant current flows in Lake Huron during winter 1974-75. The depth (m) of each current velocity measurement is shown with the current vector.

is certainly in a well-mixed condition. Short-term transports through the section, both southward and northward, were of course much greater, accelerating the mixing of lake water.

3.4 Episode Analysis

Circulation patterns depicted by the seasonal and monthly current maps are the integrated result of all the wind stress fluctuations and accompanying currents that occurred during that particular time period. It is also instructive to examine the current response and circulation patterns that develop during short-term episodes of steady wind stress.

Synoptic weather systems pass over the Great Lakes region rather quickly; therefore times when winds are directionally steady are usually limited to several days duration. The episodes discussed in the following sections were selected on the basis of wind data, primarily from Saginaw and Alpena. All periods of 3 days or longer with nearly steady wind direction and mean wind speeds of 5 m s^{-1} or greater are presented. The wind and current data are concurrent; lag time to allow for current response was not applied because the periods of steady wind stress did not always exactly coincide between stations and current response varies with several factors such as location and depth. This does not present a serious problem since there are normally generation, steady state, and decay epochs associated with significant storms so that any residual currents from a previous regime are soon overpowered by currents generated during the selected episode. Data are presented in the same form as in the previous section and are contained in Appendix B.

3.4.1 20-22 November 1974

A deepening low-pressure center moved across the northern states and passed over Lake Huron on 20 November. Strong cyclonic circulation over the northeast United States continued as the center migrated across New York on the 21st. Winds over the lakes were westerly to northerly during the 3-day period (20-22 November), with mean speeds along the perimeter of Lake Huron of 5 to 7 m s^{-1}. Not all the current meters had been deployed, but large-scale cyclonic circulation in the lake with a counterclockwise loop through the outer portion of Saginaw Bay is evident in charts (Figs. B.1a-d) for that date. The current penetrates to at least 50 m with little change in direction except at mooring 112, where the current is almost exclusively northwesterly at 15 m, northerly at 25 m, and easterly at 50 m. As pointed out in the discussion of the monthly currents, mooring 112 was positioned on a ridge and the 50 m depth flow paralleled the bathymetry during the entire winter. Although the shallow meters on moorings 110 and 112 failed shortly after this episode, the currents are indicative of what can be expected during the rest of the winter when there is a northwest wind.

3.4.2 30 November-2 December 1974

Northeasterly winds 5 to 8 m s^{-1} across Lake Huron 30 November through 2 December resulted from a deep low-pressure system that developed over the southwestern states and migrated across Tennessee and Virginia. Currents during these 3 days (Figs. B.2a-d) showed a clockwise gyre in the southern part of the lake. The counterclockwise looping through the outer region of Saginaw Bay was consistent with patterns observed by Danek and Saylor (1976). There was considerable shear in the bay. Mooring 108 showed the water moving into the bay at the 15 m level with the wind stress; however, the outflow speed at 25 m was about twice that of the inflow and caused a net eastward flow past the site. The current speed at mooring 105 was about 60 percent higher at the 25 m depth than at 15 m. Flow at the 15 m depth at mooring 109 was northwesterly, a typical response to northeast winds and not unexpected because of the shoal water south and east of the mooring. Mooring 104 showed a similar response, possibly due to the shape of the shoreline. Northwesterly flow on the shallower water of the mid-lake ridge (mooring 118) was just exactly opposite to the flow of water in the deeper water north and south of the ridge, a pattern that persisted for much of the winter due to the local bathymetry.

3.4.3 26-29 December 1974

A week of west to southwest wind across Lake Huron dominated the weather in late December as the eastern half of the United States and Canada were under the influence of a massive high-pressure system centered over the southeastern states. Figures B.3a-d show the general cyclonic flow pattern that existed in Lake Huron during the last 4 days of the week-long episode when the current patterns were well established. The currents were very similar to those observed for the entire month of December, when southwesterly winds prevailed. Southward flow along the lake's west coast was not quite as sharply delineated as it was during more westerly and northwesterly wind stresses, and a clockwise pattern of current flow existed in the mouth of Saginaw Bay. Northwestward flow along the crest of the mid-lake ridge was again evident.

3.4.4 9-11 January 1975

A deep trough extending from northwest Canada to Texas developed over the Plains States. The center moved northeastward over the Midwest and the Great Lakes Basin on 11 January and continued into Canada. The strong cyclonic air flow resulted in 7 $m\ s^{-1}$ winds from the southeast over the basin during the 3 days. Lake circulation was essentially anticyclonic, a rare event in Lake Huron since southeast winds are generally less intense with shorter ($<$ 2 days) duration (Figs. B.4a-d). The pattern of flow across the mid-lake ridge as noted in the northeasterly wind episode was repeated, with northwesterly currents along the ridge and a southeasterly return in deeper water north and south of the ridge. Clockwise water transport in the mouth of Saginaw Bay was especially clear in the currents at 25 m depth.

This episode does demonstrate that given the right combination of wind speed, direction, and duration, the characteristic cyclonic lake circulation can be reversed.

3.4.5 11-14 January 1975

The deep low continued into Canada. Winds remained about 8 $m\ s^{-1}$, but switched to the southwest as Lake Huron came under the influence of the backside of the low. The current pattern (Figs. B.5a-d) was similar to the just concluded episode, but several meters, e.g., 102, 104, were showing bidirectional characteristics, indicating that the current was adjusting to the new wind regime. This adjustment was not immediate, however, and showed that considerable time (on the order of a day or two) is required for the lake to adjust its current flow to be in harmony with the newly applied wind stress if this stress does not reinforce an already existing pattern of flow. A longer episode of southwesterly wind presented earlier showed a substantially different circulation for this wind direction.

3.4.6 9-15 February 1975

During the first 3 days of the 9-15 February episode, anticyclonic circulation prevailed over the Great Lake Basin from a weak high. On the 12th, a weak trough over the Lakes area extended to the Gulf of Mexico. Flat pressure gradients prevailed during the remainder of the period. This episode was selected to determine the effect of ice cover on current patterns. Ice, of 70- to 90-percent concentration, extending from Alpena to Port Huron and eastward to moorings 103 and 101, was observed on 12 February. Winds were west to northwest during the period so cyclonic lake circulation would be expected. The current rose map does show the anticipated cyclonic flow (Figs. B.6a-d); however, the four moorings at the head of Saginaw Bay were less directional than when the lake was ice free and current speeds were much less.

3.4.7 26 February-6 March 1975

The Great Lakes were under the influence of a low centered in eastern Canada during 26-29 February, followed by another closed low north of Lake Huron on the 1st of March. This low moved over Quebec, while yet another low travelled up the East Coast, causing cyclonic circulation over the East. Lake Huron therefore experienced generally westerly winds for the 9-day period with mean speeds up to 9 m s^{-1} at Saginaw. The lake circulation (Figs. B.7a-d) was again cyclonic, with little variation with depth except in Saginaw Bay at mooring 108 where the 15 m current was eastward and the 25 m current more westward. Also the 50 m currents at 109 were northwesterly, opposite to that at 15 m, due to the local bathymetry. Temperatures were between 0.0" and 0.8°C in the western half of the lake, and 1.6' and 2.8°C in the eastern half.

3.4.8 1-8 April 1975

A cold front passed over Lake Huron on 1 April and a deep upper trough over the West spawned a low-pressure center, which passed over the lower Great Lakes on the 3rd. This system moved over New England, moved offshore, and filled over the next 5 days. The resulting northwest winds over Lake Huron produced the familiar cyclonic circulation pattern (Figs. B.8a-d). Temperatures illustrated little spatial variation. The minimum was 0.3°C at mooring 102 and the maximum was 1.8°C at mooring 113 in the deep northern basin. Current flow during this important episode was especially steady and gave an extraordinary picture of lake circulation during northwest wind in those areas of the lake covered with functioning current meters. An identical picture of circulation, and some idea of its persistence is afforded by the current roses prepared for a slightly different interval of time, 3-13 April, shown in Figures B.9a-d.

3.4.9 3-7 May 1975

This episode was selected to determine what circulation pattern exists during light, variable wind conditions. The atmospheric pressure gradients were small during most of the period, interrupted by two weak lows moving over Lake Huron on the 4th and 6th. The resulting winds for the 5-day period were north to northeasterly at about 3 m s^{-1}. A conduction inversion, discussed in a previous section, undoubtedly formed over the lake, reducing the overwater wind stress. The Canadian moorings had been retrieved so only currents in the western part of the lake were measured. The current pattern (Figs. B.10a-c) was somewhat disorganized. Water flowed through the outer reaches of Saginaw Bay in one large counterclockwise loop as is characteristic of the bay mouth during episodes of northeast wind. Current directions at 15 m were north and northwest off Alpena (mooring 109) and Harbor Beach (mooring 102), respectively, which must have been in response to the northeasterly winds, as seen on other occasions, and the bathymetry, even though the winds were light.

The circulation pattern was confused, not unlike the monthly histograms, which showed considerable transport variability. As pointed out earlier, May was a somewhat unique month; wind speeds decreased considerably around the lake, and the conduction inversion that was present a large percentage of the time effectively decoupled the water from direct wind stress; hence currents were very weak and directionally variable.

3.5 Effects of Ice Cover

The 1974-75 winter season saw the first successful attempt at year-round navigation on the Great Lakes due in part to less than normal ice cover. Air temperatures well above normal through early January delayed significant ice growth. A month of cold temperatures beginning in mid-January produced rapid ice growth with Lake Huron's maximum ice cover of 45 percent occurring in mid-February (Leshkevich, 1976). Warm temperatures during the last half of February significantly decreased the amount of ice and, although March and April air temperatures were well below normal, the number of freezing degree-days was not sufficient to redevelop significant ice cover on the lake. The percentages of lake surface that can be expected to be ice covered during a mild, normal, and severe winter are about 40, 60, and 80 percent, respectively, for Lake Huron (Rondy, 1969).

In an effort to describe qualitatively the effect of ice cover on circulation patterns in Lake Huron, currents during the 9-15 February 1975 maximum ice period were compared with currents of the 26 February-6 March 1975 period, which had similar wind conditions but little ice cover. Results from Side Looking Airborne Radar (SLAR) surveys on 8, 10-13, and 16 February revealed the basic features of ice coverage at its maximum development. Figure 9 shows a SLAR image on 12 February 1976. Winds during the ice period were light to moderate westerly with the exception of light easterly winds on the 11th and 15th. A 10 to 20 km-wide band of close pack ice (70-90 percent ice cover) along the western shore of the lake persisted through the period, while the southern portion was almost totally covered. The eastern shore showed a 5 km-wide ice pack along the shore up to at least Clark Point. Both shores responded somewhat to winds and cold temperatures. The western band moved offshore somewhat during stronger westerly winds with new ice forming behind it, while the eastern band became more compact. The opposite occurred during easterly winds. Even though the wind was westerly during most of the period, no evidence of ice moving across the lake was seen. Only shifting of the outer boundary and the degree of compactness was noted. The cyclonic character of the circulation was evidenced by strong shear zones and lakeward extention of

Figure 9. Side-Looking Airborne Radar image showing the ice cover on western Lake Huron on 12 February 1975. White areas indicate edges and cracks in the ice.

ice near Alpena and the head of Saginaw Bay and by the northward movement of pack ice along the Ontario shore. A combination of warm air temperatures and wind and current activity broke up the ice into smaller floes, so that by 16 February the amount of ice decreased and only a 5 to 10 km band of floe ice remained on the western half of Lake Huron.

Figures 10 and 11 show the resultant speed and direction for each meter and the average ice cover for the two episodes (Leshkevich, 1976). Currents displayed in histogram form for the two periods are included in Appendix B. Current direction and magnitude appeared unaffected in most parts of the lake except off the Saginaw Bay area, where the resultant speeds were near zero during the ice period and 5-17 cm s^{-1} at the end of February. Particularly obvious was the greatly reduced speed at mooring 104 off Point aux Barques. This particular site was in an area of intense currents. The resultant speeds at 15 and 25 m were 2.3 and 0.5 cm s^{-1} respectively, during ice cover and 10.3 and 16.7 cm s^{-1} during the comparison period. Offshore currents north (mooring 107) and south (mooring 102) of Saginaw Bay showed little change in speed or direction. A decrease'in mean monthly kinetic energy of the lake in February was attributable in part to ice growth.

The only empirical study of currents in a large lake with partial ice cover that is known to the authors was reported by Palmer and Izatt (1972).

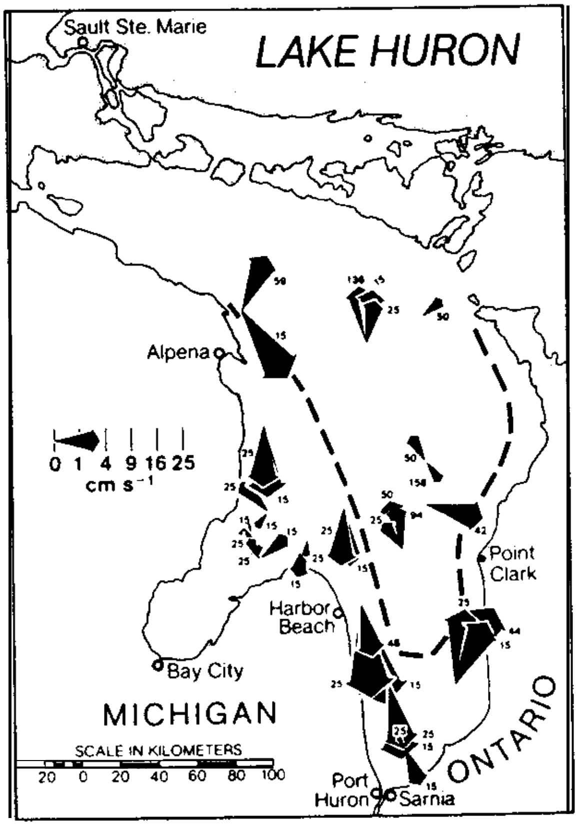


Figure 10. Vector resultant current flows in Lake Huron during 9-15 February 1975. The average ice cover during the interval is shown by the broken line.

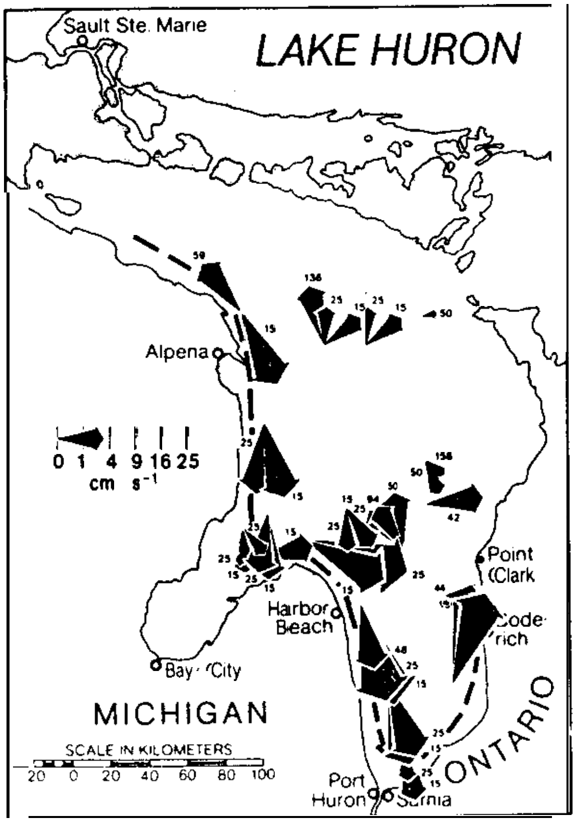


Figure 11. Vector resultant current flows in Lake Huron during 26 February-6 March 1975. The average ice cover during the interval is shown by the broken line.

Their results from one current meter 0.8 km offshore at Nanticoke, Lake Erie, indicate that during the ice formation period, with ice extending 0.5 km beyond the meter site, the currents did not vary appreciably from those when the lake was ice free. When the ice cover extended 1.5 km beyond the mooring location, currents were weak, with long periods of no movement. Also no significant energy was detected at the free oscillation periods as there was during the ice formation period. Palmer and Izatt gave no information on the amount of ice cover on the whole lake so that the surface area available for direct wind stress forcing is not known. Arctic ice investigations have concentrated on determining the momentum exchange from the atmosphere through the ice into the oceanic boundary layer and ice-water stress. Sheng and Lick (1973) calculated numerically the steady-state wind-driven currents in Lake Erie when the eastern third or western third of the lake was ice covered and compared these results with those calculated for ice-free conditions. The comparison basically showed that currents under the ice were weak except near the ice boundary, where velocities were comparable to ice-free conditions.

The presented evidence indicates that ice on the western portion of Lake Huron does result in dramatic current speed decreases in areas, such as the head of Saginaw Bay, where the meters are far enough removed from the open water to prevent significant lateral momentum transfer. There may be little or no change in the observed current velocity north and south of the Bay because the meters were not always within the ice-cover area or were very near the ice boundary. Distribution of ice cover is controlled by the general cyclonic lake circulation, forcing it southward along the western side and northward along the east coast. Ice forced into midlake, as occurs north of Point Clark and the Alpena area, is melted by the higher temperature of the water.

The 1974-75 winter season was mild, with little ice cover, and we can only speculate on what effects greater amounts of ice would have on the current pattern in Lake Huron. Obviously as the ice cover increases, the area upon which wind stress can act decreases and the kinetic energy of the lake will decrease. As the ice cover approaches the severe classification as in 1967 (80 percent coverage), the currents would probably be greatly diminished.

3.6 The Annual Cycle of the Variation of Current Speeds with Depth

There have been few studies of currents and concomitant water temperature distributions during winter in the Great Lakes. It is therefore instructive to look at the distribution of current speeds throughout the water column as winter progresses and to compare this distribution with what is known during other seasons of the year. Figure 12 presents mean monthly current speeds observed at all moorings at the four levels of measurement in the water column. Mean current speeds in November exhibited considerable variation with depth, with speeds highest at the 15 m level and decreasing monotonically with depth. The November currents were associated with the last vestiges of summer density stratification. December mean currents decreased from November values at the 15 and 25 m levels and increased at 50 m and near the bottom. There were no significant differences in current speeds in the upper 50 m of the water column in December, establishing a pattern of flow variation with depth that continued for the remainder of the winter months in nearly isothermal water.

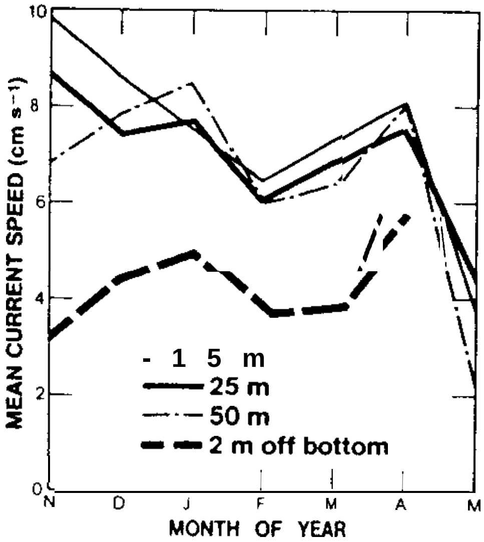


Figure 12. Monthly mean current speeds at the four levels of measurement in Lake Huron during winter 1974-75. Scalar mean speeds were *averaged for all operating current meters at each depth.*

Mean monthly wind speeds at five stations scattered about the perimeter of Lake Huron were shown in Figure 4. The average winds were nearly the same at all stations during November and December, peaked at all stations in January, and then exhibited a rather uniform decrease through the winter and into April. The station most representative of overwater wind speed was the Bruce Ontario Hydro installation at Douglas Point, Ont., as its location on the shoreline gives good exposure to the prevailing westerly winds. Wind speeds measured here were, as expected, greater than those recorded at the other four stations, which varied in exposure and were not situated as close to the lake shore. All stations showed markedly decreased wind speeds in May, with the Bruce station on the lake shore showing the largest relative decrease.

Mean current speeds at the three levels of measurement in the upper 50 m of the water column showed only insignificant differences during the months of December 1974 through April 1975, when the water mass of Lake Huron was nearly homogeneous. Current speeds near the bottom were less, but followed closely the trend of speed increase or decrease in the near surface water. The slackening of current speeds during February and March 1975 was greater than would be predicted by simple relationships with the observed wind speeds and was probably caused by ice cover during these months. Since a majority of the current meters were placed within 20 km of the coast, the mean current speeds are weighted toward what is occurring in the coastal zone. But this area is where the ice is. A rapid decrease in current speeds at all levels in May, as the nearshore waters were rapidly warming, was caused by lessening wind stress on the lake surface, due in part to the intense atmospheric stability over the lake surface.

For the ice-free, warm weather months of April through October, a comparatively large quantity of current and water temperature data has been collected in the Great Lakes. Figure 13 (Bennett and Saylor, 1974) shows a typical result of current studies during this season of the year, with mean current speeds

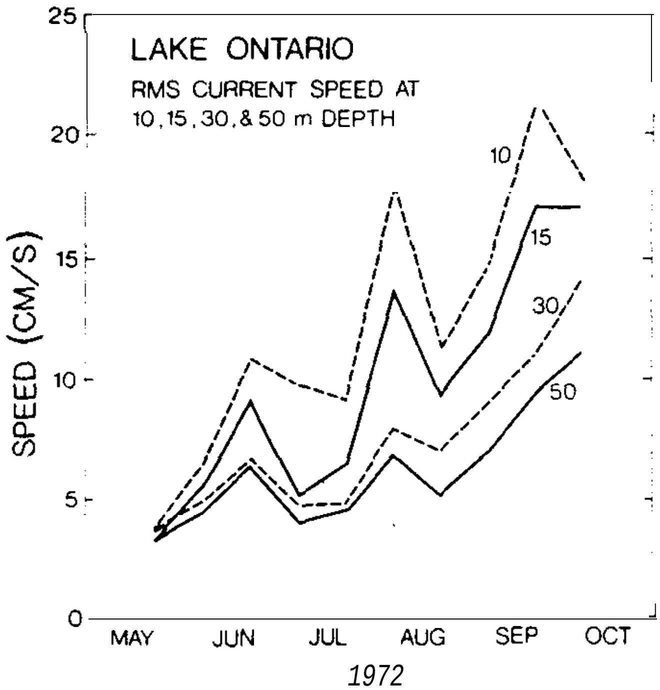


Figure 13. Lake-wide average of the RMS current speed at four depths observed in Lake Ontario during 1972 (from Bennett and Saylor, 1974).

increasing steadily from small values in May and with considerable vertical gradients of horizontal current velocity from higher speeds near the surface and decreasing with depth. RMS values of current speed are presented in this figure and the trend of increasing kinetic energy at all depths throughout the ice-free season is clear. The general increase in energy in Lake Ontario was found to be associated with a similar trend in the surface wind stress over the lake, a trend characteristic of the Great Lakes region. Peak energy levels in late June, early August, and early October were related to three intense storms. Studies in the other Great Lakes have shown similar trends of seasonal kinetic energy increase.

Comparisons of power spectra computed from flow data collected during the ice-free months indicate that the seasonal increase in kinetic energy is general across all frequencies and is especially pronounced at near-inertial frequencies, when the lakes are strongly density stratified. While these seasonal changes correspond with increasing momentum flux from the surface wind stress, the greater growth at near-inertial frequencies represents the fact that, with stratification, the dominant response of the lake to forcing is in the form of inertia-gravitational internal waves. The internal wave activity causes the mean current speeds to be greater than would be observed in the absence of stratification and accentuates the vertical gradient of horizontal velocity.

It is apparent that we observe an annual cycle in the lakewide distribution of kinetic energy. Starting from very low current speeds in late spring, which result from high stability in the overlake boundary layer because of warm air over a cold lake surface, average current speeds increase in a rather steady fashion at all water depths in response to a similar seasonal trend in applied wind stress. Horizontal current speeds decrease rapidly with depth, with vertical gradients in harmony with the spreading and thickening density discontinuities in a stably Stratified water ma** as summer progresses. With very stable stratification, kinetic energy grows rapidly in favored near-inertial frequencies because of the dominant response of the lake to forcing in the form of inertio-gravitational internal waves. With the breakup of stratification in late fall, kinetic energy is evenly distributed in at least the upper 50 m of the water column in Lake Huron and rises or falls in close agreement with the winter-long trend of applied wind stress. Volume transports are large during winter because of strong wind Stress and the deep penetration and stability of the mea" current flow patterns. Currents in very deep water are Significant during winter and respond to increases or decreases in wind stress in the same fashion as nearer surface intensities. Ice formation is evidenced by reduced current speeds, as a part of the water Surface is sheltered from the wind. Kinetic energy falls catastrophically during late spring with the formation of a stable boundary layer of warm air over the cold lake surface. Subsequent warming of the surface water and the *tart of stable density Stratification initiates the gradual lakewide increase of current speeds all over again.

3.7 Comparison of Summer Current Patterns

Harrington's (1895) current chart of Lake Huron, which was compiled from drift bottle releases and recoveries during summer, is summarized in Figure 14. His studies revealed persistent southward flowing currents along the west shore of the lake and a return northward flow along the Ontario coast as far north as the mouth of Georgia" Bay. Drift bottles released to the east of Georgian Bay had a tendency to meander through the mouth of the bay and disperse about its perimeter. This feature led Harrington to close a counterclockwise flow cell in latitudes just south of the bay mouth. Another cell of cyclonic flow was tucked into the northwestern corner of Lake Huron to account for westward drift observed along the northern coast of the lake, i.e., the shore extending northwestward from the mouth of Georgian Bay.

Sloss and Saylor (1975) analyzed current meter recordings made in Lake Huron during the summer of 1966 and deduced a pattern of flow in epilimnion water (Fig. 15). Again the circulation of surface water was found to be of a cyclonic nature. Essential differences from the Harrington studies consisted of enlargement of the cyclonic circulation cell over the deep northeastern basin of the lake. The northern limit of this cell was placed just east of the shoal water that protrudes nearly 30 km southward from the western end of Manitoulin Island. Another cyclonic pattern was found to exist to the west of the shoal, occupying a" area about half the size indicated by Harrington. Sloss and Saylor also reported a rather steady flow of Lake Huron surface water into Georgian Bay and a subsurface return flow of bay water into the lake. This feature probably accounts for a large part of the difference in flow patterns reported in the reaches of Lake Huron east of the bay mouth in the two studies.

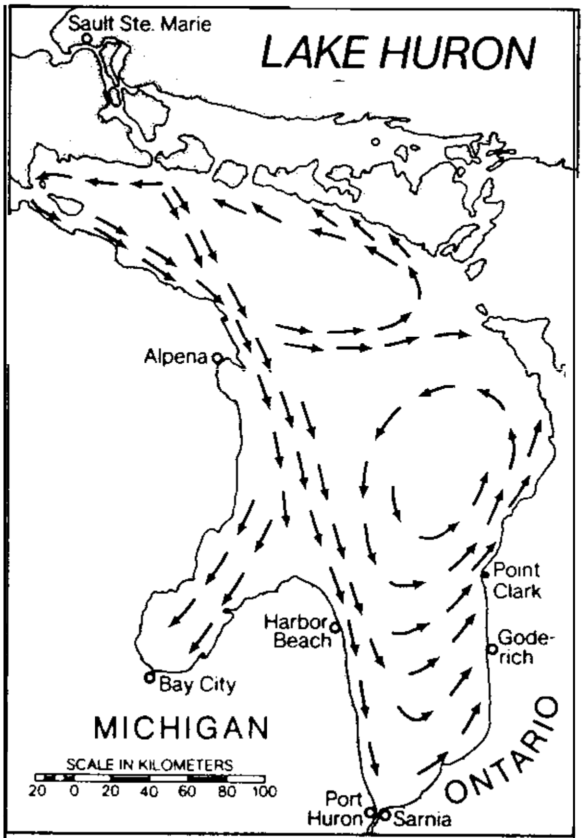


Figure 14. Surface water flow patterns in Lake Huron during the open water navigation season (after Harrington, 1895).

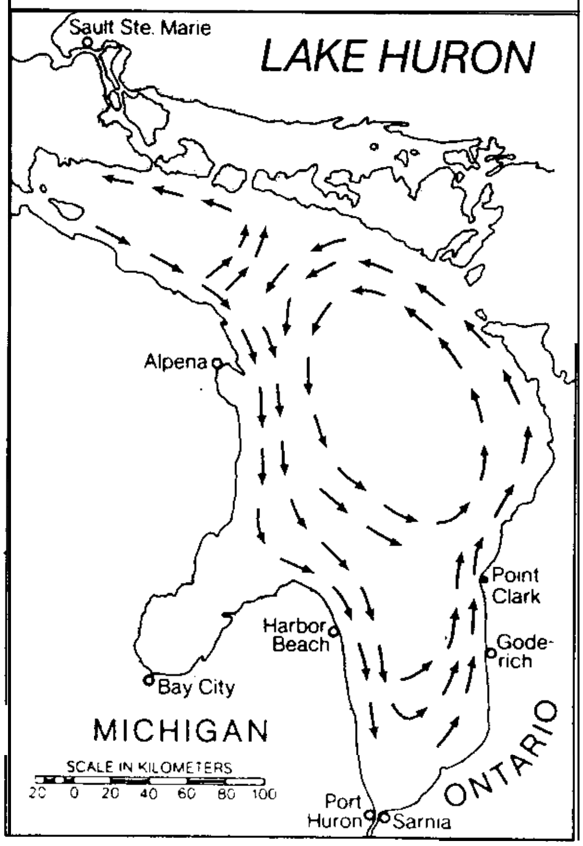


Figure 15. Flow patterns of epilimnion water in Lake Huron during summer (after Sloss and Saylor,1975).

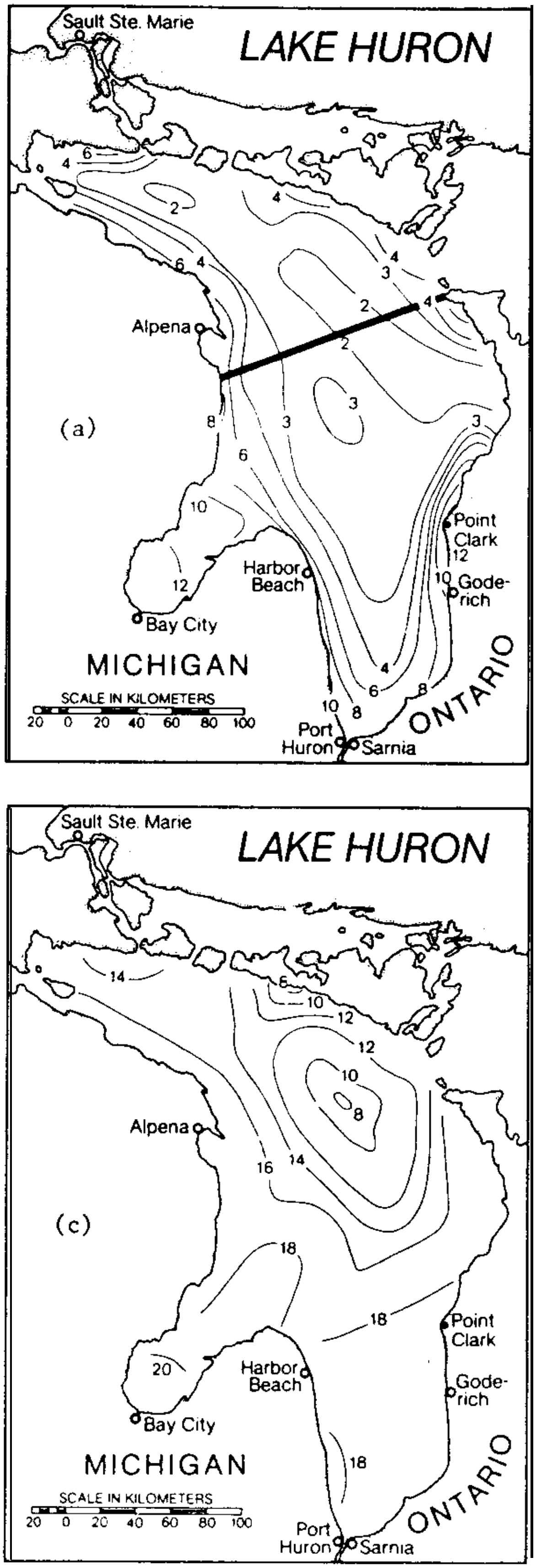
As the surface water warms in spring and early summer, an epilimnion forms initially near shore and gradually spreads and thicken* as summer progresses. Typical features of surface water temperature distributions observed during the warming cycle are shown in Figure 16. Warm water confined in May to coastal areas gradually expands lakeward in July to surround a colder, denser pool of water centered over the deep northeastern basin of Lake Huron. Similar distributions observed in 1966 have been reported by Bolsenga (1976). Temperature distributions within the lake basin on a cross section of the lake from Black River, Mich., to Tobermory, Ont., were taken during the same time intervals as the surface temperature measurements (Fig. 17). All isotherms exhibit similar characteristics, being depressed near the coast* and shallow near the center of the lake basin. This feature is not unique to Lake Huron, but rather appears to be characteristic of the development of summer stratification in all of the Great Lakes.

The importance of the temperature distributions to lake circulation arises because of observations that show that in the Great Lakes, as in oceans, persistent horizontal water density gradient* are supported by nearly geostrophic current flows, which represent a balance between pressure and Coriolis forces. A cold core of dense water surrounded by warmer, less dense water is supported by currents flowing counterclockwise about the cell, characterized by convergence (sinking) along the coasts and divergence (upwelling) over the core. Thus, the horizontal temperature gradients observed during the warm weather season on Lake Huron and repeatedly observed year after year give supporting evidence to a circulation pattern very similar to the reported current surveys.

Now it is also apparent that the winter current patterns in Lake Huron are very similar to those observed in summer. The winter observations reveal a deeper penetration of high current speeds in the nearly isothermal water mass and larger volume transports, which can be attributed to larger momentum fluxes because of increased wind speed*. Winter circulation persists in a characteristic cyclonic pattern unsupported by significant horizontal water density gradients. The small gradients observed exhibit features similar to summer distributions, with a denser core of water over the lake's deep basin surrounded by colder, less dense water and ice about the lake coasts. The obvious conclusion drawn from these observation* is that the prevailing wind-driven current patterns support the observed thermal structure (the currents are similar with or without horizontal temperature gradients). It is not the thermal structure that drives the current*.

4. CONCLUSIONS

Winter in Lake Huron is accompanied by an almost isothermal water mass. In 1974 the last vestiges of summer stratification were observed in November. Following a month of no discernible temperature gradient* (December), the winter months of January, February, and March showed faint temperature differentials consisting of a pool of warmer water (1° to 2°C warmer) centered over the lake's deep northeastern basin surrounded by colder water and ice about the lake coasts. April exhibited a return to near isothermal conditions, followed in May by the start of the cyclical w rming trend.



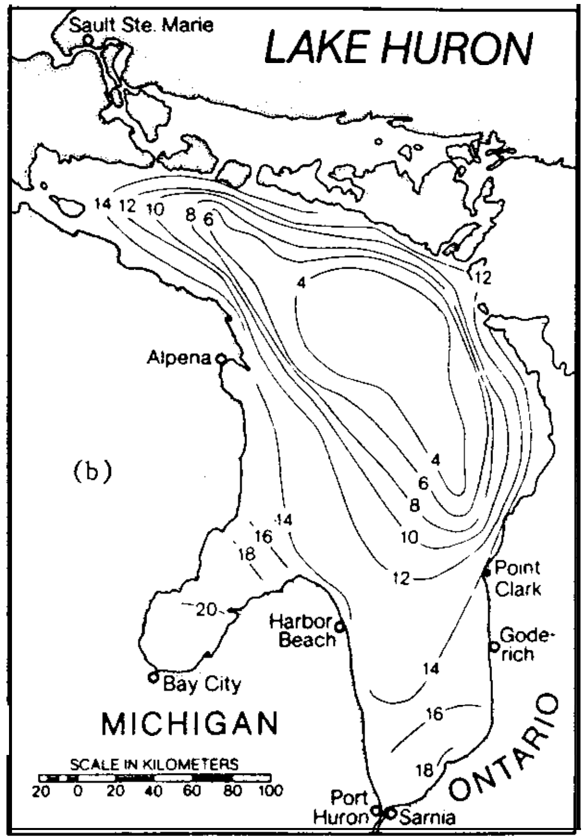
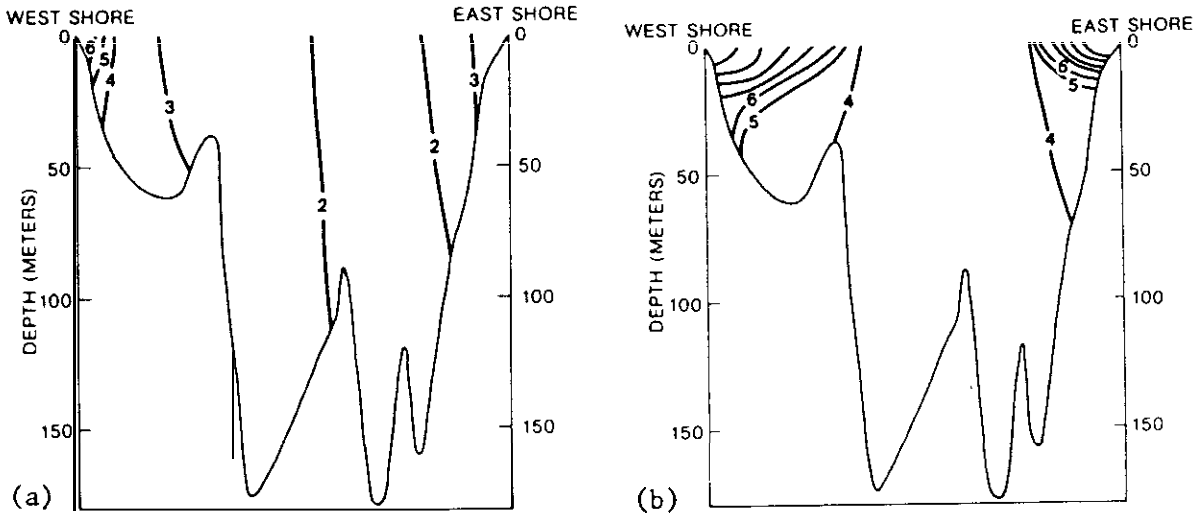


Figure 16. Surface water temperatures (°C) of Lake Huron as observed in 1971 on three CCIW monitor cruises. Clockwise from upper left the cruise dates were: a) 17-25 May, b) 12-28 June, and c) 19-27 July. Temperature structure of the lake water mass is shown in Figure 17 along the cross section of the lake shown here from Black River, Mich., to Tobermory, Ont.



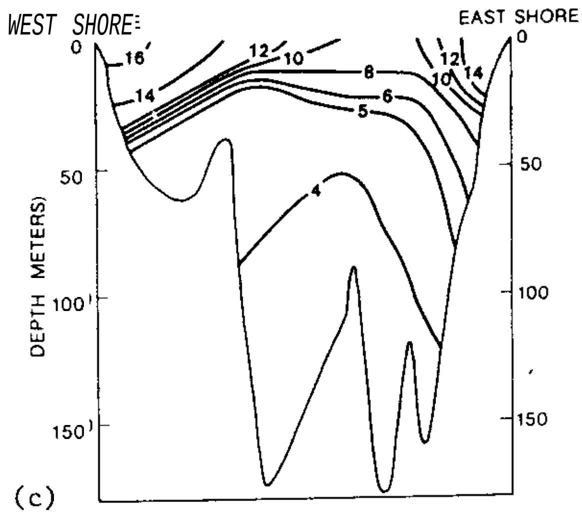


Figure 17. Temperature isopleths (°C) of the Lake Huron water mass on a cross section of the lake from Black River, Mich., to Tobermory, Ont., for the cruise intervals of Figure 16.

Wind speeds about the perimeter of the lake during winter were relatively high compared with winds during summer. Instability in the overwater atmosphere caused by cold air moving over a warmer water surface peaked in January, as did observed wind speeds. Unstable conditions endured from November through March. April was a month of nearly neutral atmospheric stability over the lake and May was a month of extreme stability. With large momentum fluxes from the atmosphere to homogeneous water in winter, mean current speeds were nearly the same throughout at least the upper 50 m of the water column. This distribution contrasted vividly with summer observations showing strong vertical gradients of horizontal current velocity with depth, the velocity gradients being very closely related to vertical water temperature (or density) gradients. Month-to-month variations of mean current speeds in winter closely paralleled the month-to-month variations in mean wind speeds observed about the lake's perimeter, although ice cover in February and March appeared to reduce the momentum flux from air to water on a whole basin view. Intense stability in the ova-lake boundary layer in May was very effective in shielding the lake surface from significant wind stress and caused a remarkable decrease in the lake's kinetic energy.

Current patterns in Lake Huron in winter 1974-75 were dominated by southward flow along the entire west coast south of Alpena. This southward current was especially intense during episodes of strong west and northwesterly winds. With westerly winds prevailing throughout the winter months, southerly flow along the west coast persisted from month to month and was the most prominent feature of the resultant winter current flow. The steady southward flow penetrated to at least the 50 m level of coastal bathymetry and apparently occupied a wide coastal strip with rather uniform characteristics (at least 30 km wide just east of the mouth of Saginaw Bay). Large volumes of water were transported southward in this current. Much less data was collected in the eastern half of the lake. The available information suggests that a broad northward return flow characterizes the current field in this area. This return flow appeared well established in the south end of the lake, but the pattern was uncertain in the northern parts because of the scarcity of data. Perturbations to this lakewide pattern occurred during episodes of strong wind stress, but long period mean flows showed a definite preference for cyclonic flow during the winter season.

Flow patterns during winter 1974-75 were very similar to those observed in summer. Long-lived horizontal gradients of water density established in summer were supportive of observed large-scale cyclonic flow and in fact may have established almost geostrophic equilibrium. The winter current studies, which established similar current features existing in a homogeneous lake, suggest that the summer thermal structure is supported in part by the wind-driven lake circulation, as it is certainly not the temperature field that is controlling current patterns.

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Appendix A

MONTHLY AND SEASONAL WATER CURRENT TRANSPORT AND WIND RUN ROSES FOR CONDITIONS OBSERVED IN LAKE HURON DURING WINTER 1974-75.

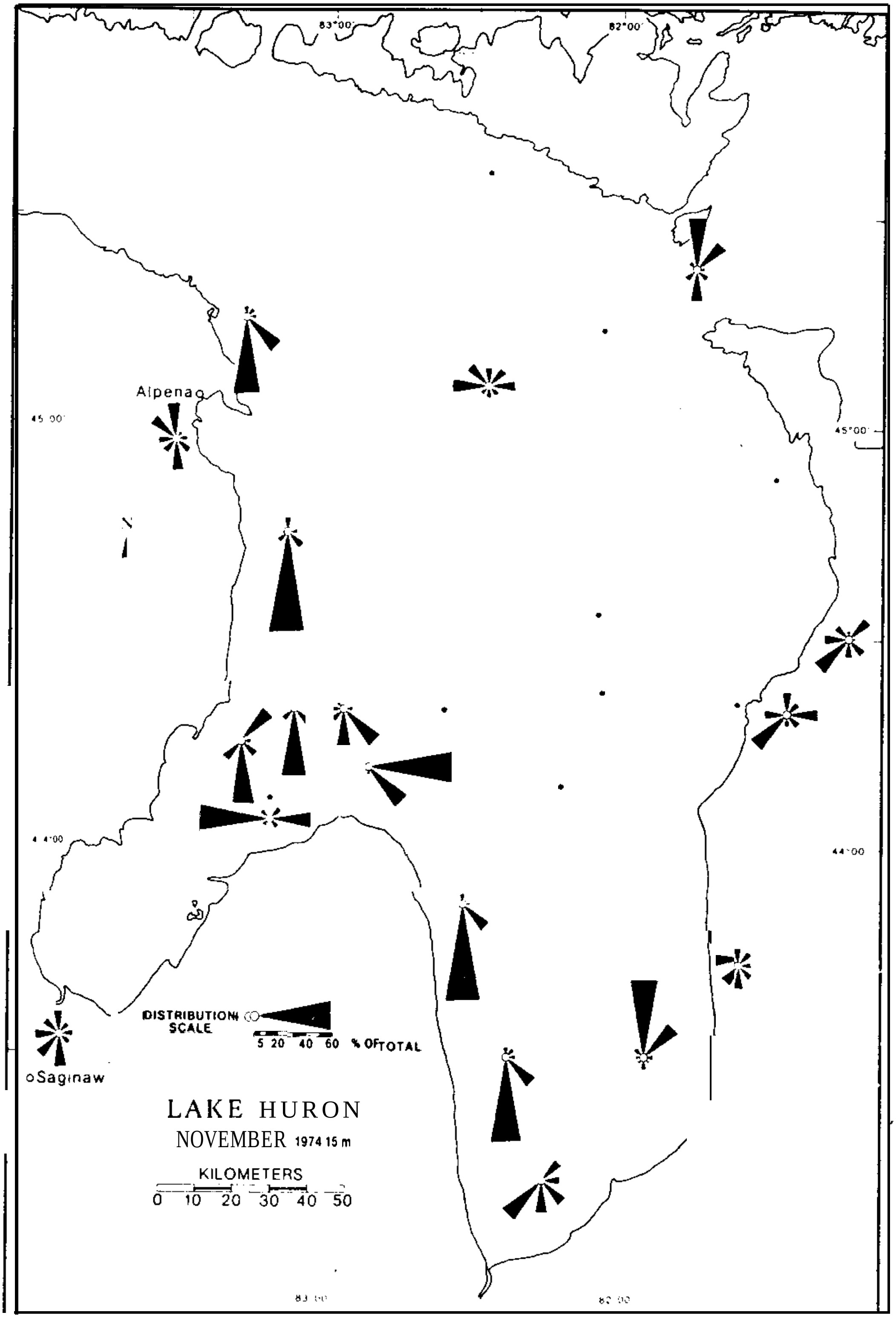

Figure A.1a. Water current transport roses at 15 m depth in Lake Huron and wind run roses at five perimeter meteorological stations for November 1374. *Current roses show the percentage of current run* toward each *octant, while wind roses show the percentage of wind run* from *each octant.*

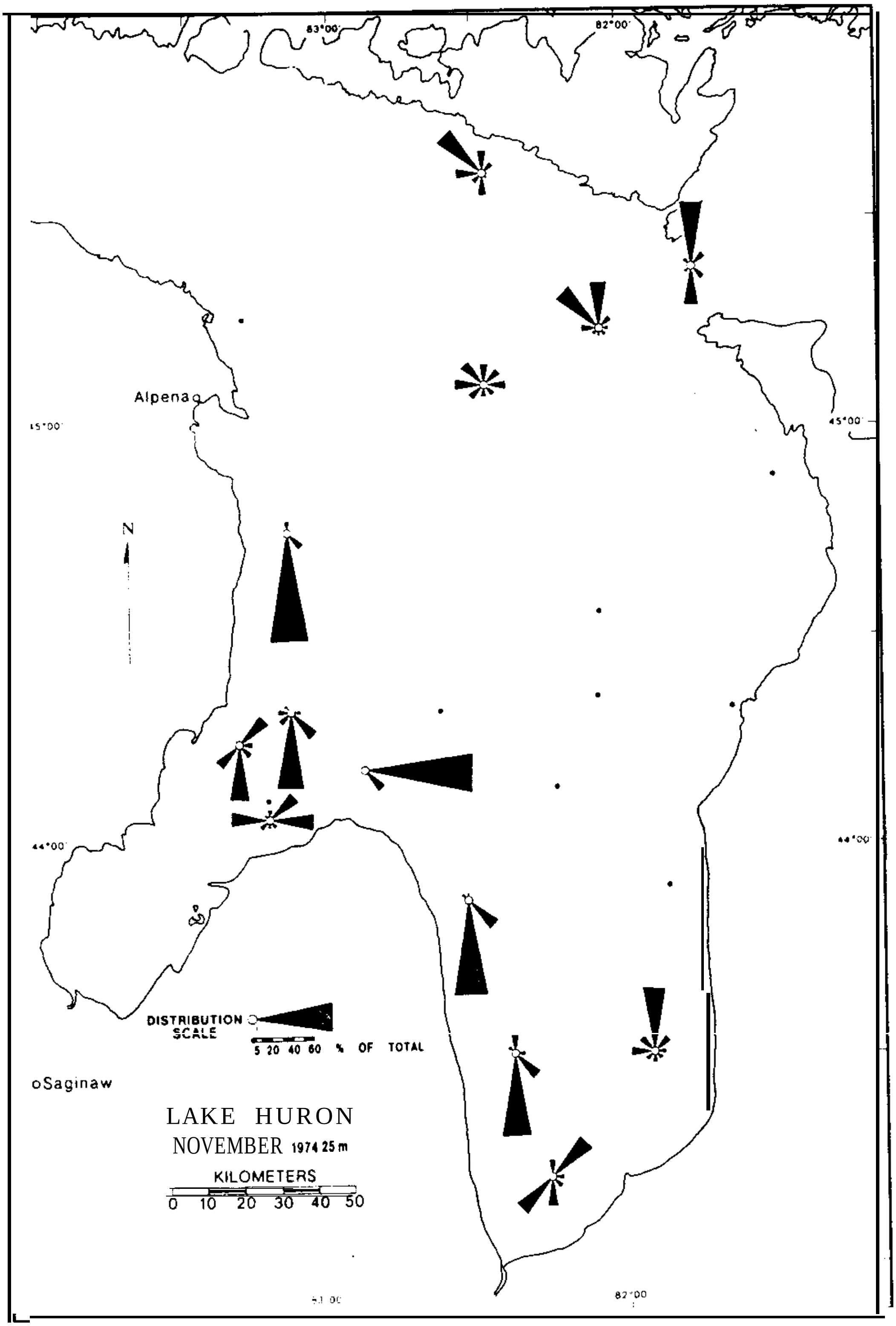

Figure A.1b. Current roses at 25 m depth for November 1974.

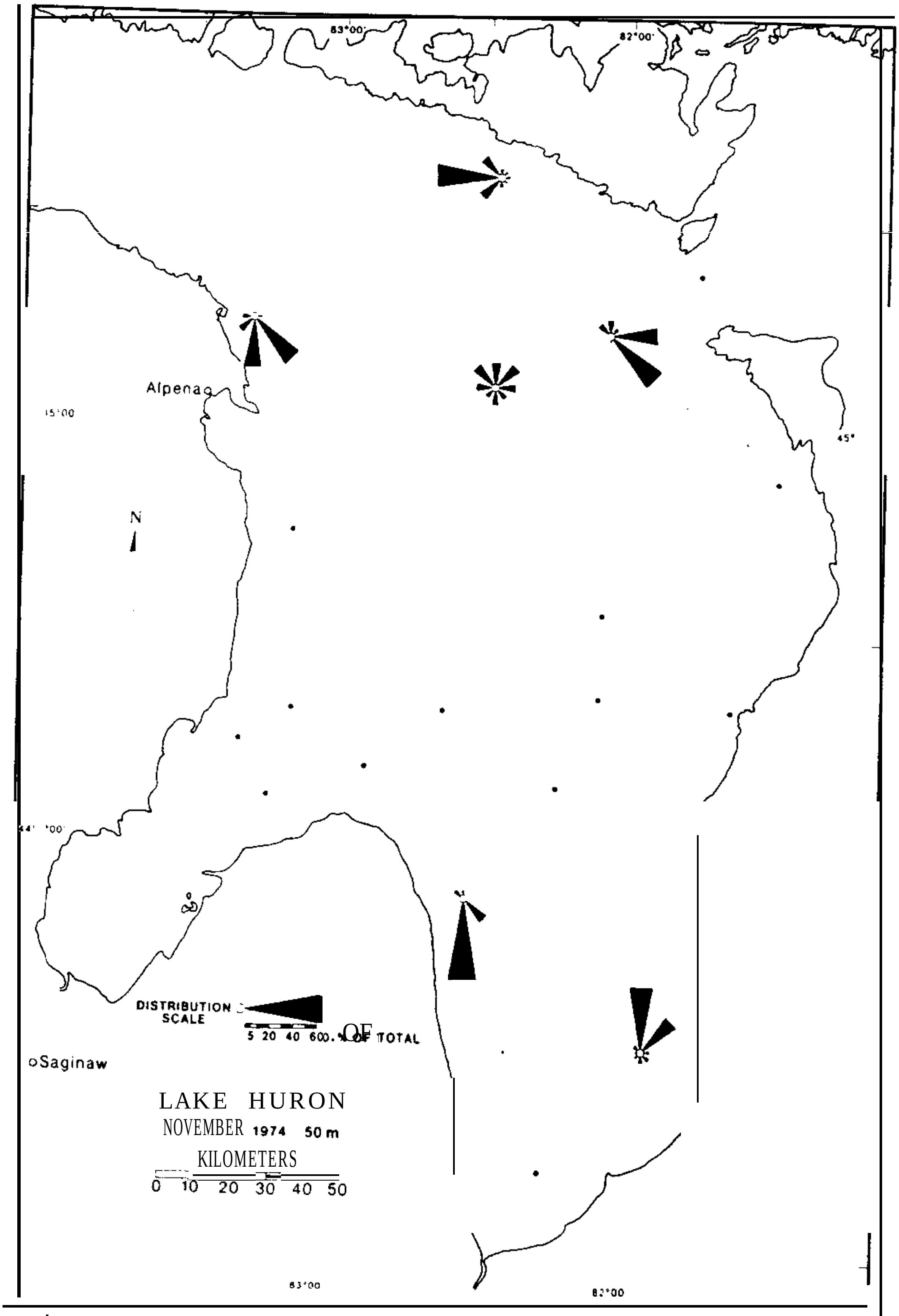

Figure A.1c. Current roses at 50 m depth for November 1974.

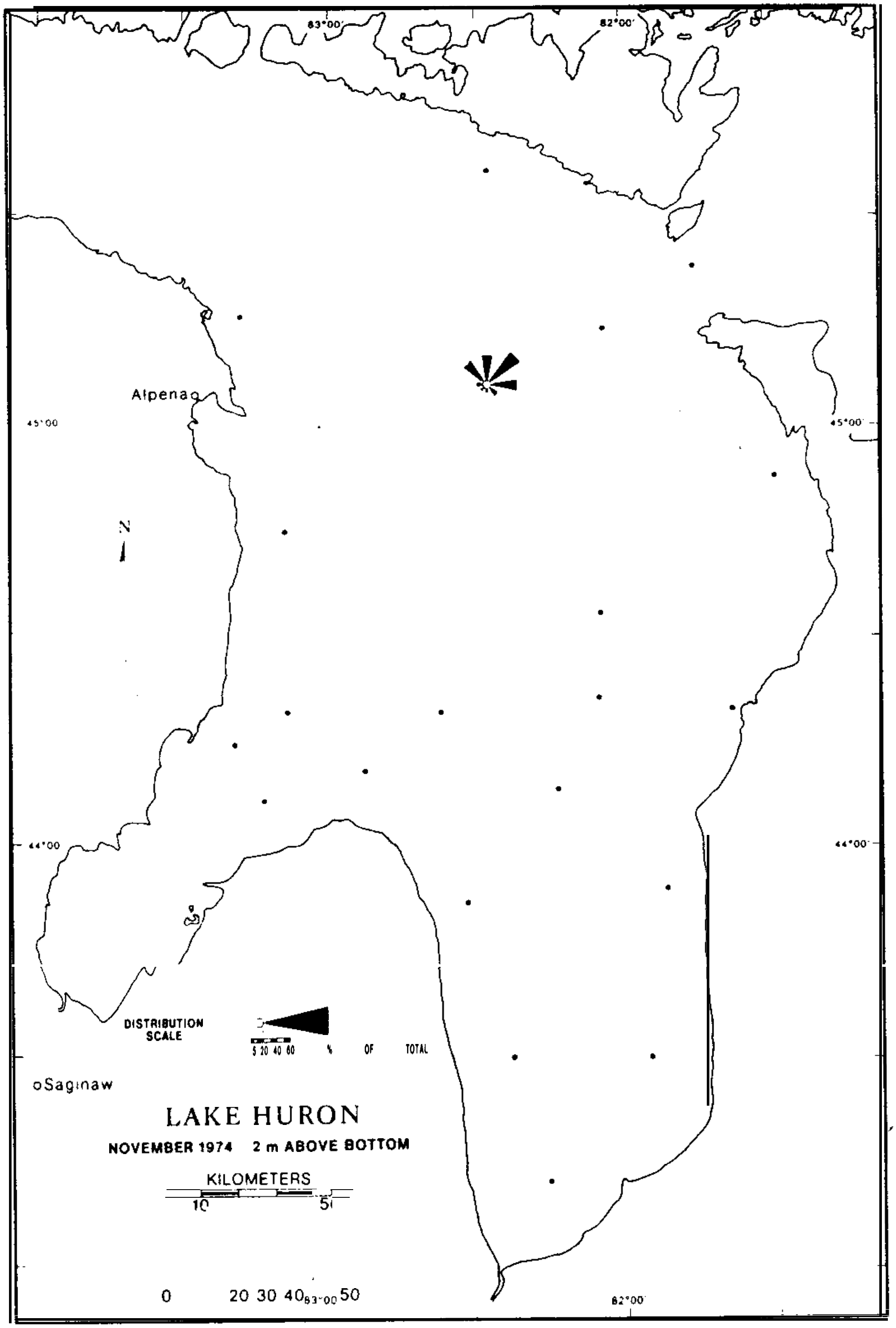

Figure A. 1d. Current roses at 2 m above the bottom for *November 1974.*

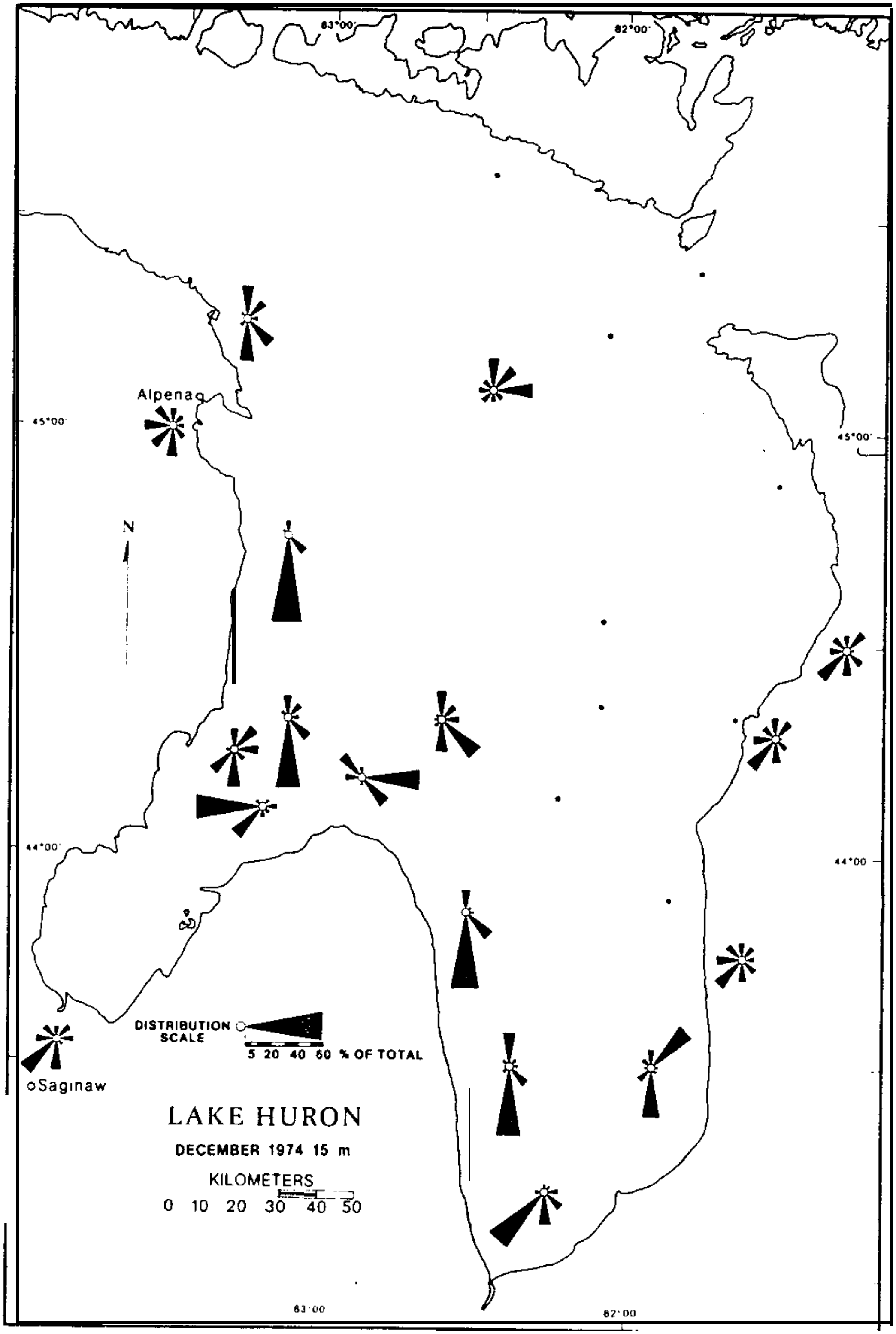

Figure A.2a. Current roses at 15 m depth and wind roses for *December 1974.*

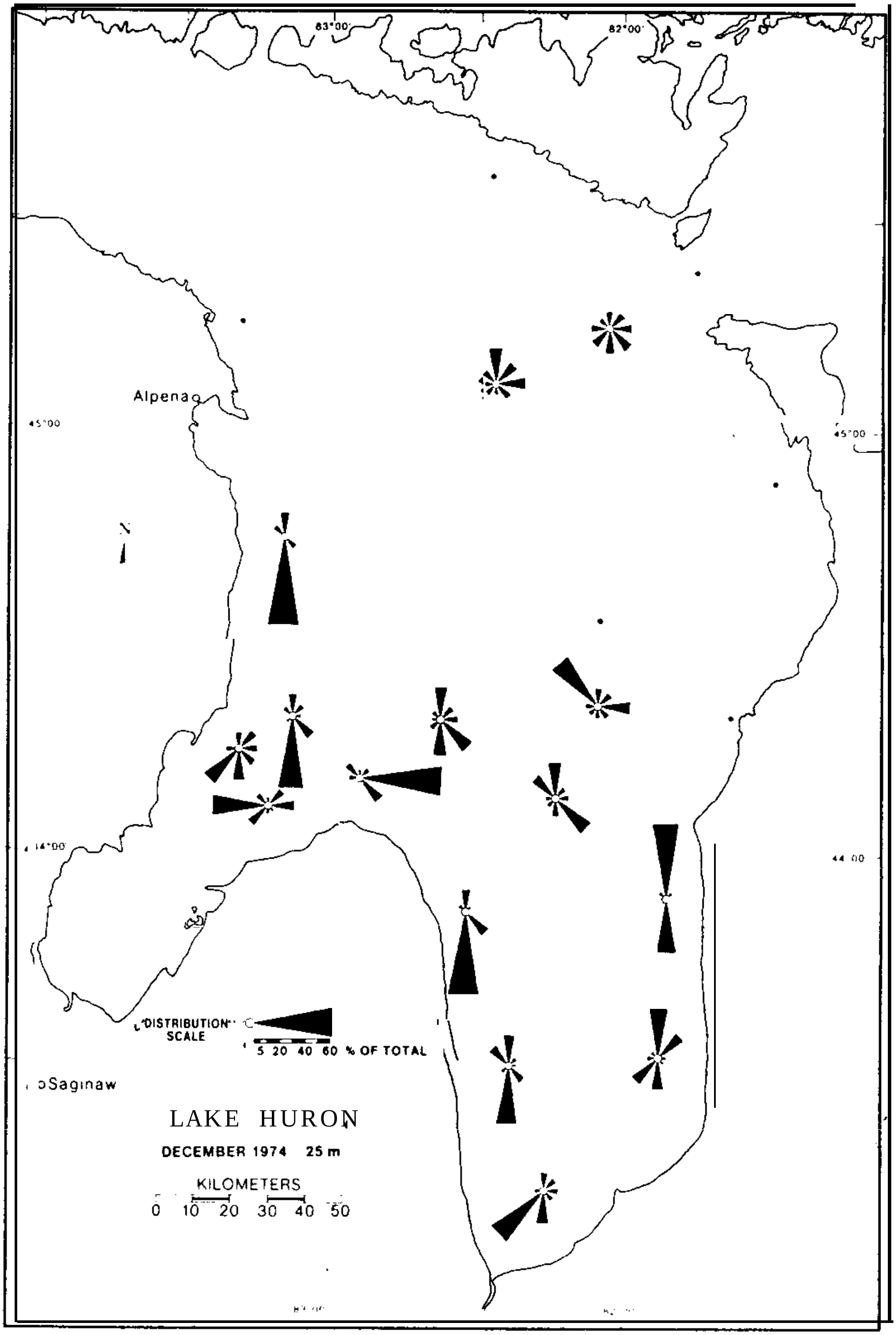

Figure A.2b. Current roses at 25 m depth for December 1974.

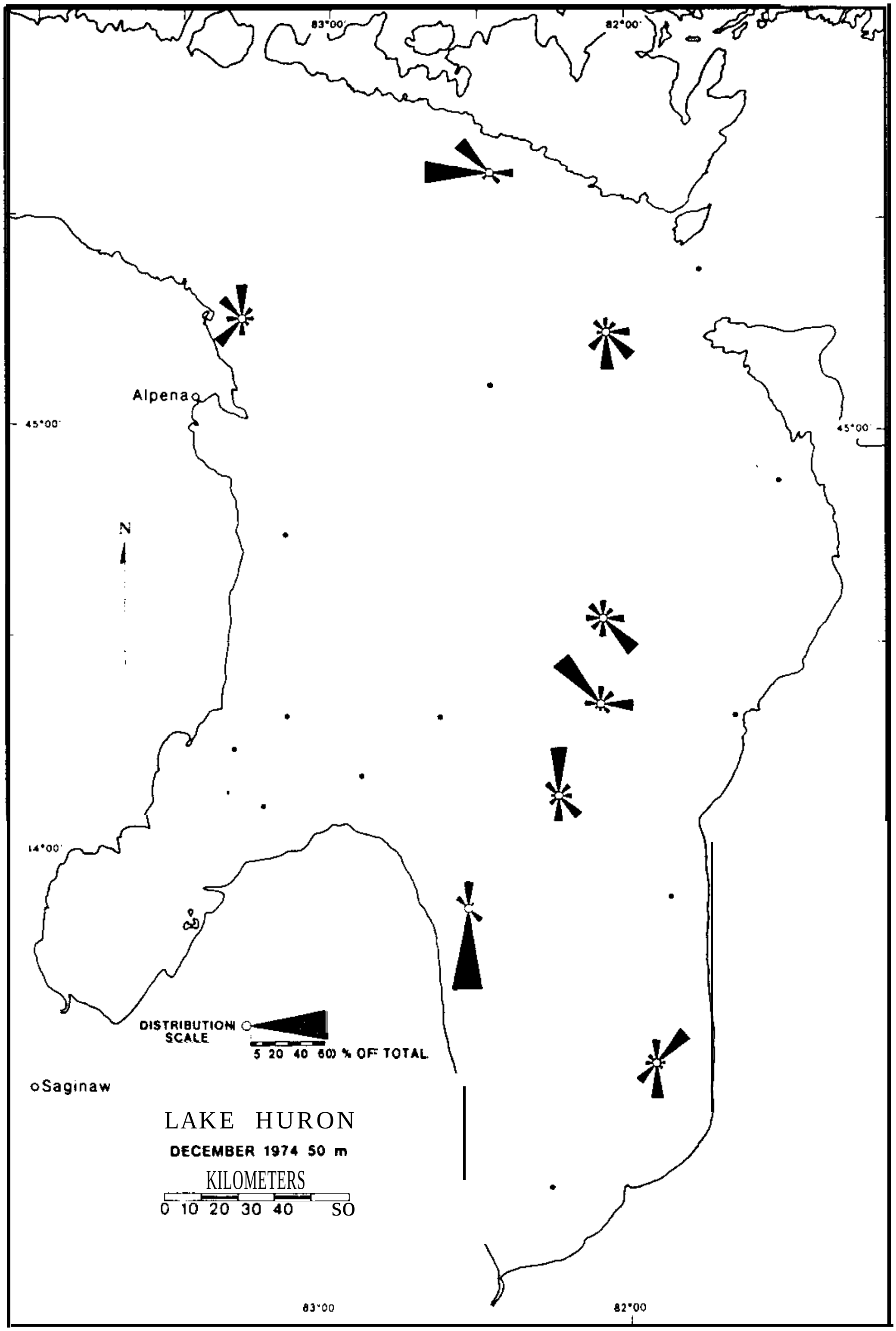

Figure A. 2c. Current roses at 50 m depth for December 1974.

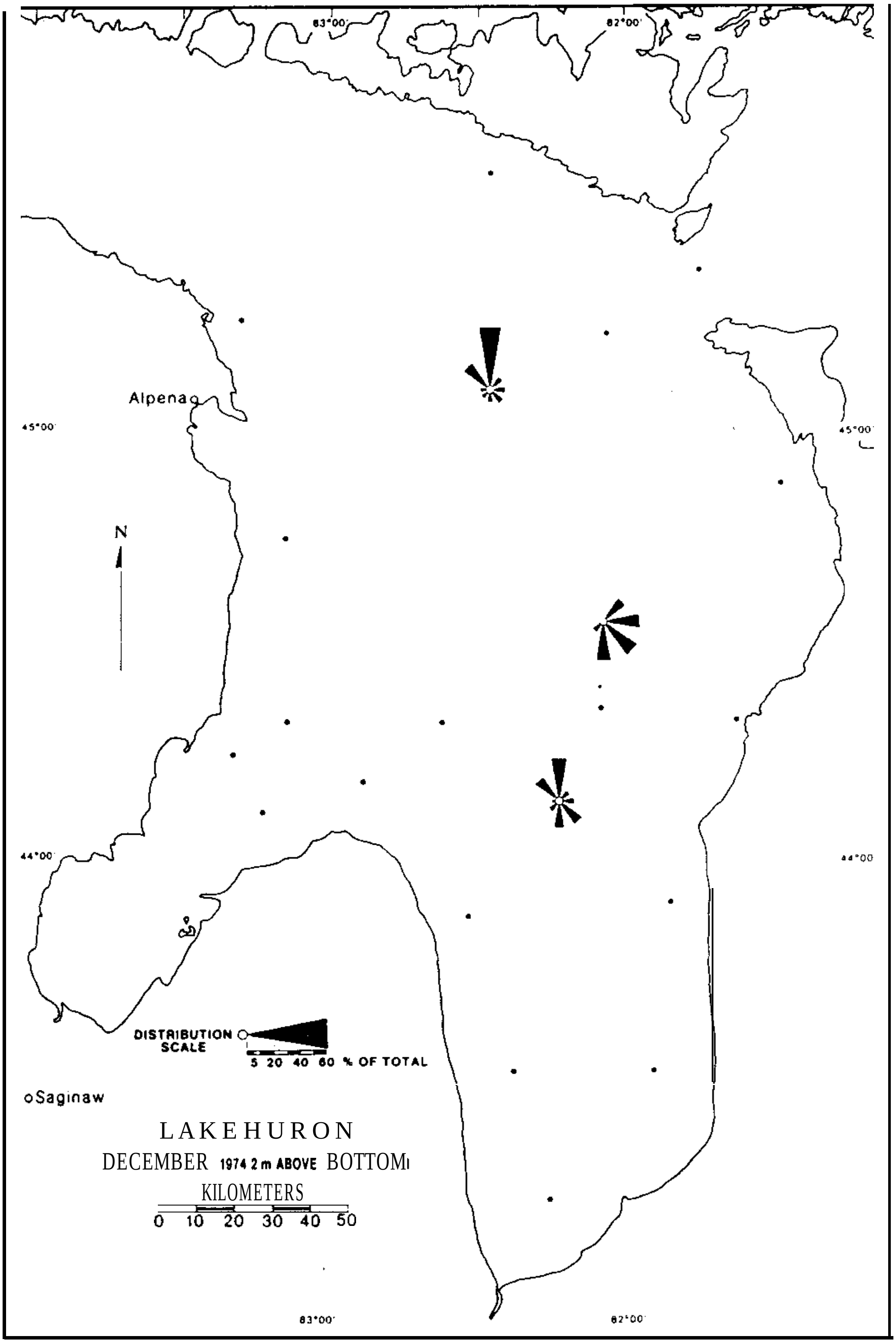

Figure A. 2d. Current roses at 2 m above the bottom for December 1974.

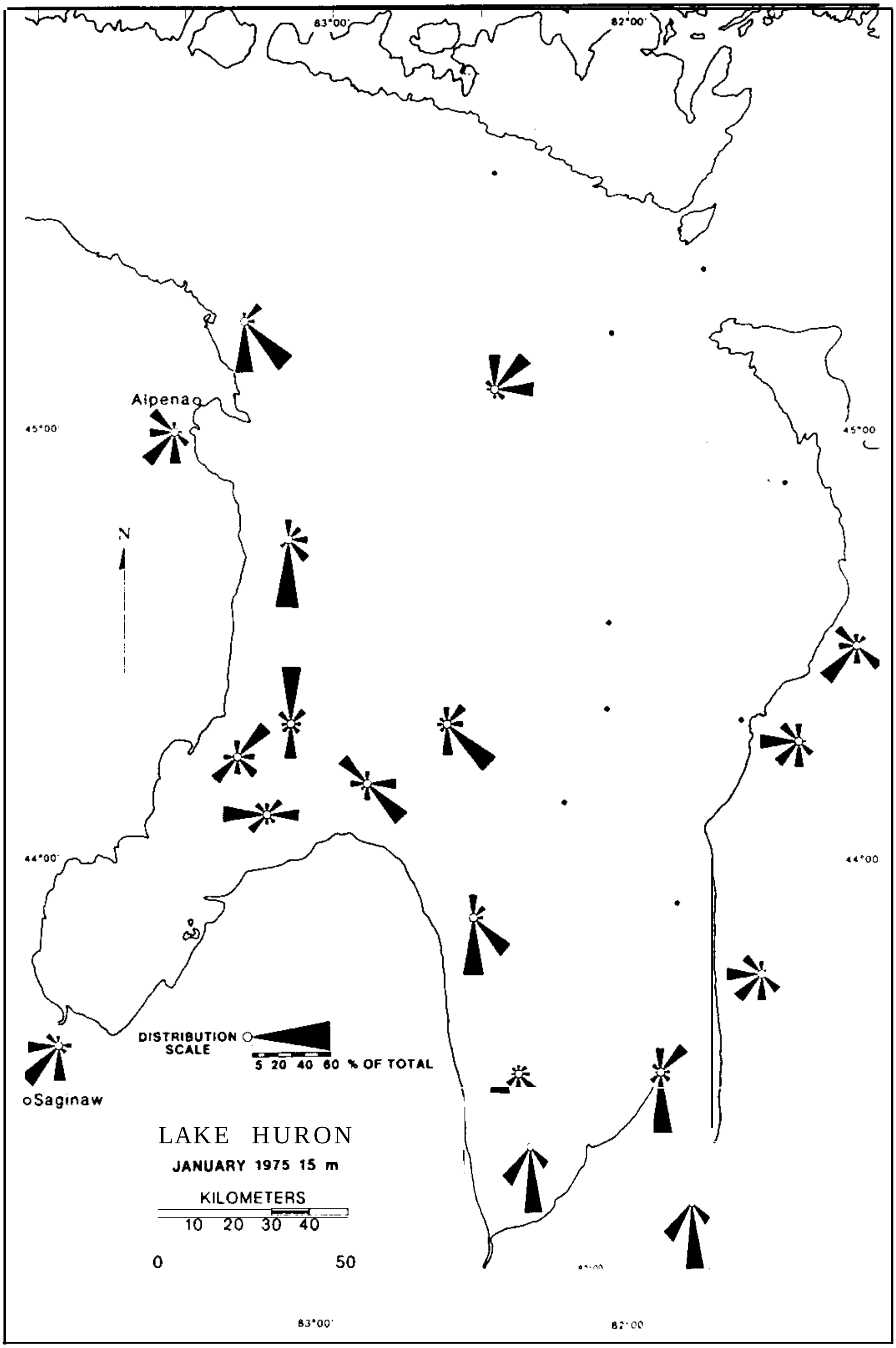

Figure A.3a. Current roses at 15 m depth and wind roses for January 1975.

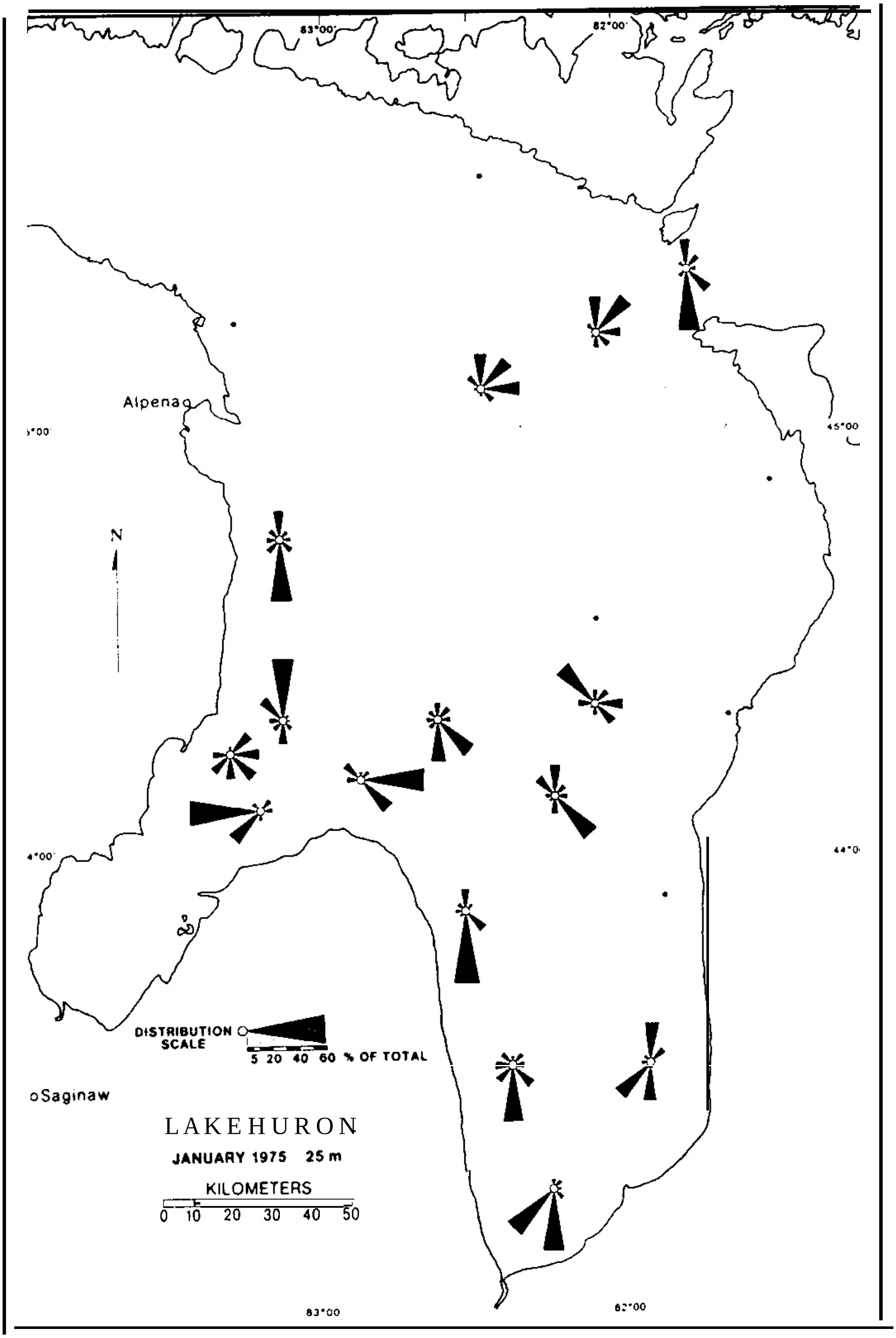

Figure A. 3b. Current roses at 25 m depth for January 1975.

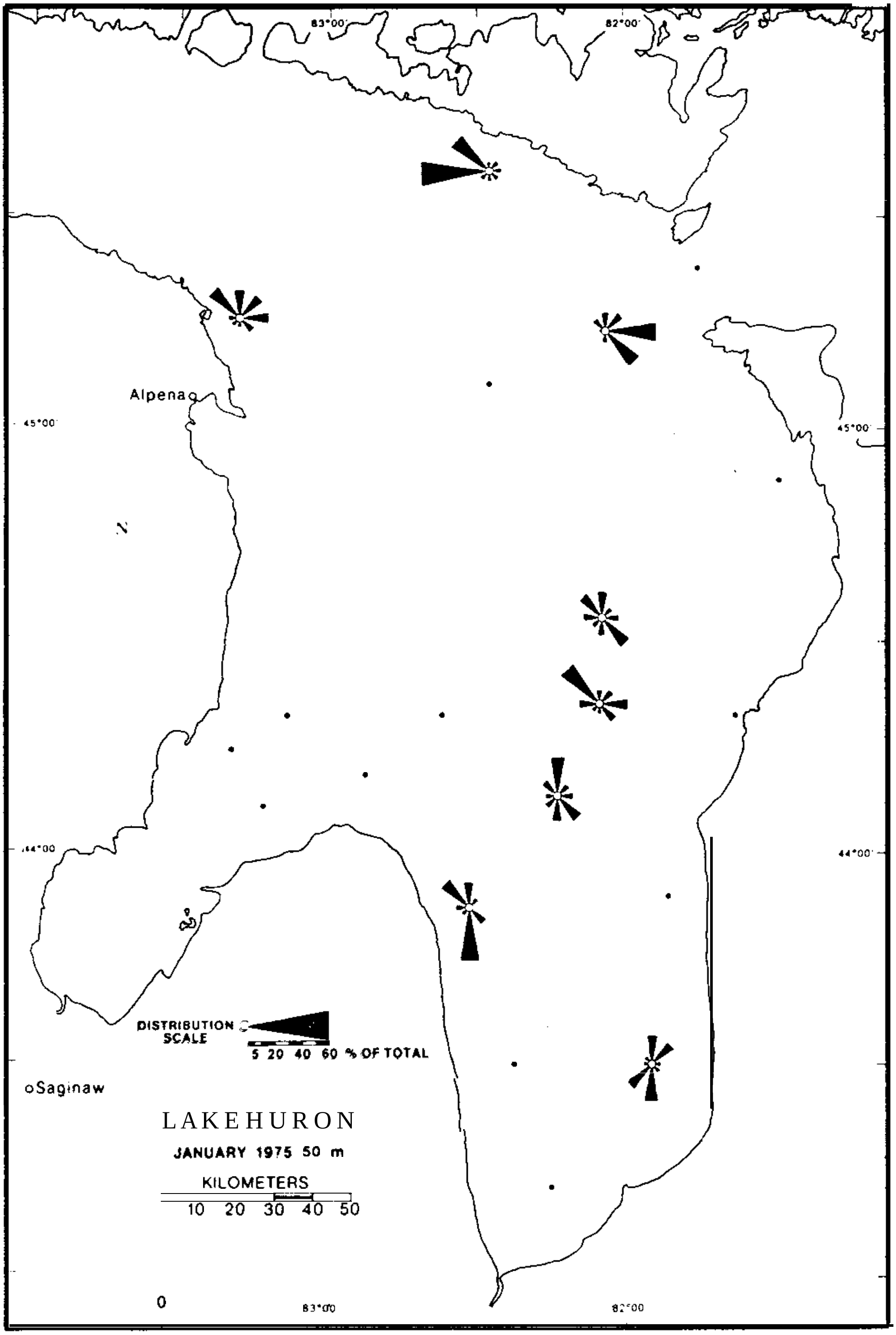

Figure A.3c. Current roses at 50 m depth for *January 1975.*

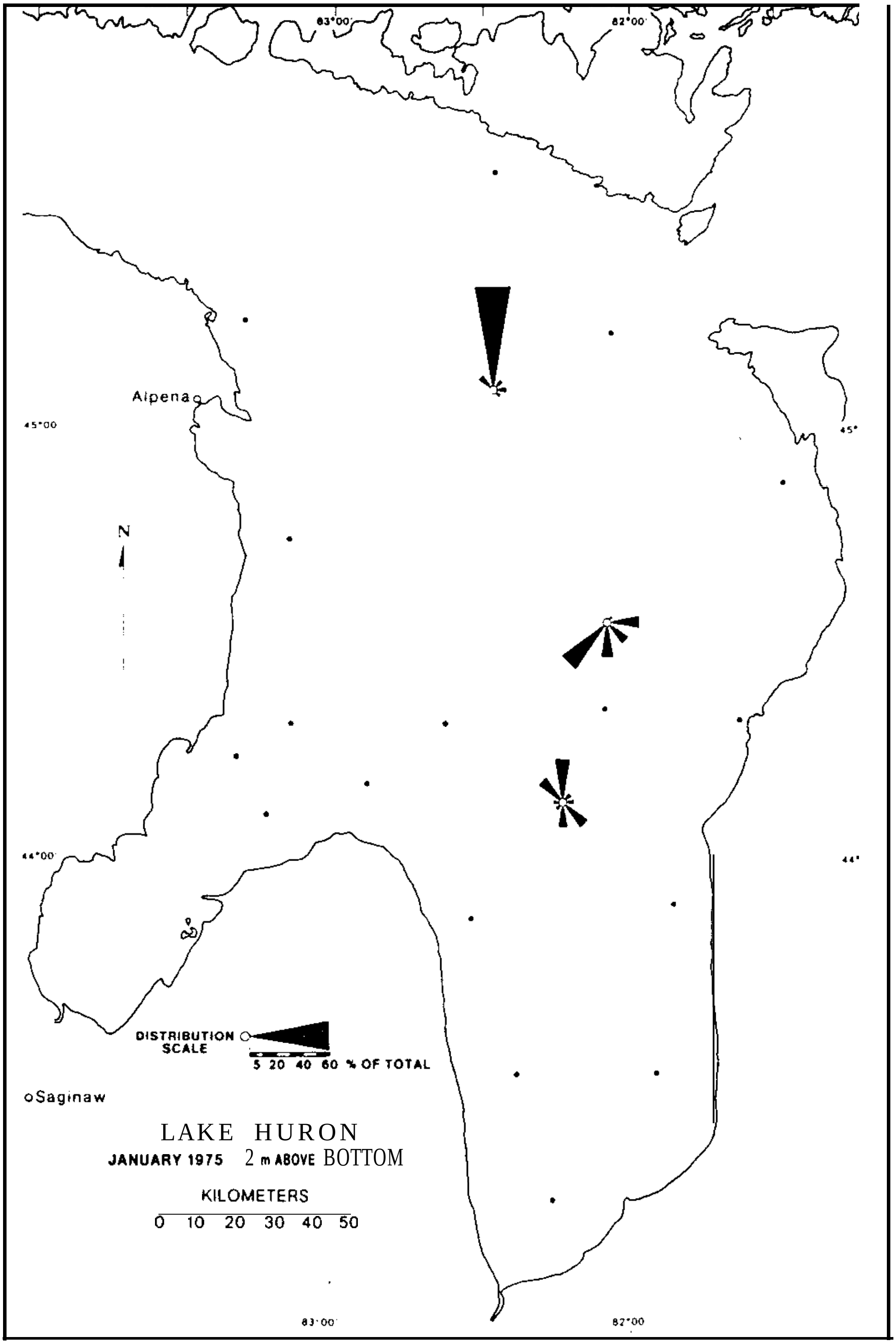

Figure A. 3d. Current roses at 2 m above the bottom ***for*** *January 1975.*

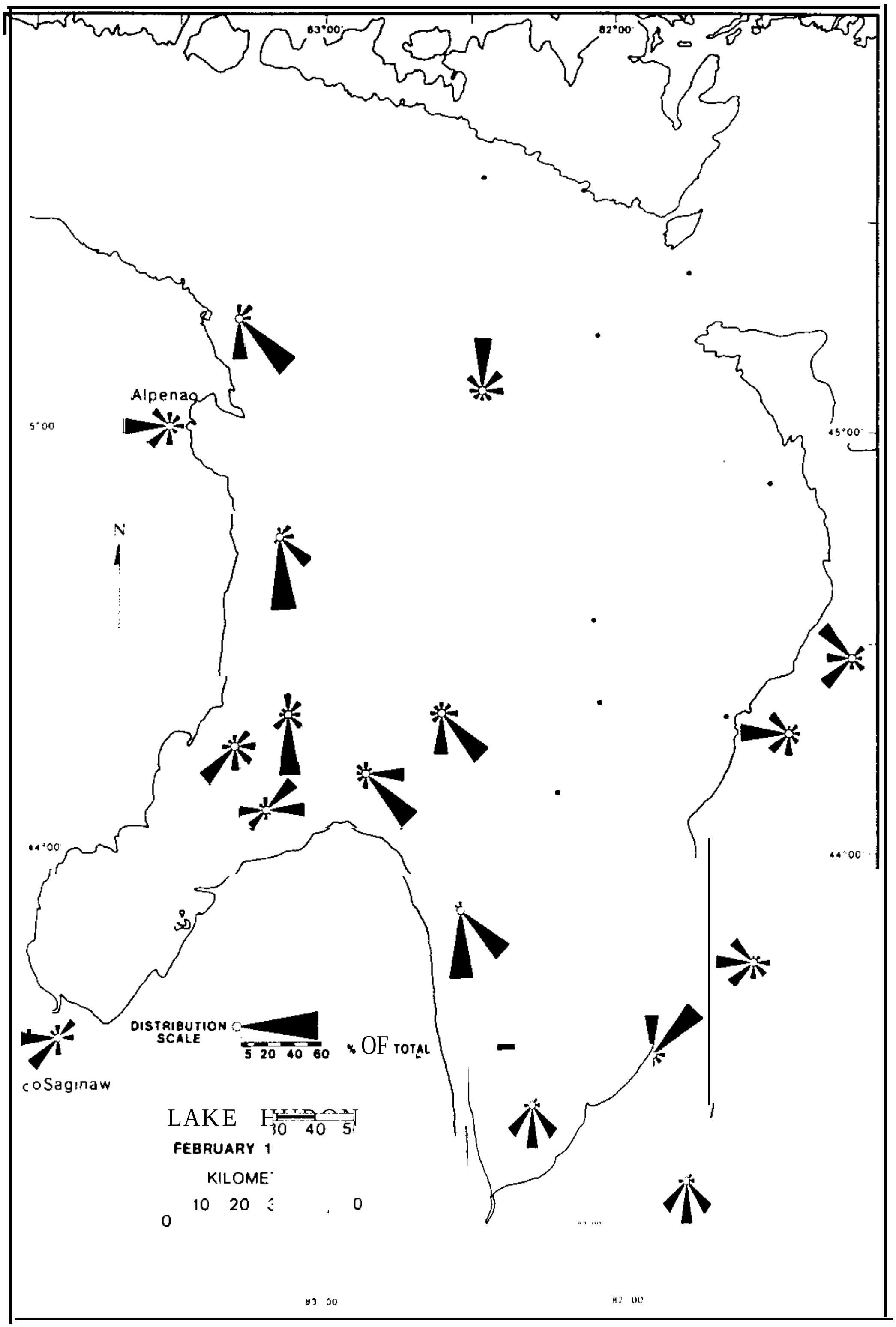

Figure A.4a. Current roses at 15 m depth and wind roses for February 1975.

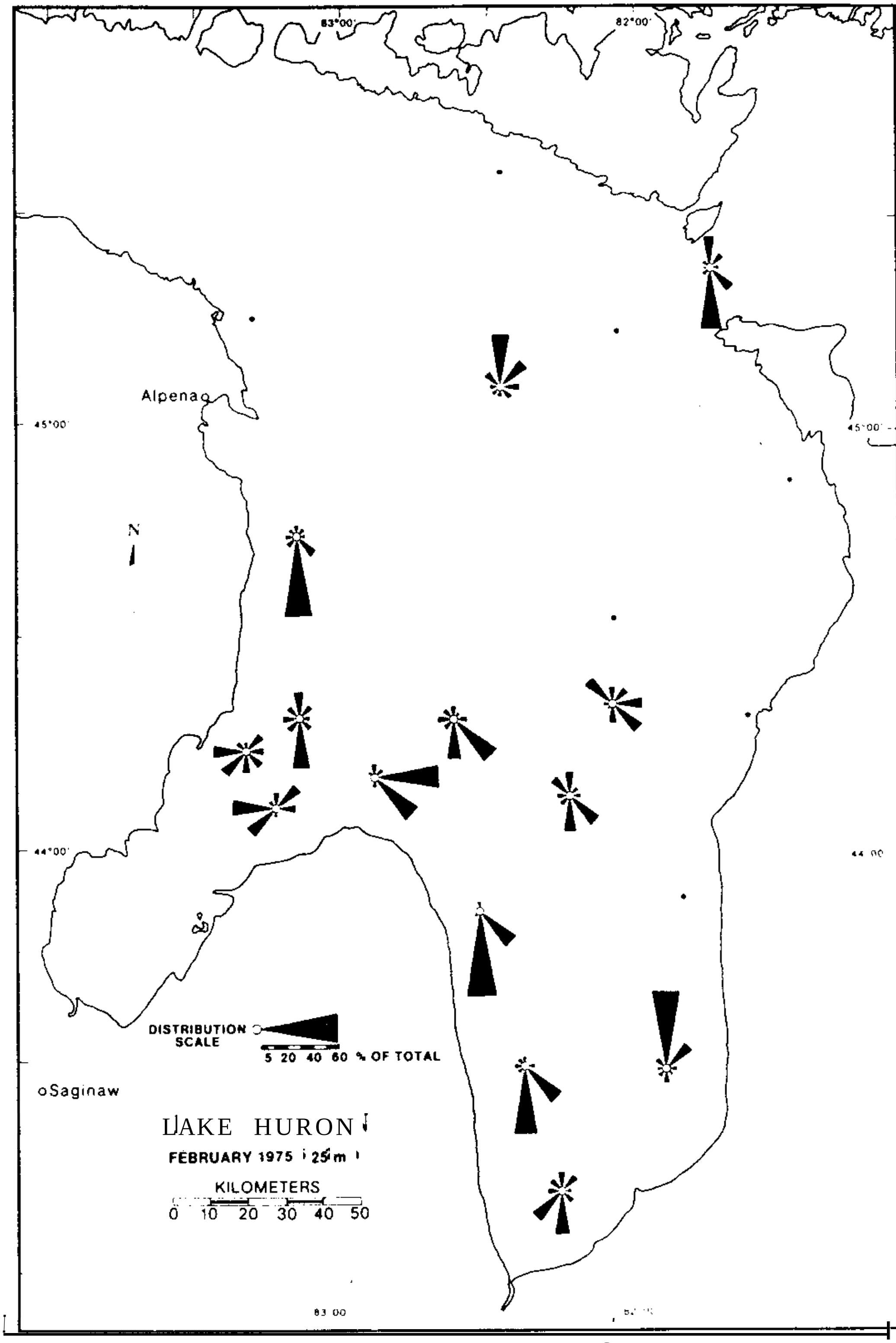

Figure A. 4b. Current roses at 25 m depth for February 1975.

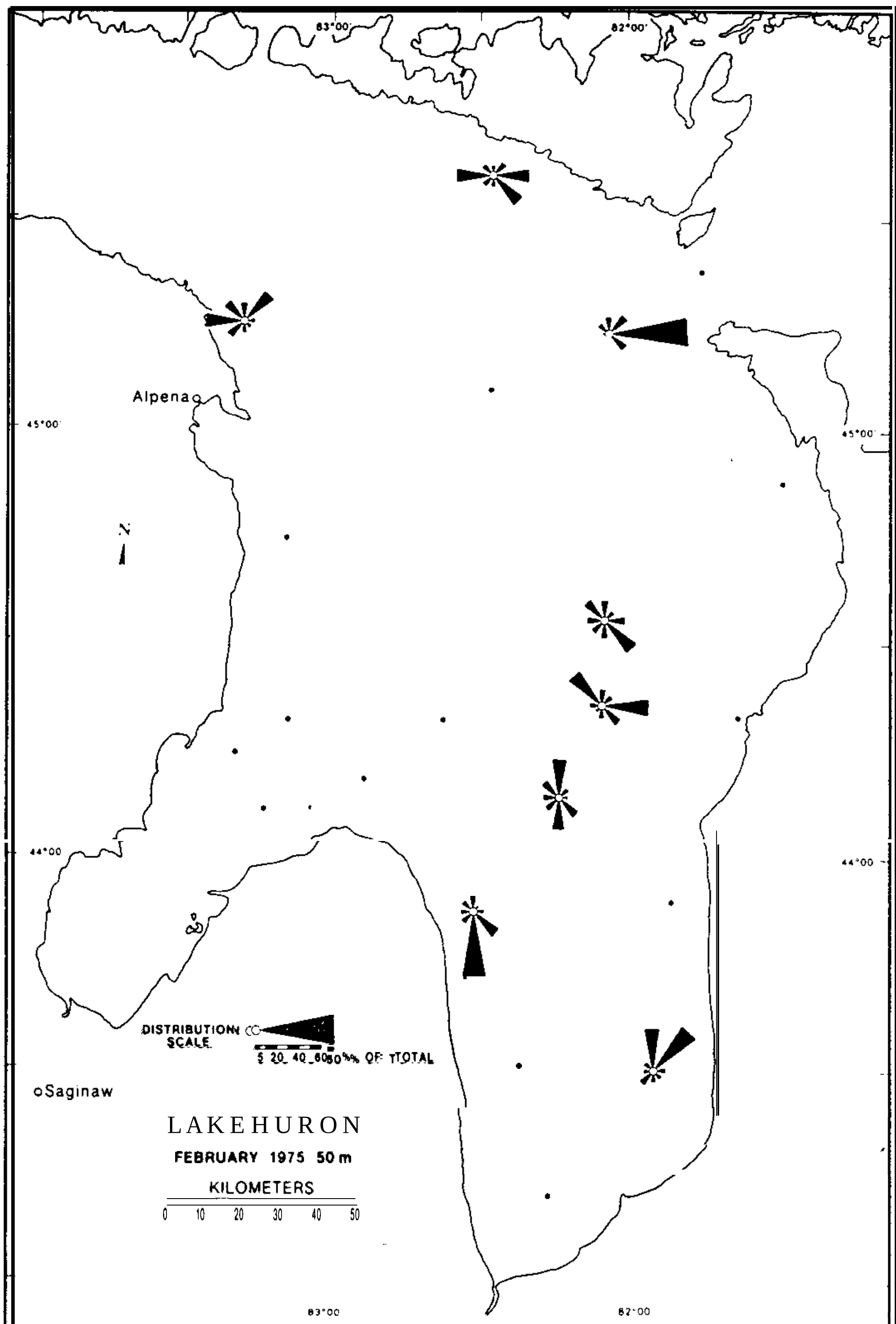

Figure A. 4c. Current roses at 50 m depth for *February 1975.*

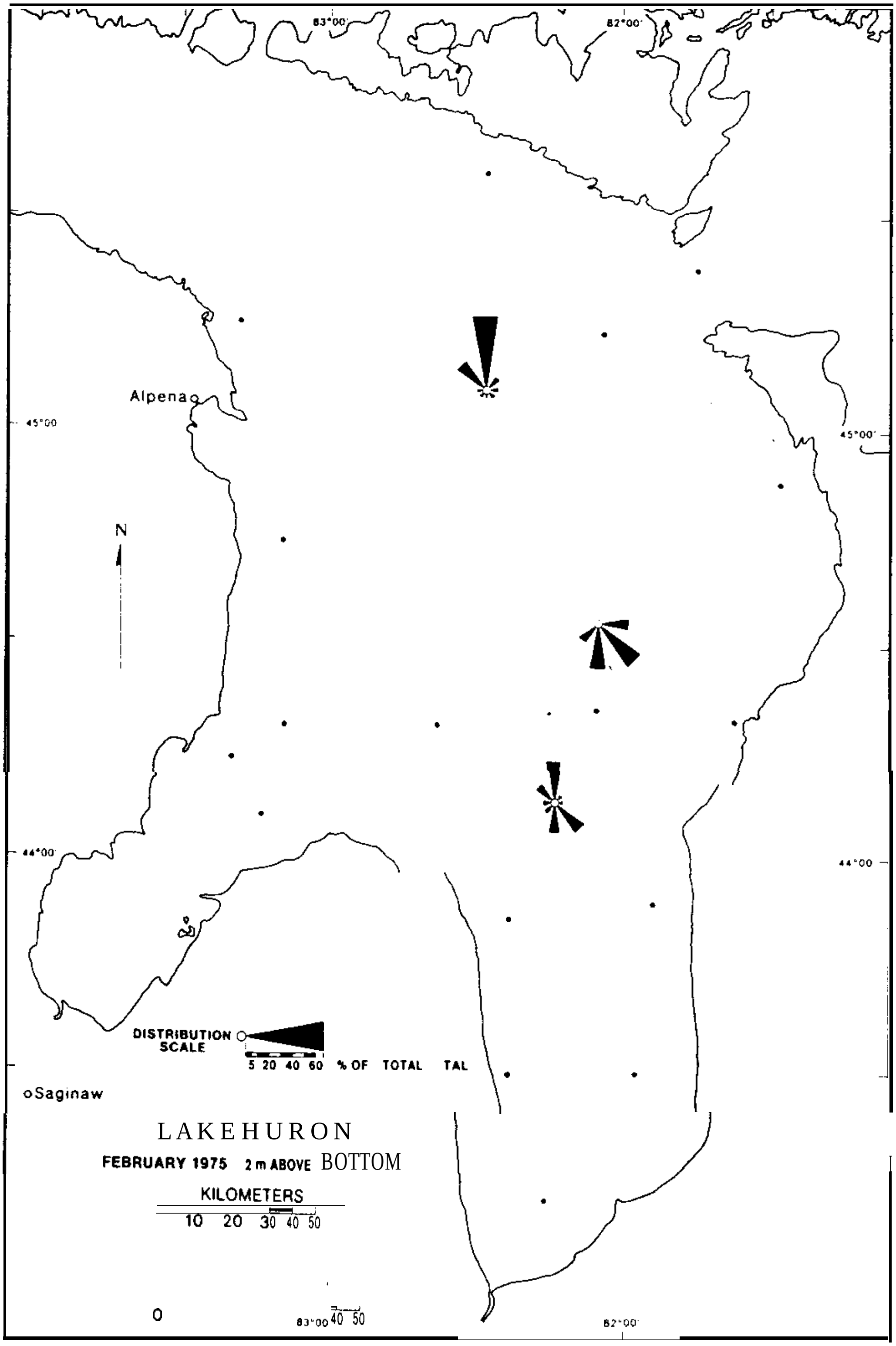

Figure A. 4d. Current roses at 2 m above the bottom for February 1975.

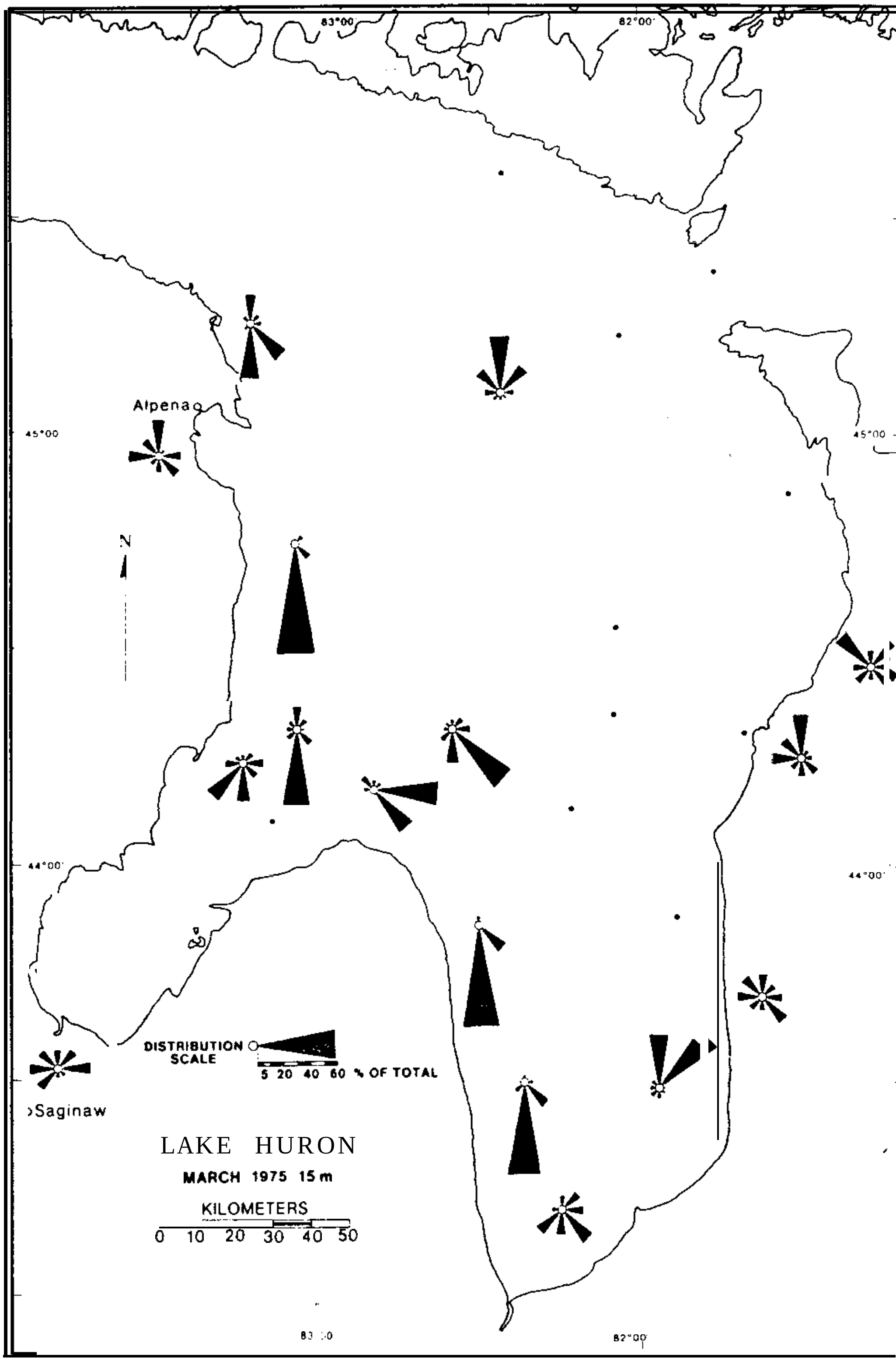

Figure A.5a. Current roses at 15 m depth and wind roses for March 1975.

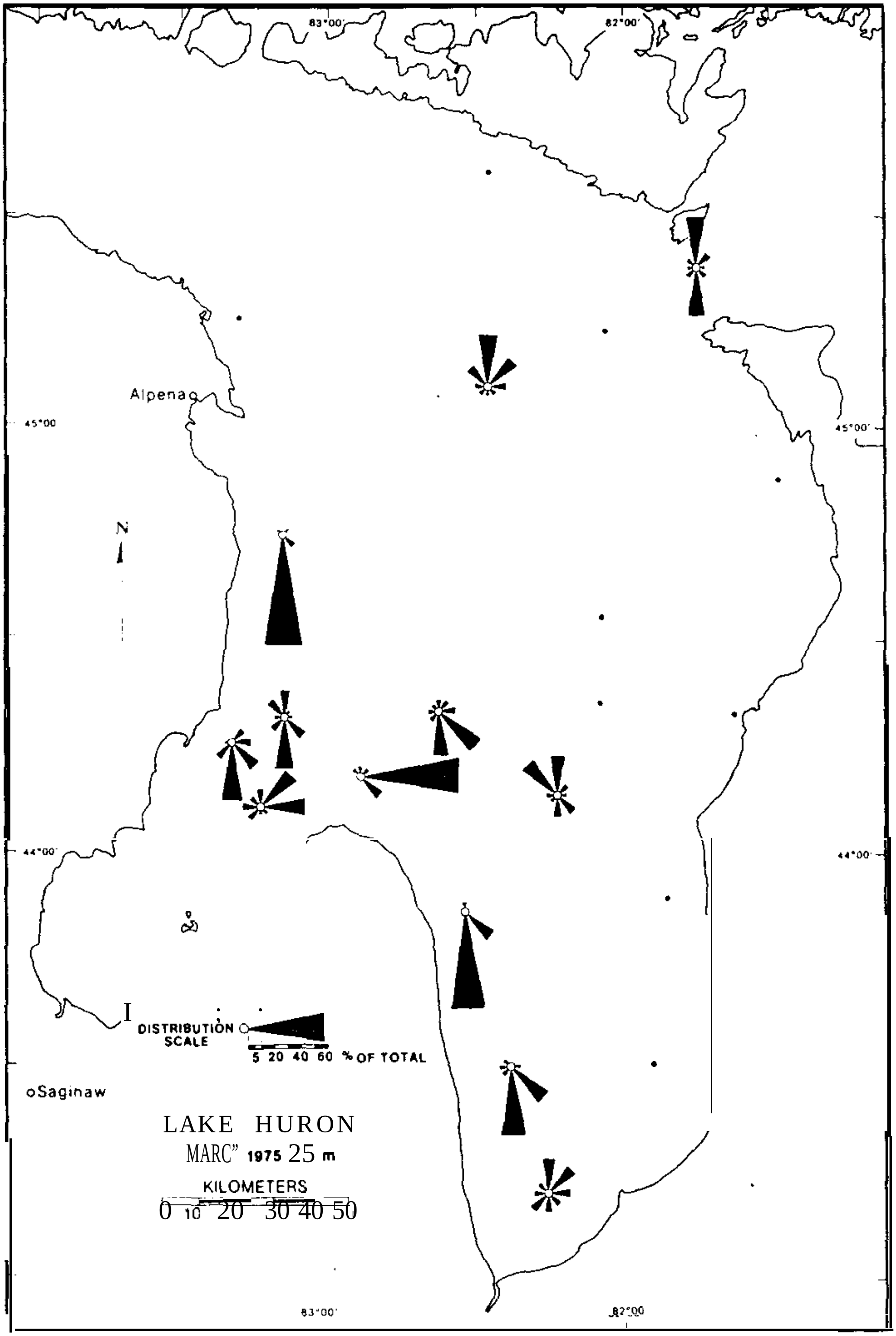

Figure A. 5b. Current roses at 25 m depth for March 1975.

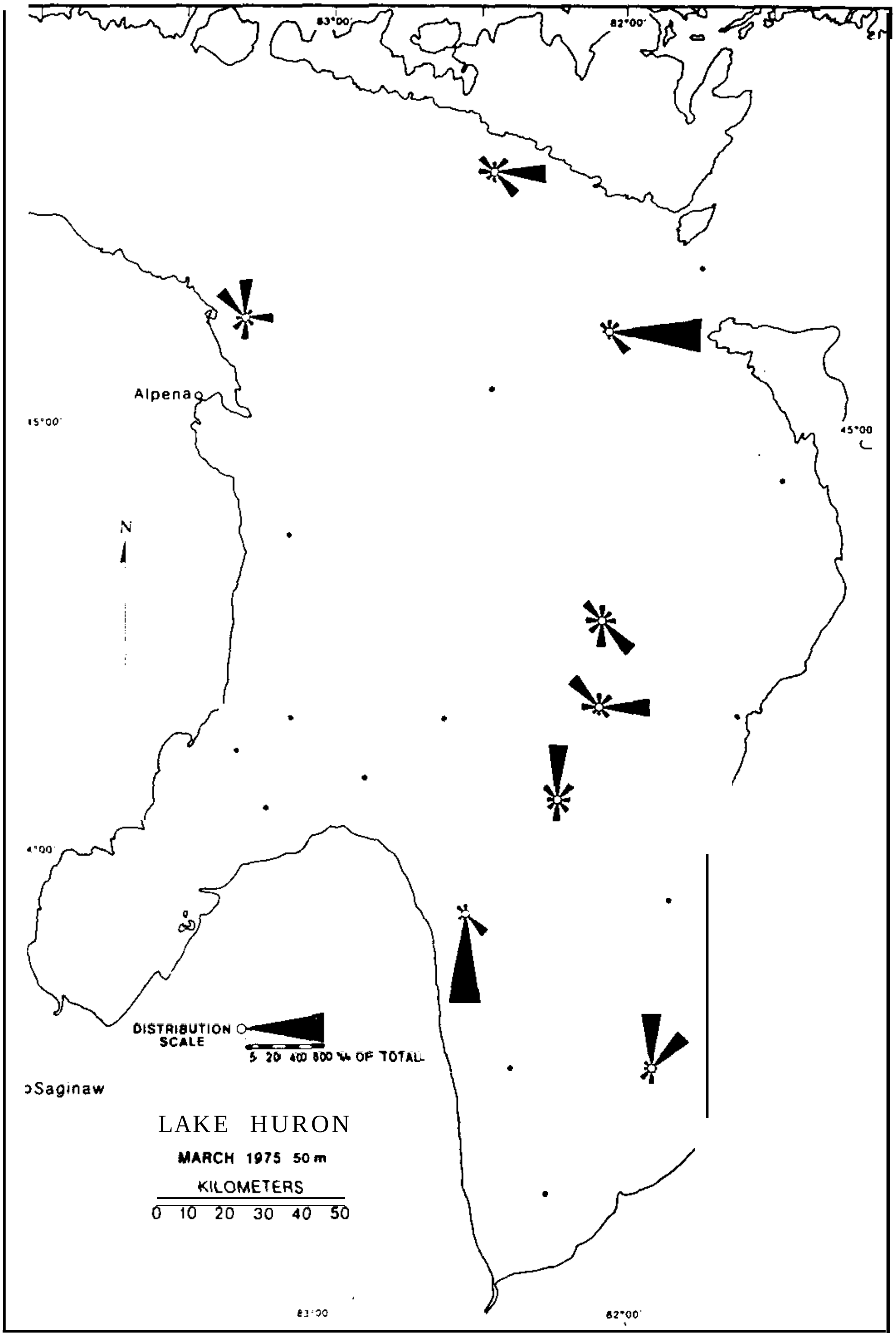

Figure A.5c. Current roses at 50 m depth for March 1975.

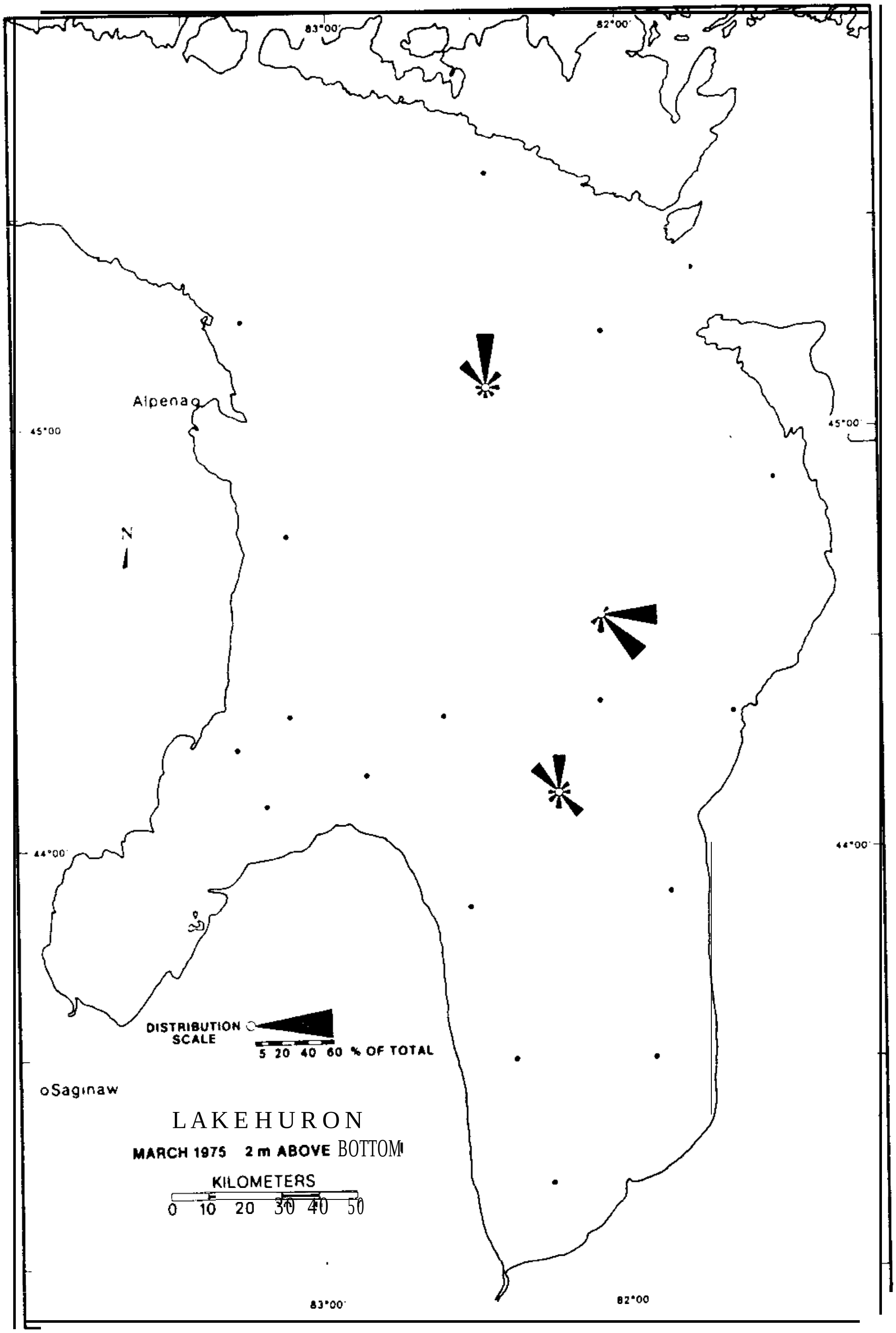

Figure A. 5d. Current roses at 2 m above the bottom for Marc 1975.

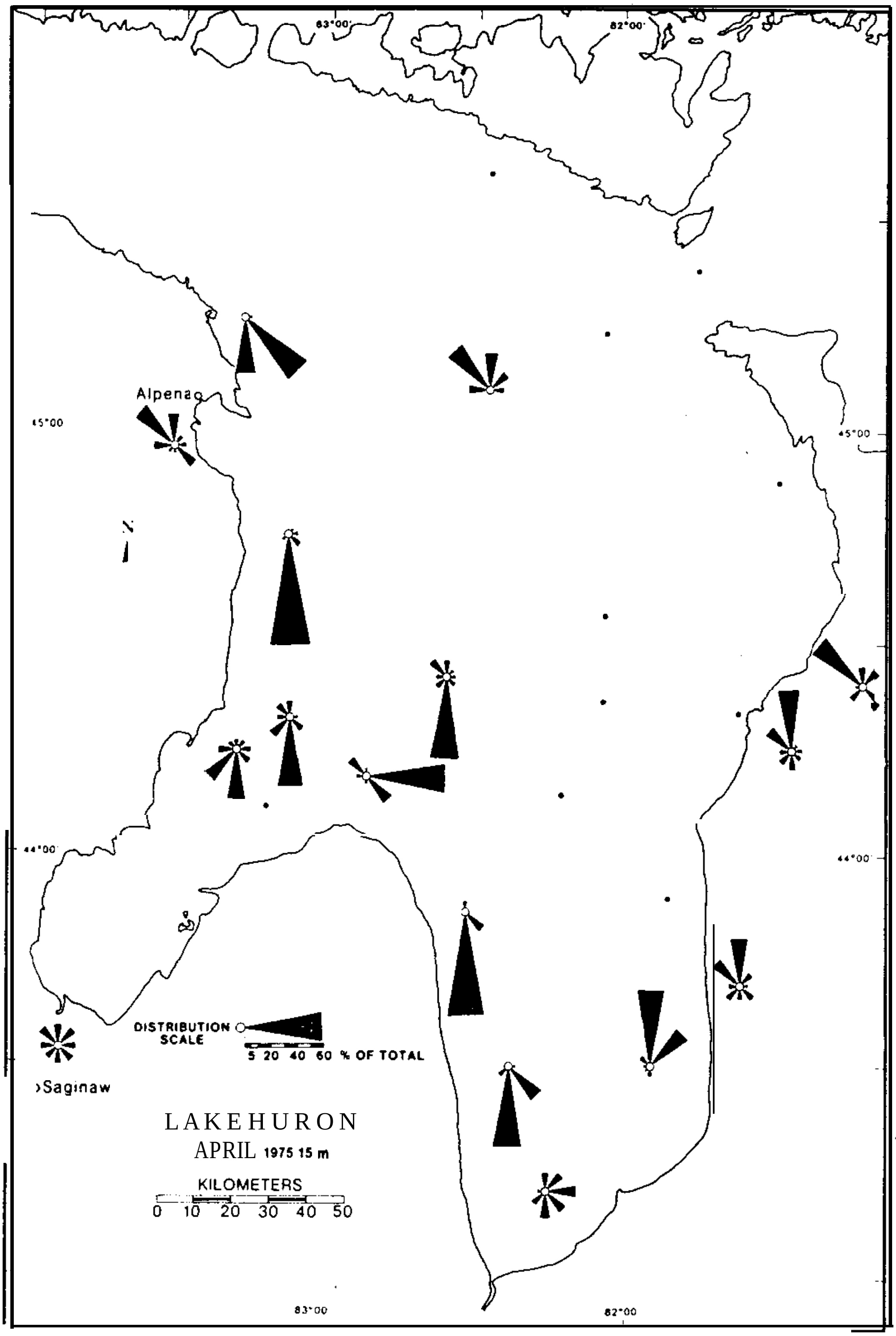

Figure A.6a. Current roses at 15 m depth and wind roses for April 1975.

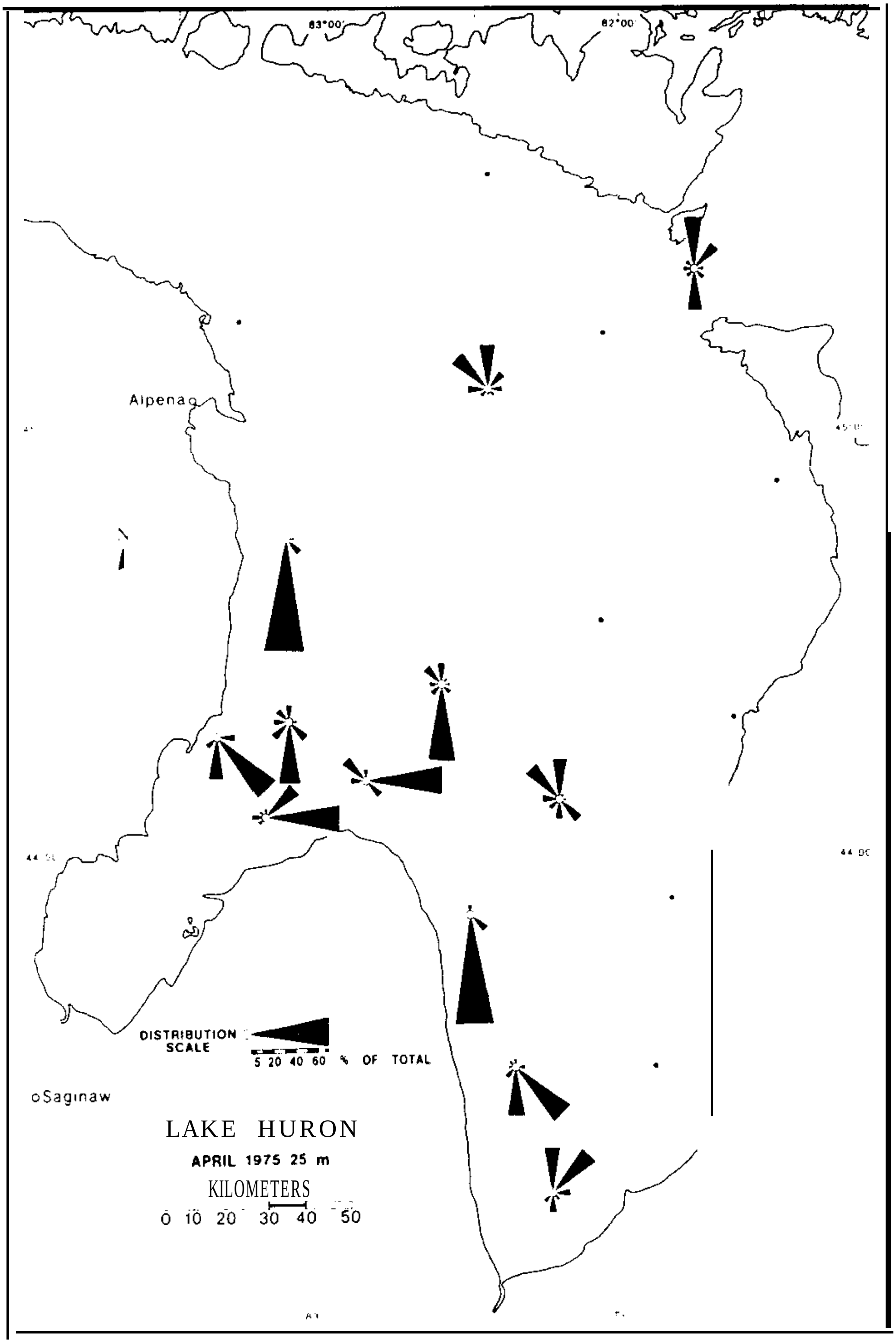

Figure A. 6b. Currentrosesat25mdepthfor April 1375.

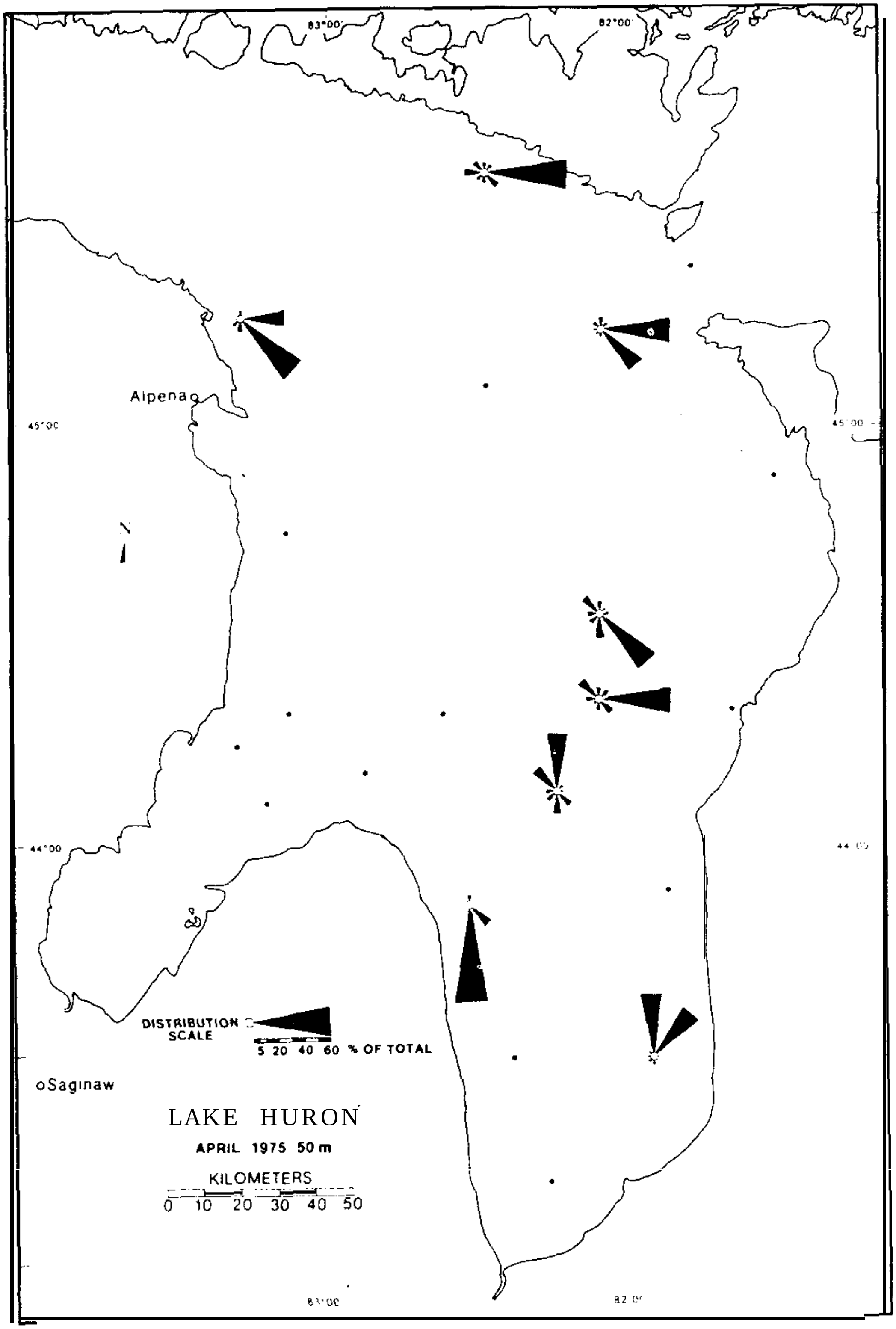

Figure A.6c. Current **roses at 50 m depth** for **April** 1975.

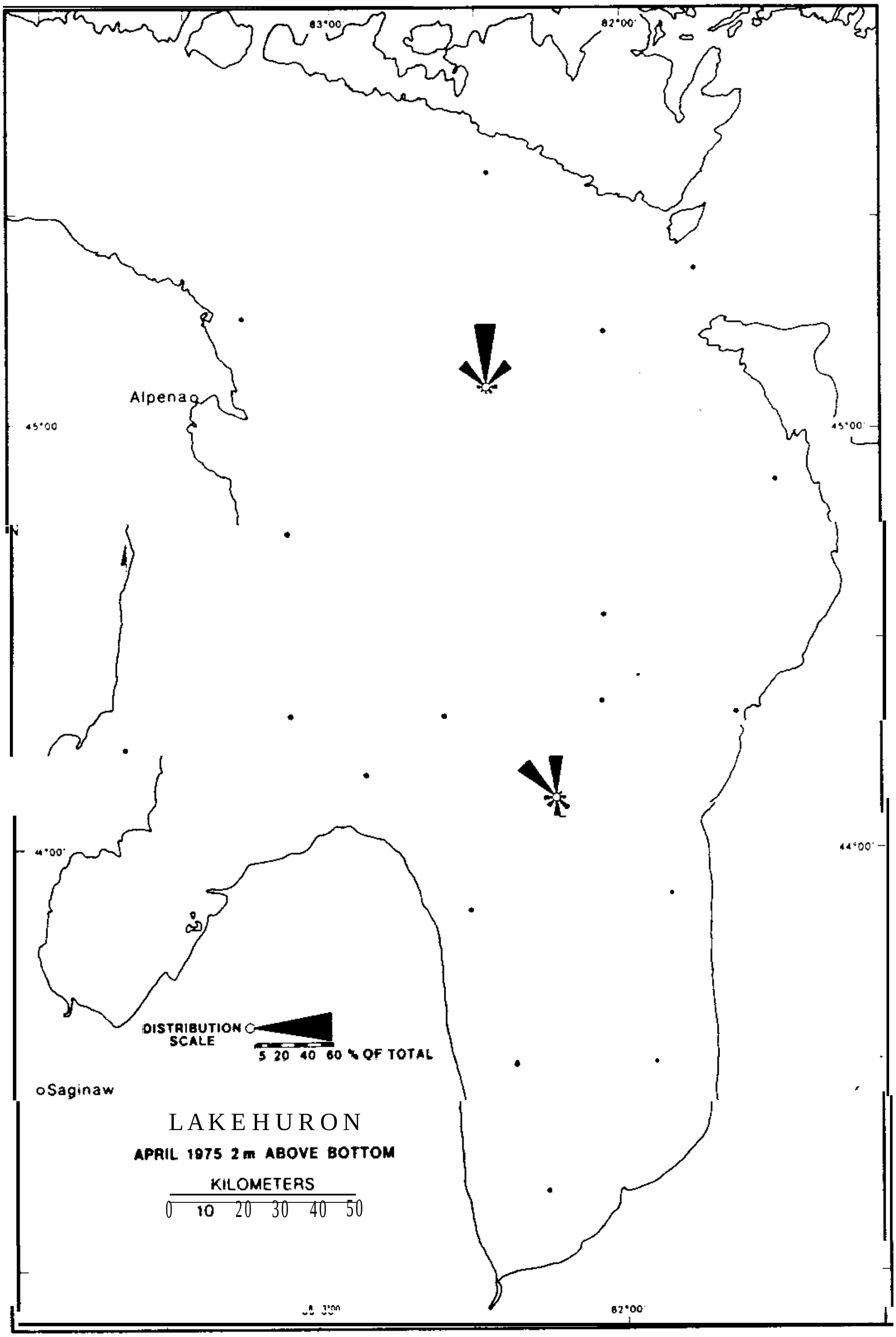

Figure A.6d. Current roses at 2 m above the bottom for April 1975.

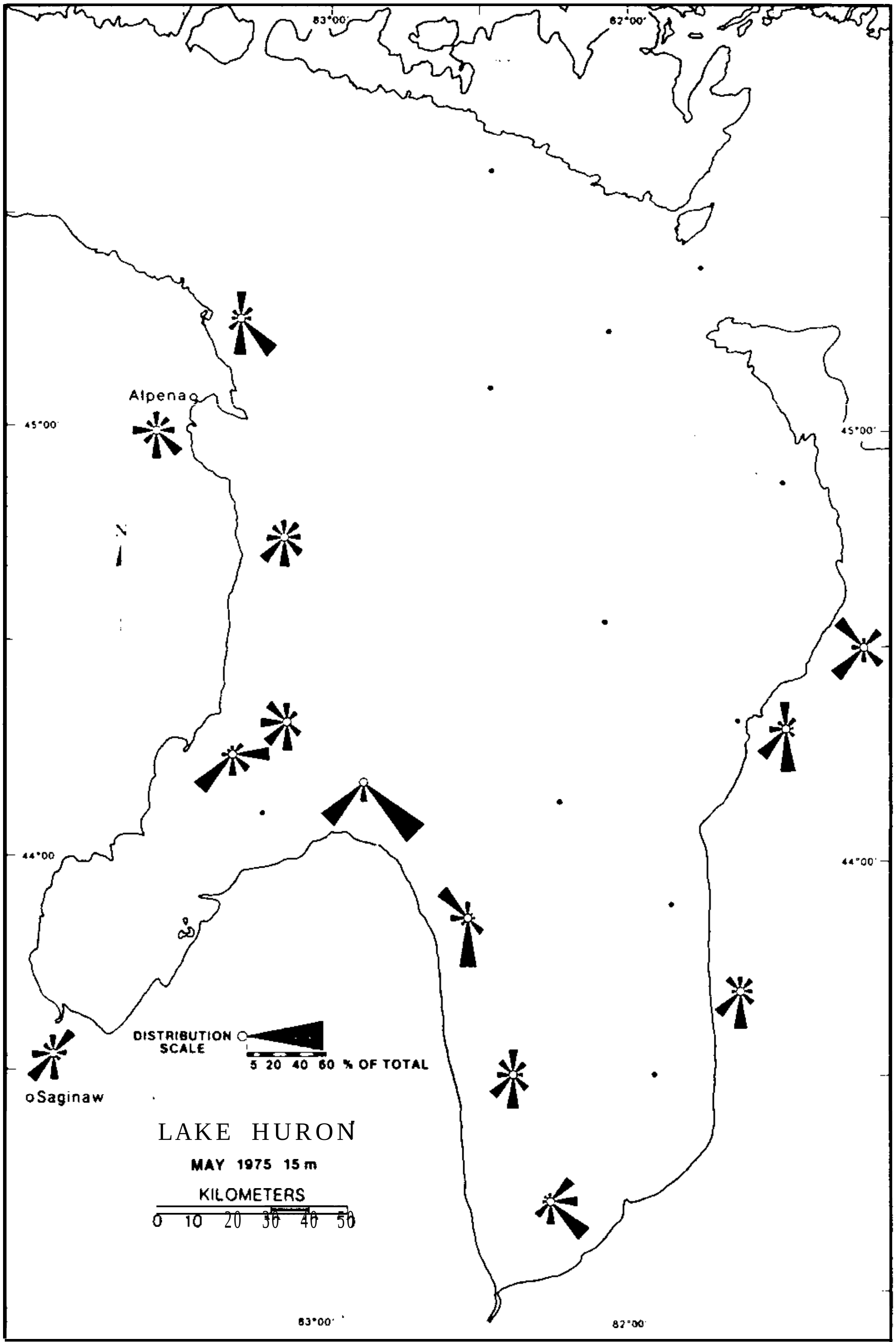

Figure A.7a. Current roses at 15 m depth and wind roses for May 1975.

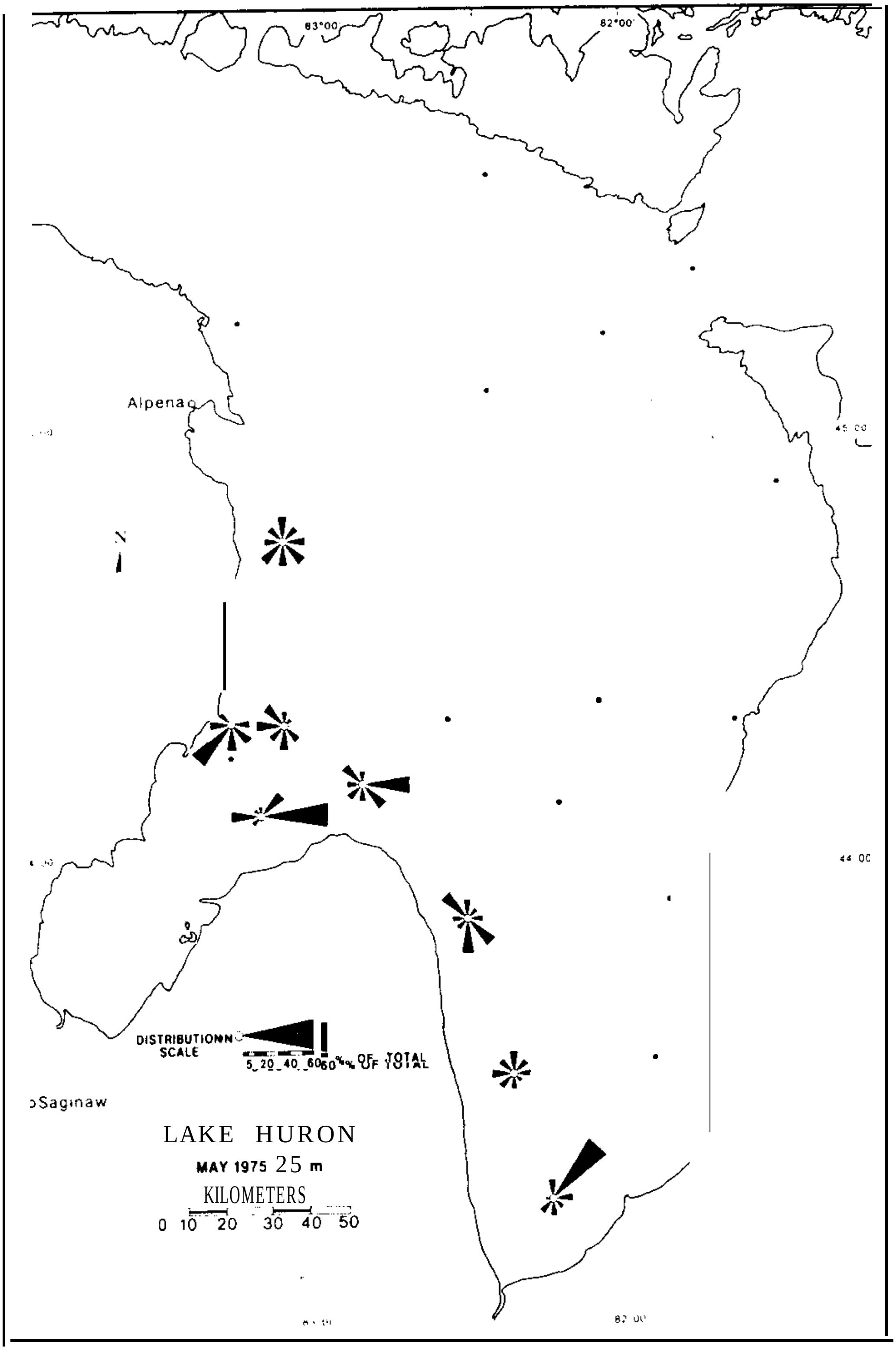

Figure A.75. Current roses at 25 m depth for May 1975.

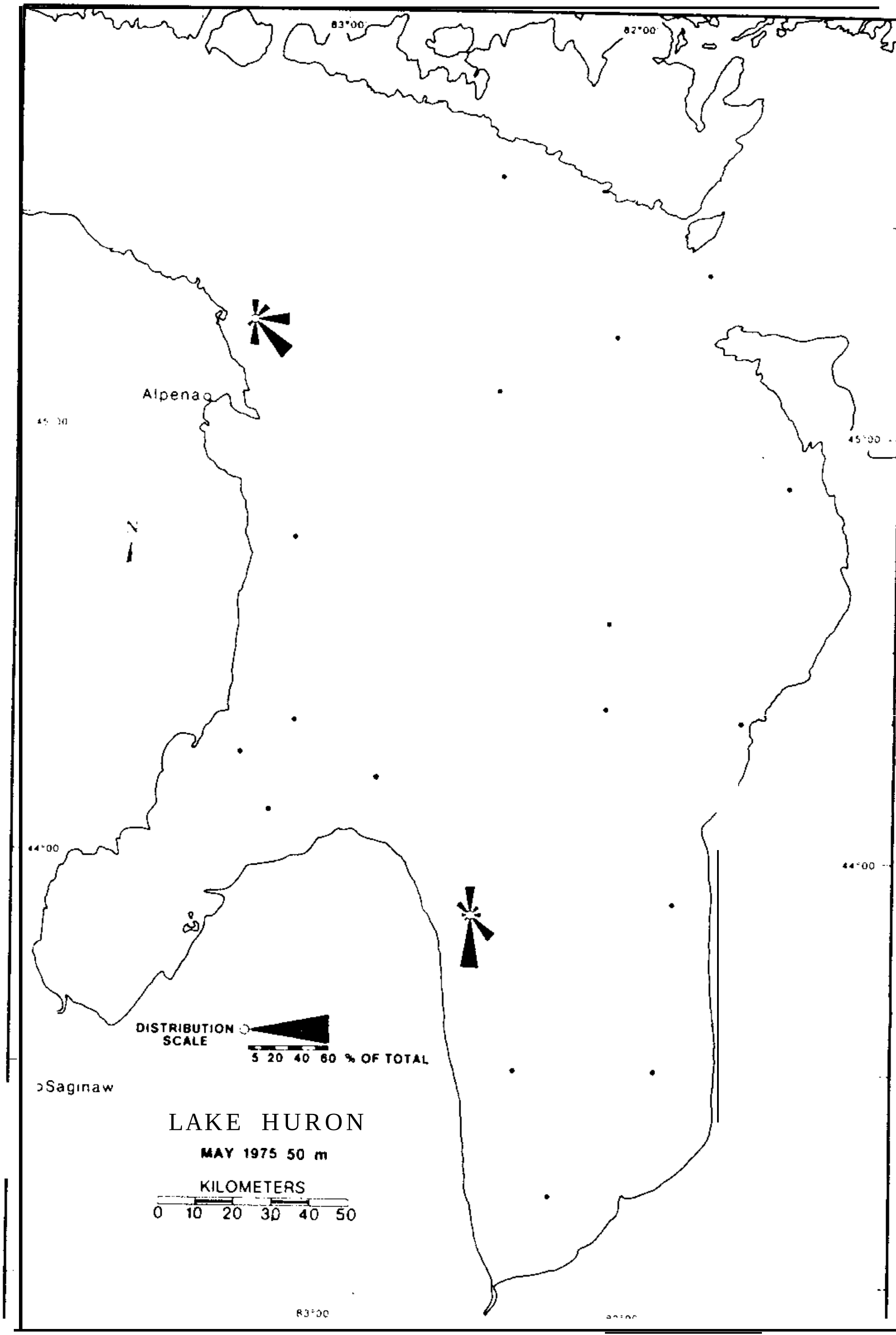

Figure A.7c. Current roses at 50 m depth for May 1975.

No current data received from 2 m off the bottom for May 1975.

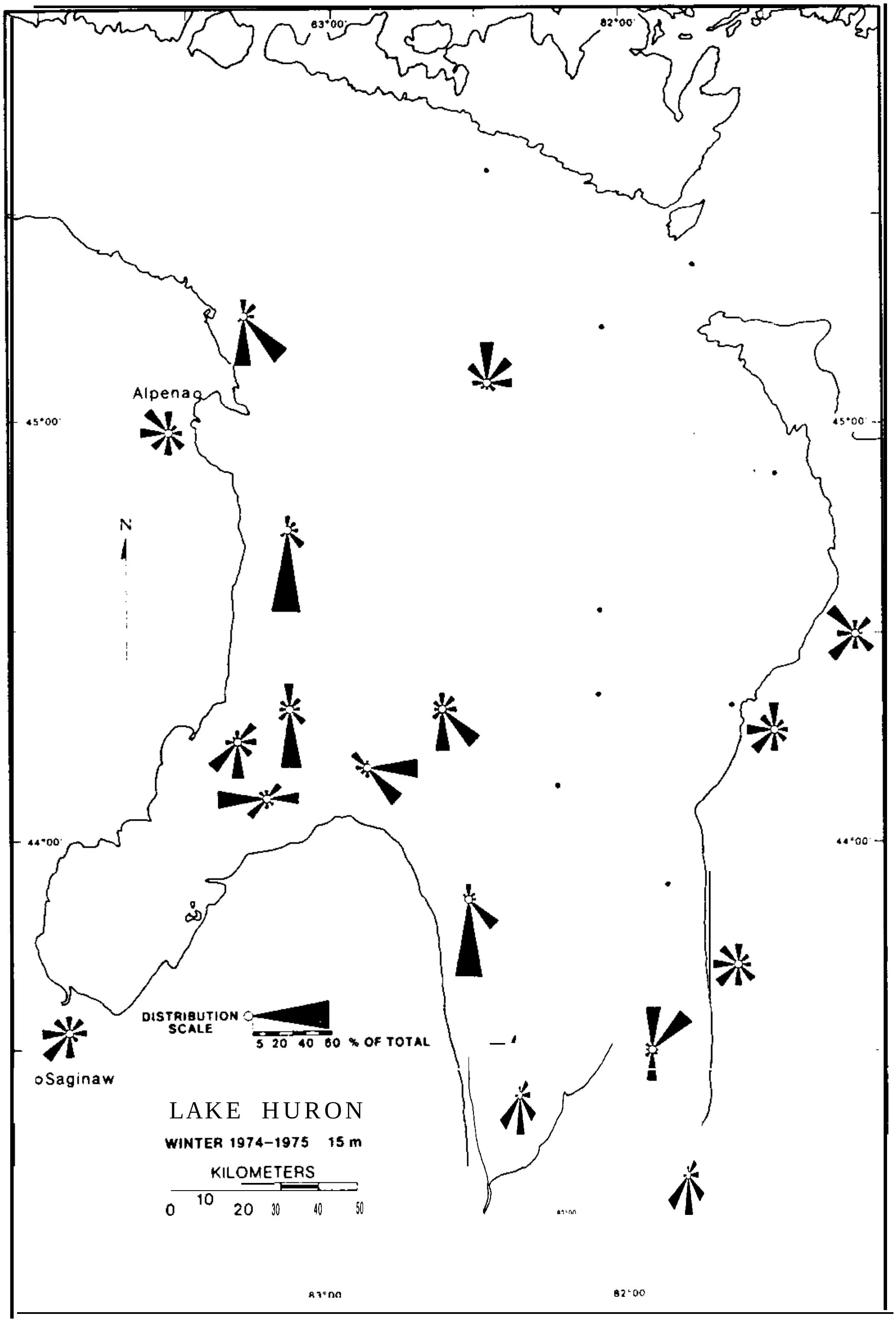

Figure A.8a. Current roses at 15 m depth and wind roses for winter 1974-75.

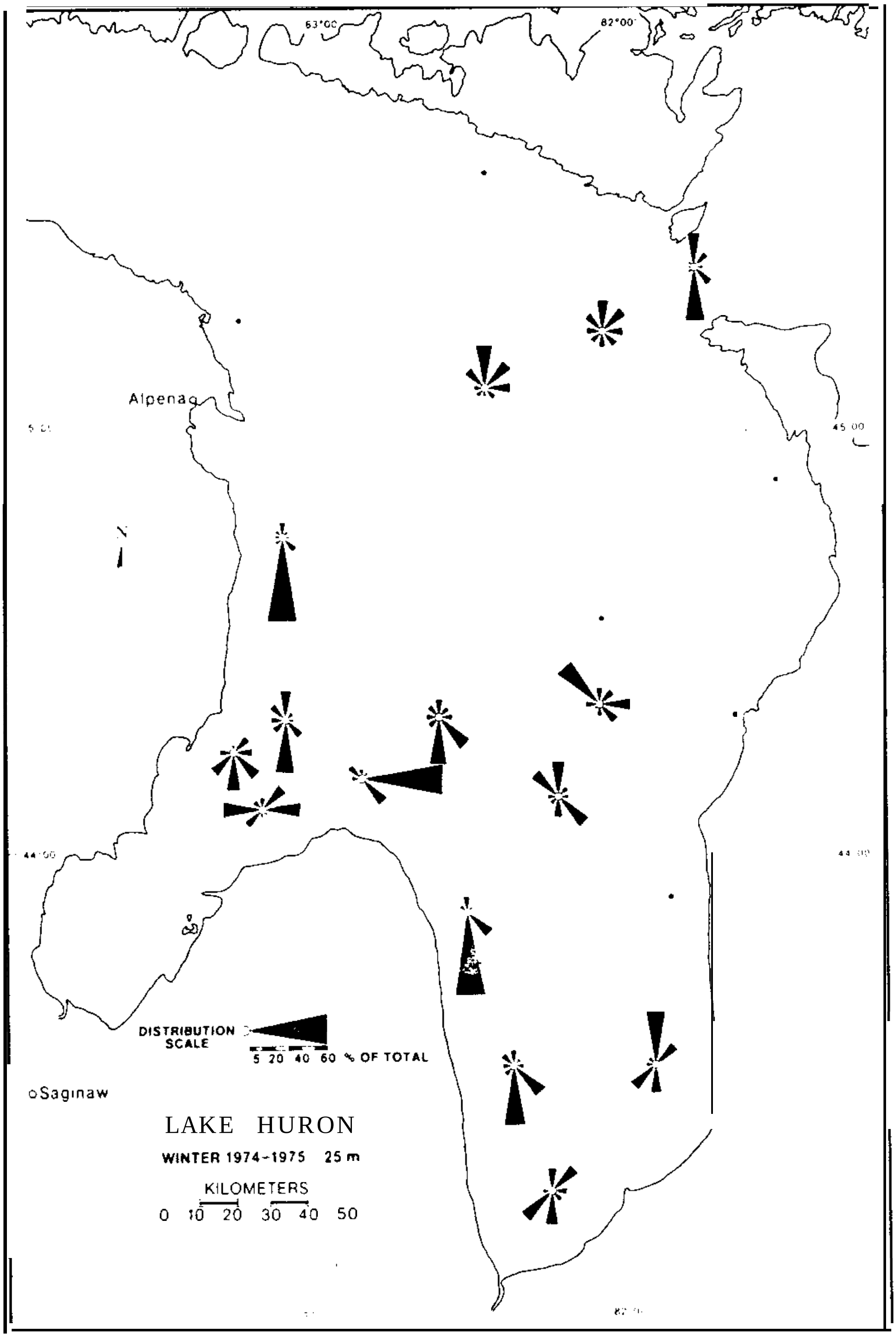

Figure A. 8b. Current roses at 25 m depth for winter 1274-75.

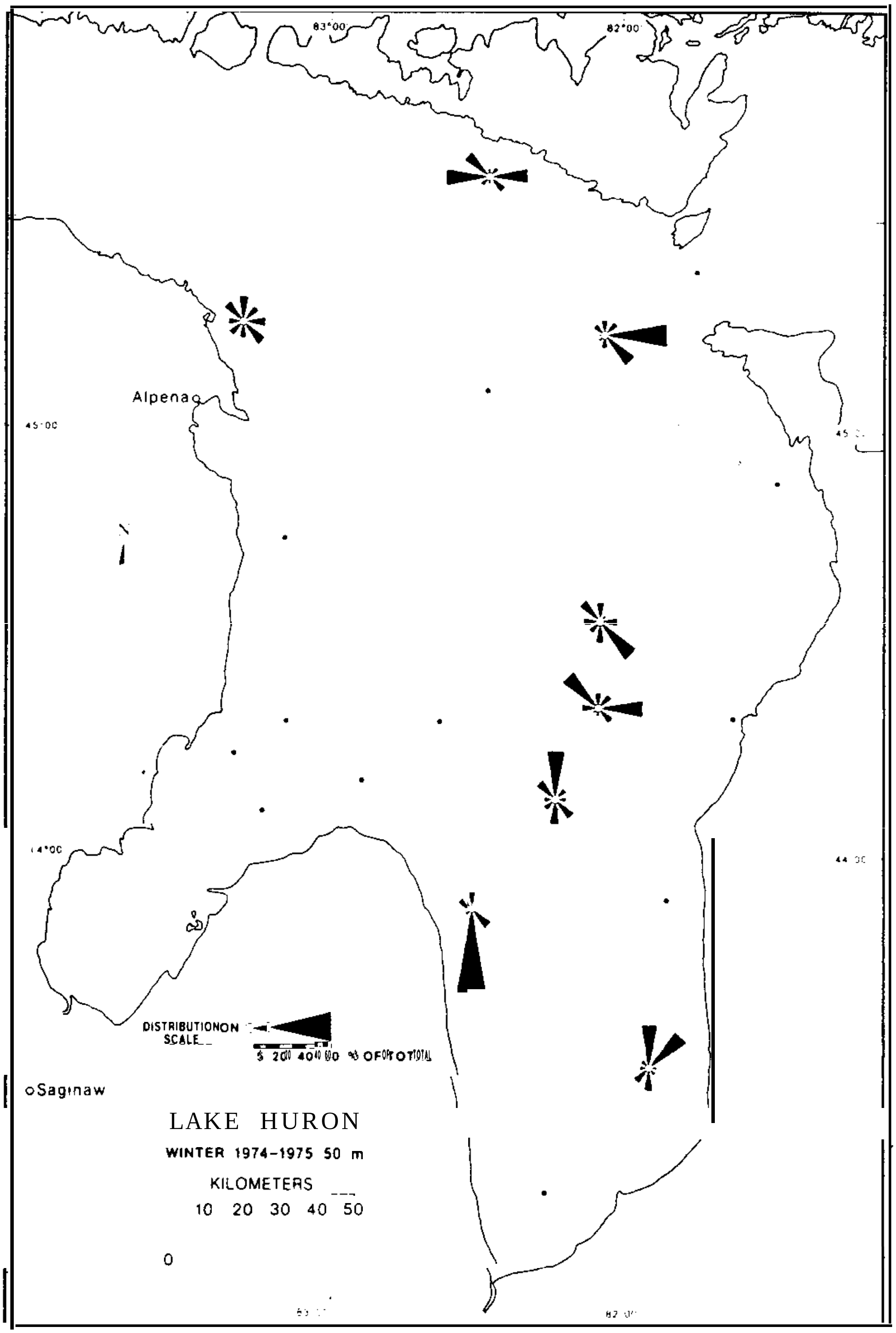

Figure A.8c. Current roses at 50 m depth for winter 1974-75.

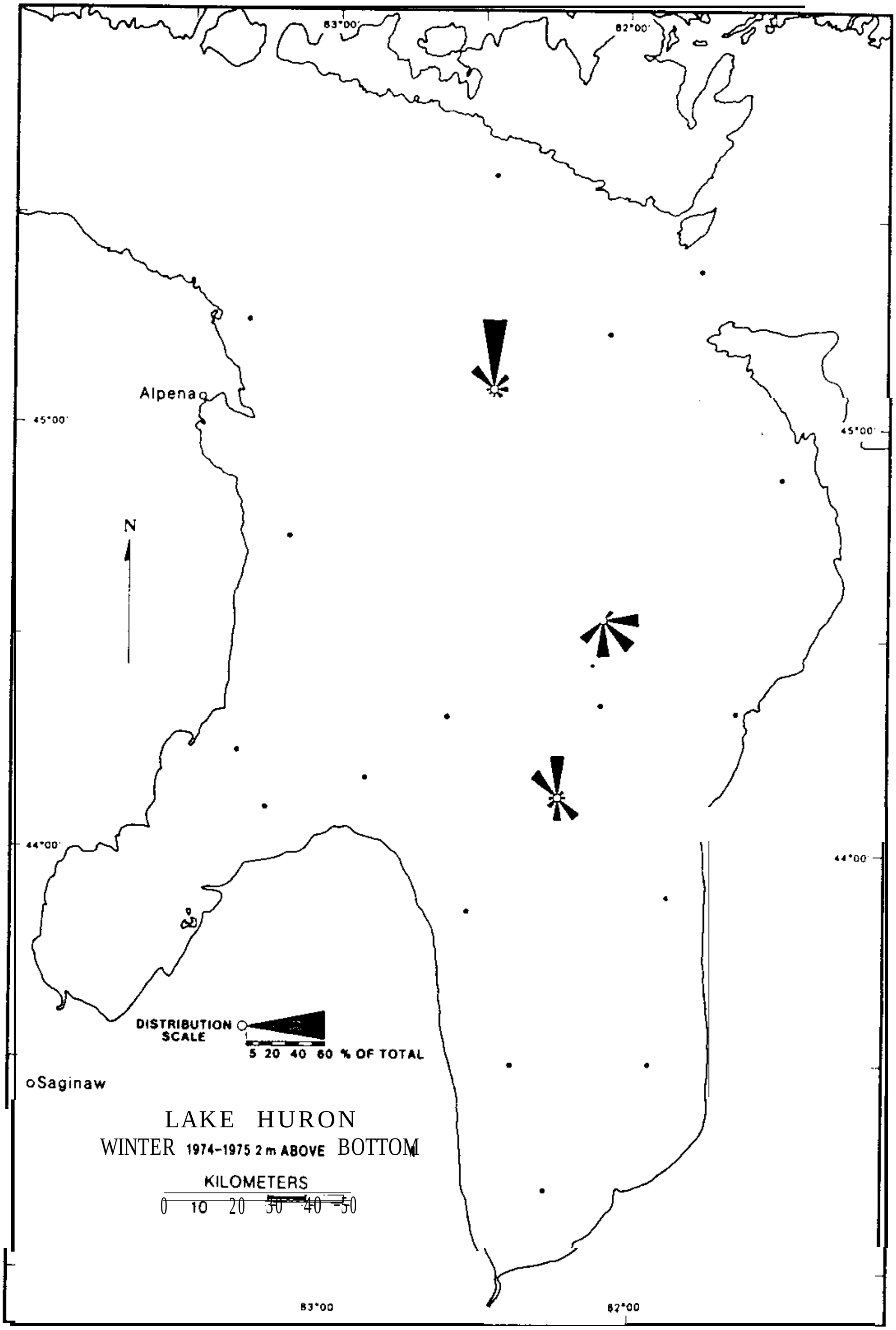

Figure A. 8d. Current roses at 2 m above the bottom for winter 1974-75.

Appendix B

WATER CURRENT TRANSPORT AND WIND RUN ROSES FOR SELECTED EPISODES OF DIRECTIONALLY STEADY WIND STRESS IN LAKE HURON DURING WINTER 1974-75.

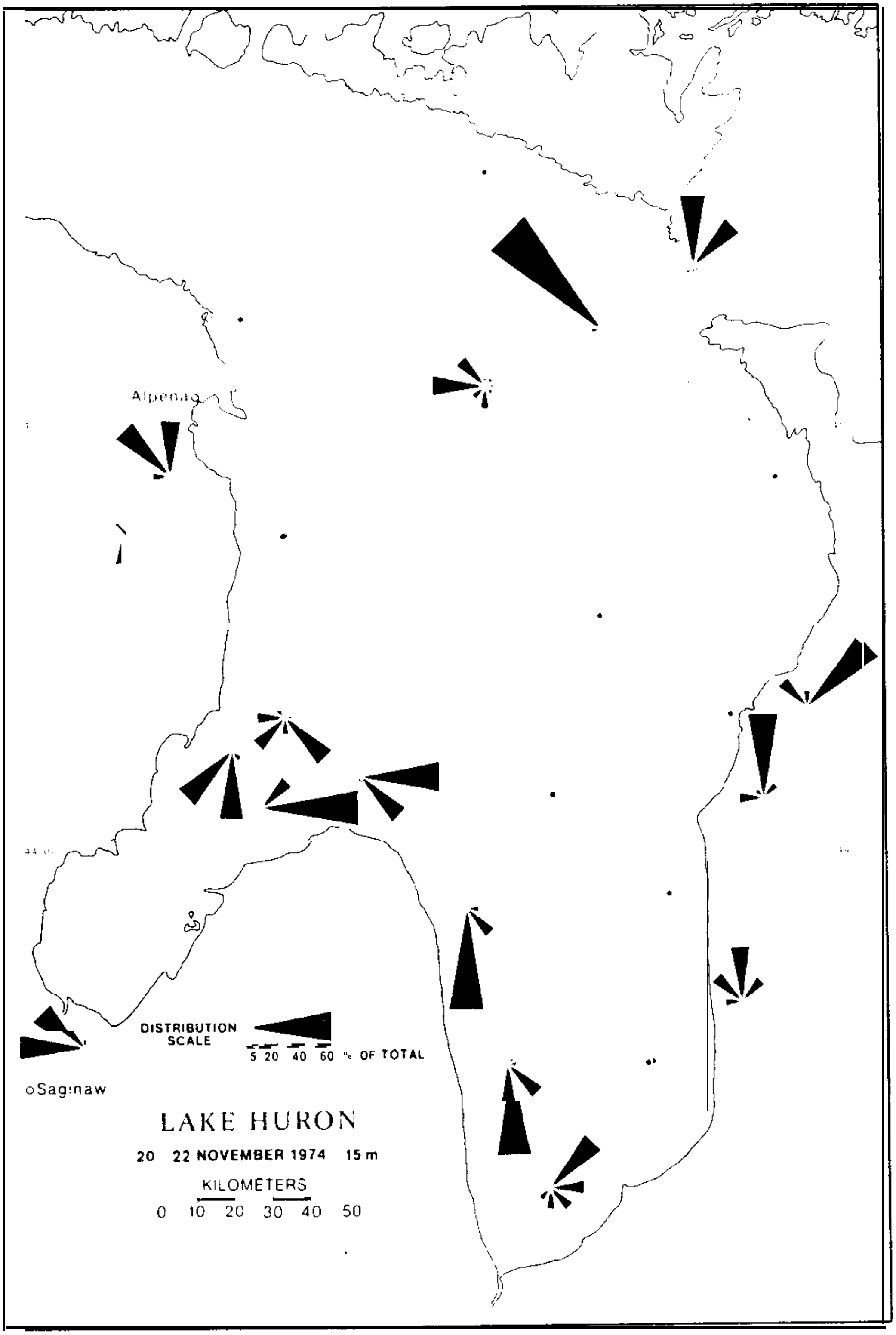

Figure B.1a. Current roses at 15 m depth and wind roses for 20-22 November 1974.

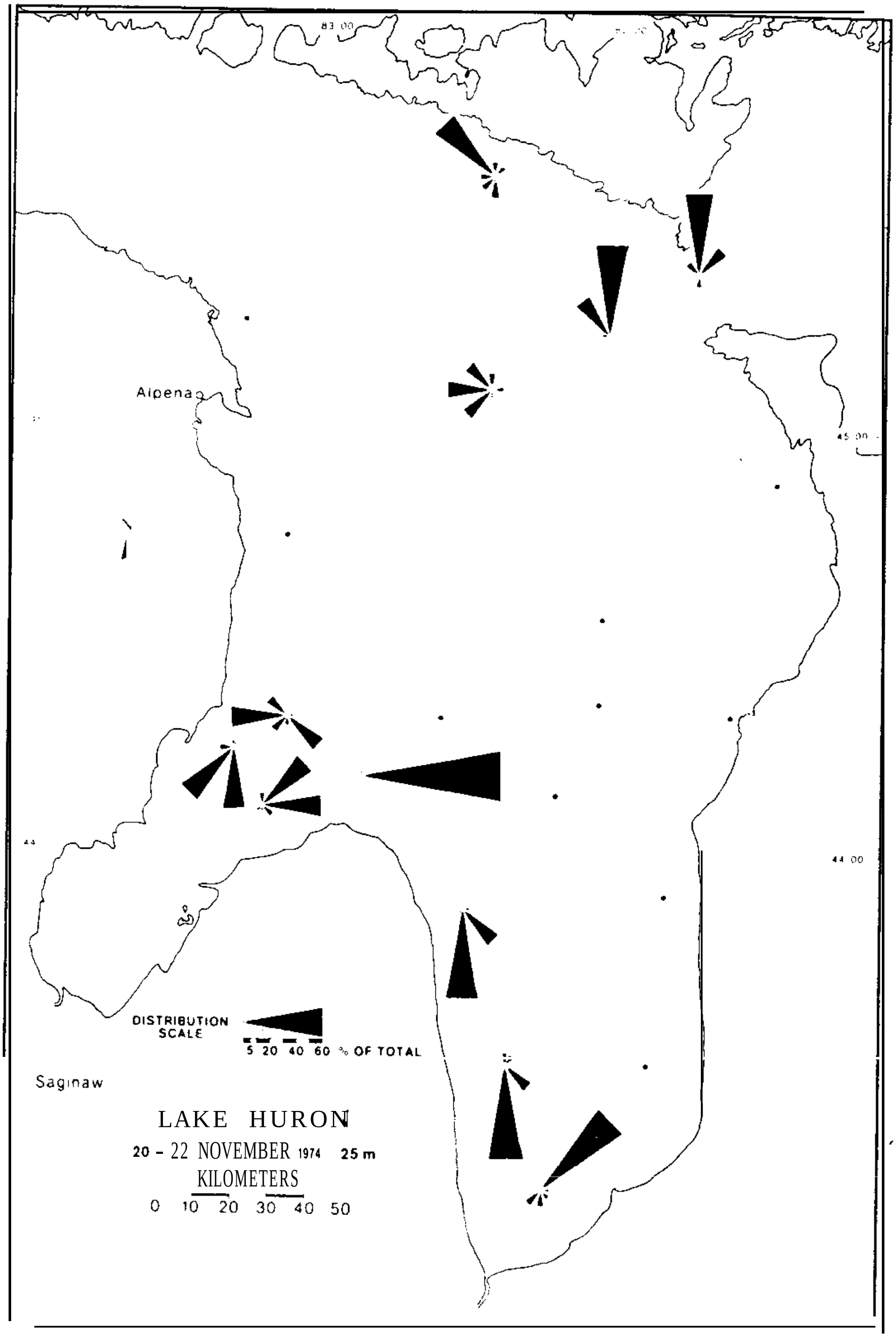

Figure 3. lb. Current roses at 25 m depth for 20-22 November 1974.

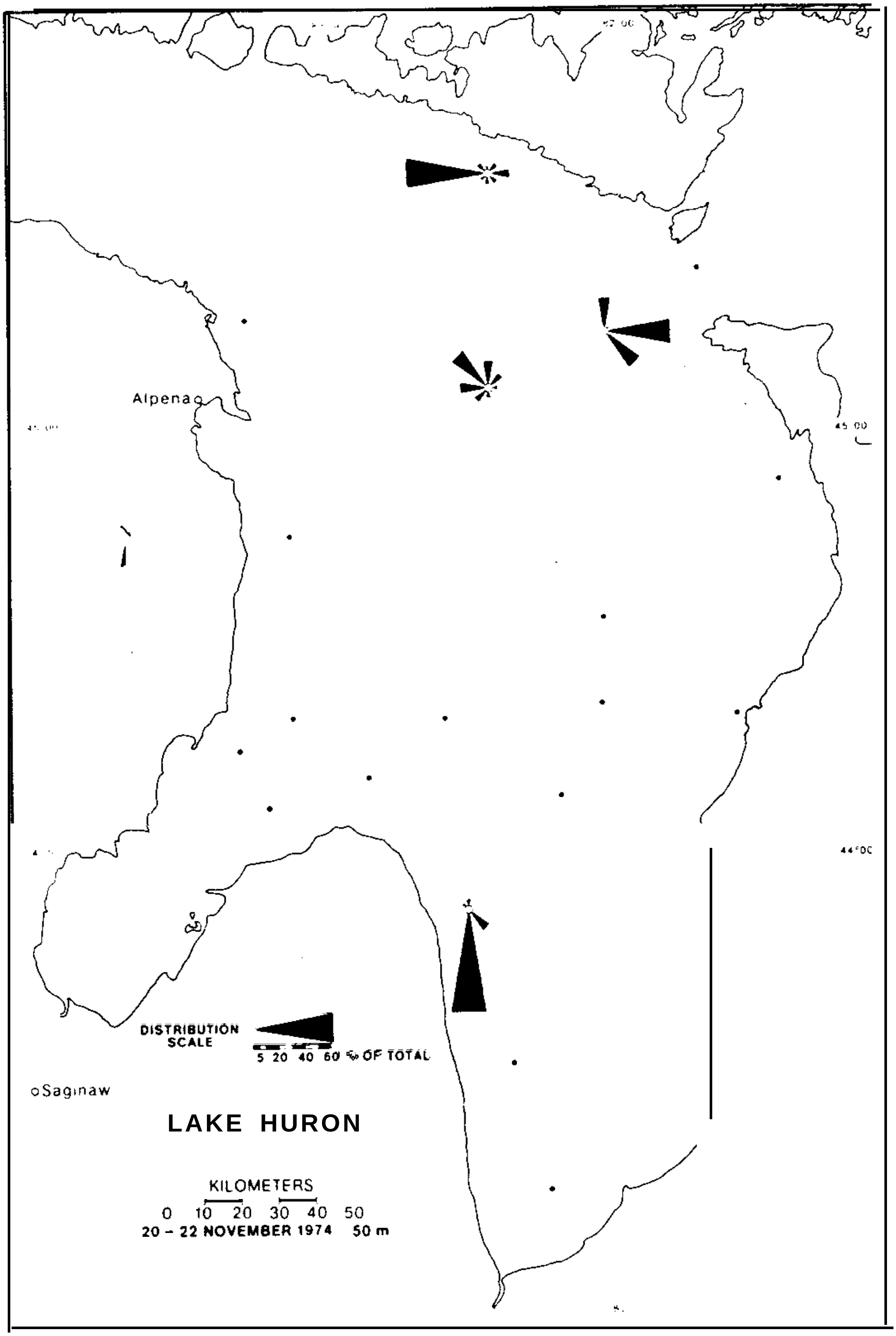

Figure B.1c. Current roses at 50 m depth for 20-22 November 1974.

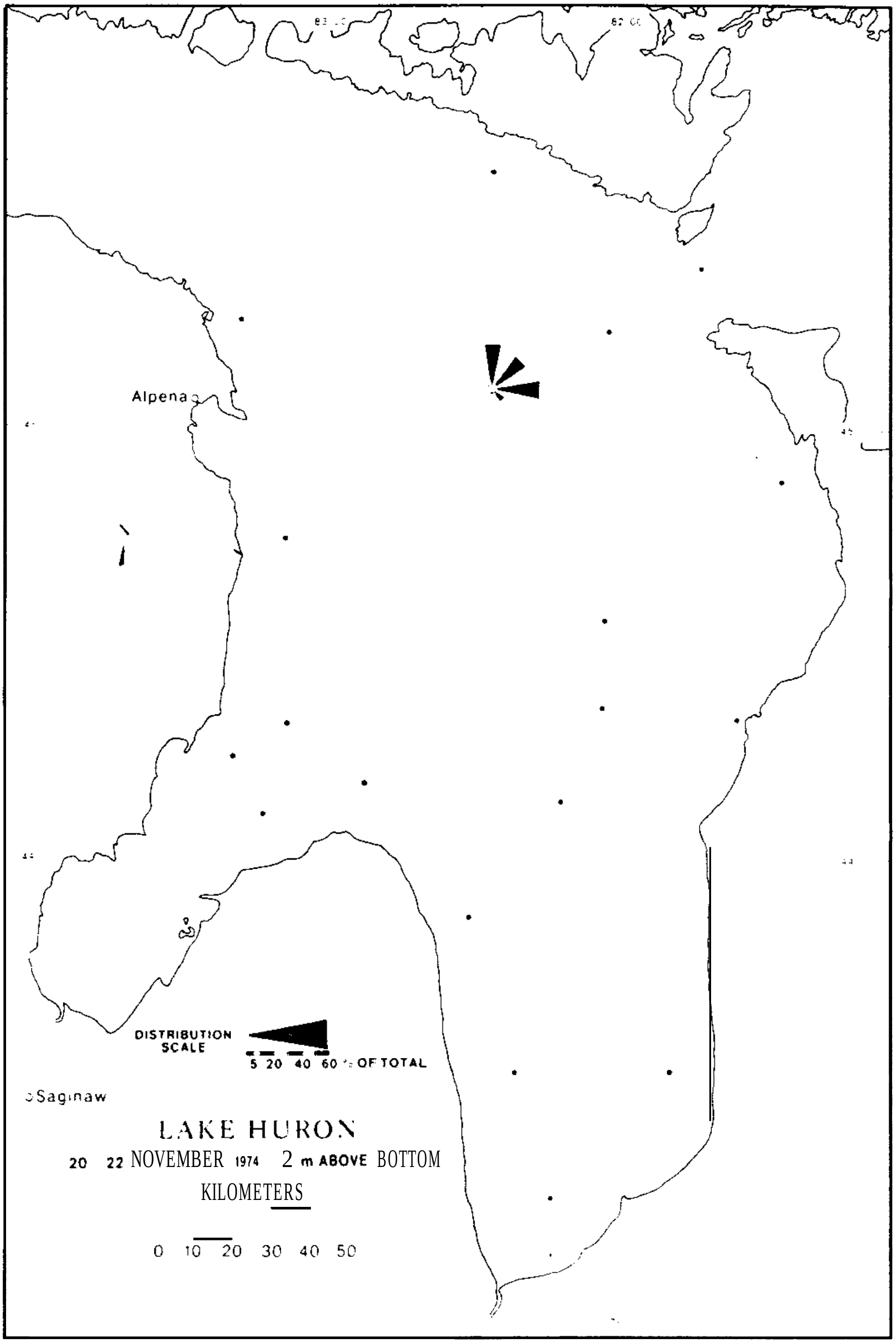

Figure B.1d. Current roses at 2 m above the bottom for 20-22 November 1974.

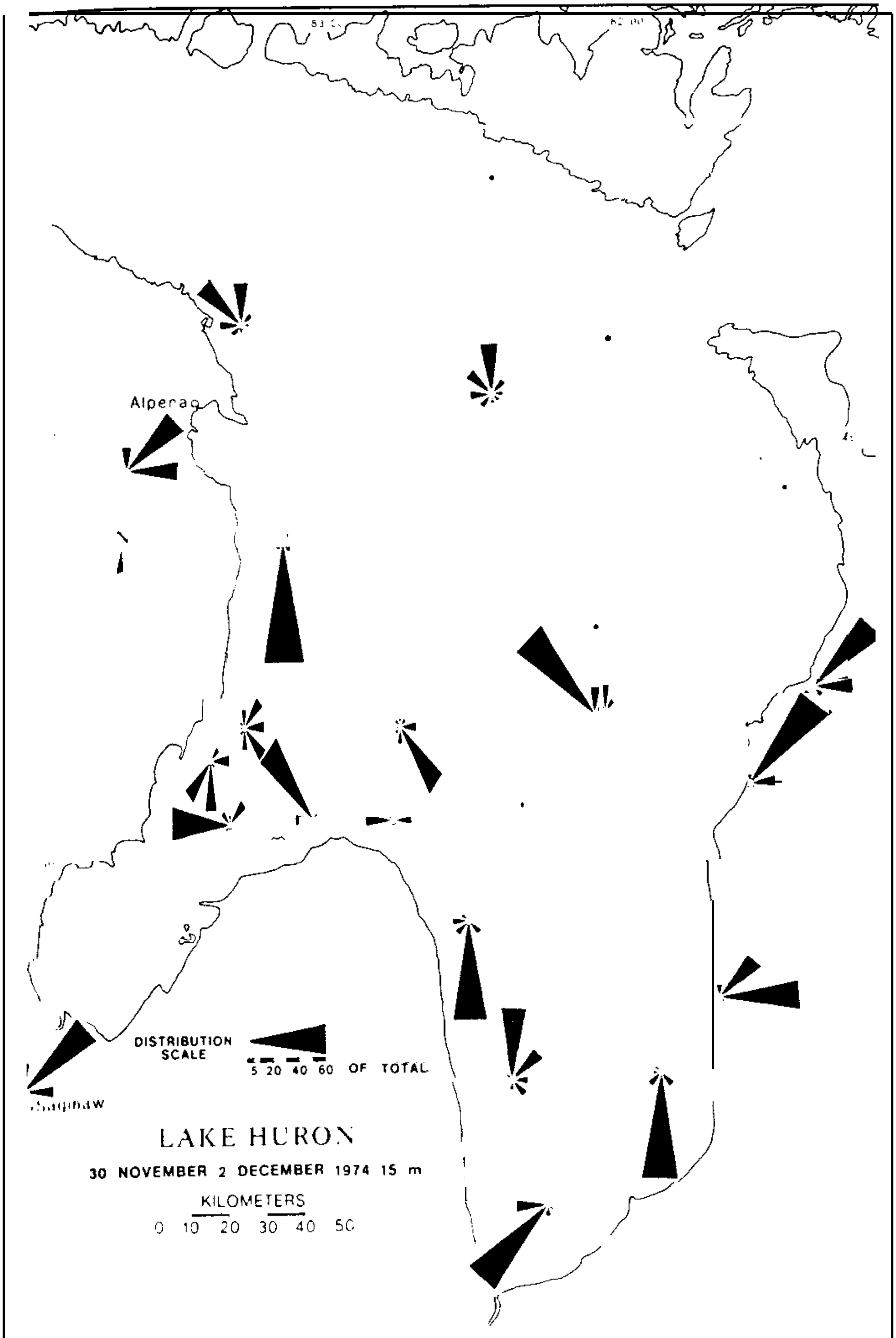

Figure B. 2a. Current roses at 15m depth and wind roses for 30 November-2 December 1974.

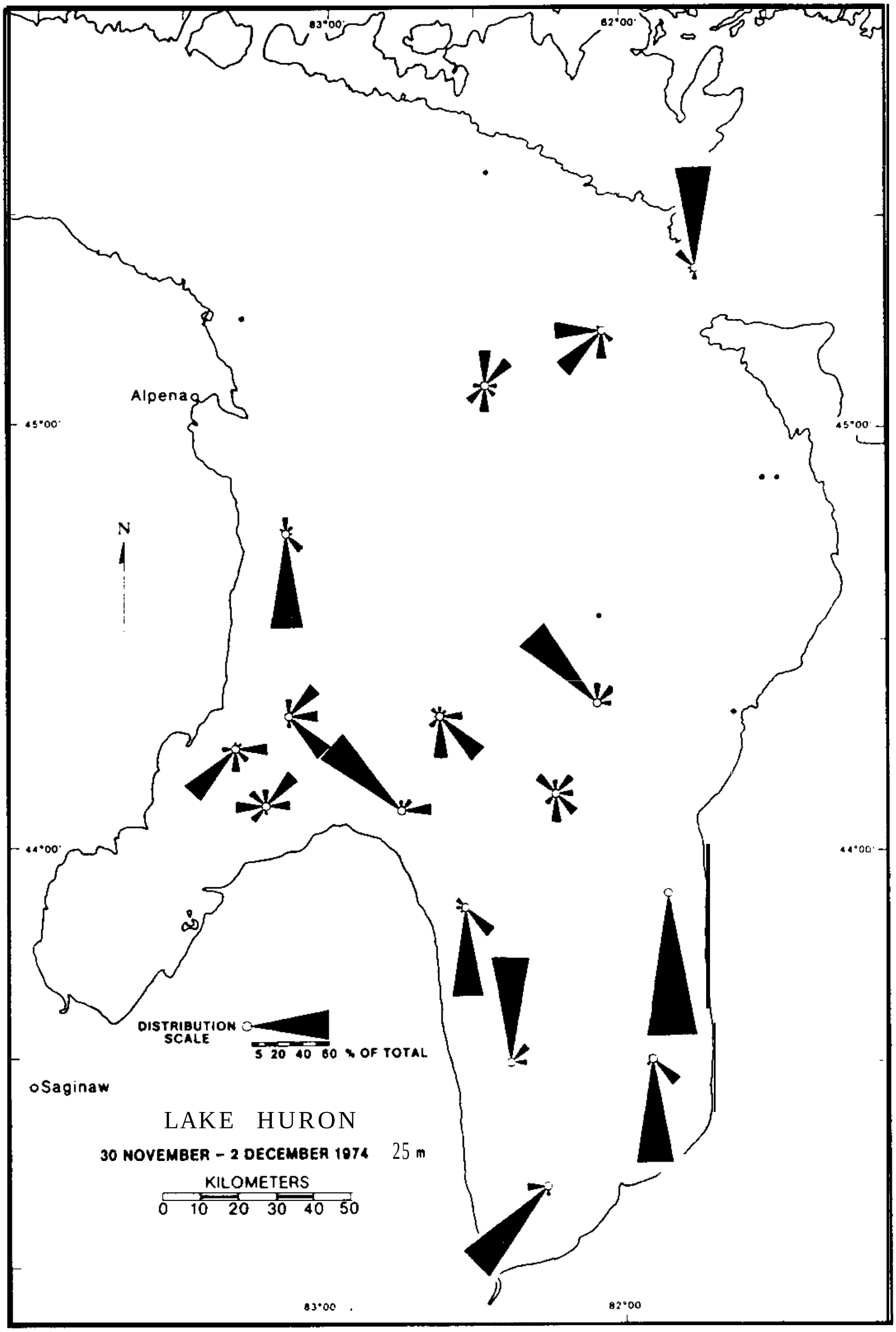

Figure B. 2b. Current roses at 25 m depth for 30 November-2 December 1974.

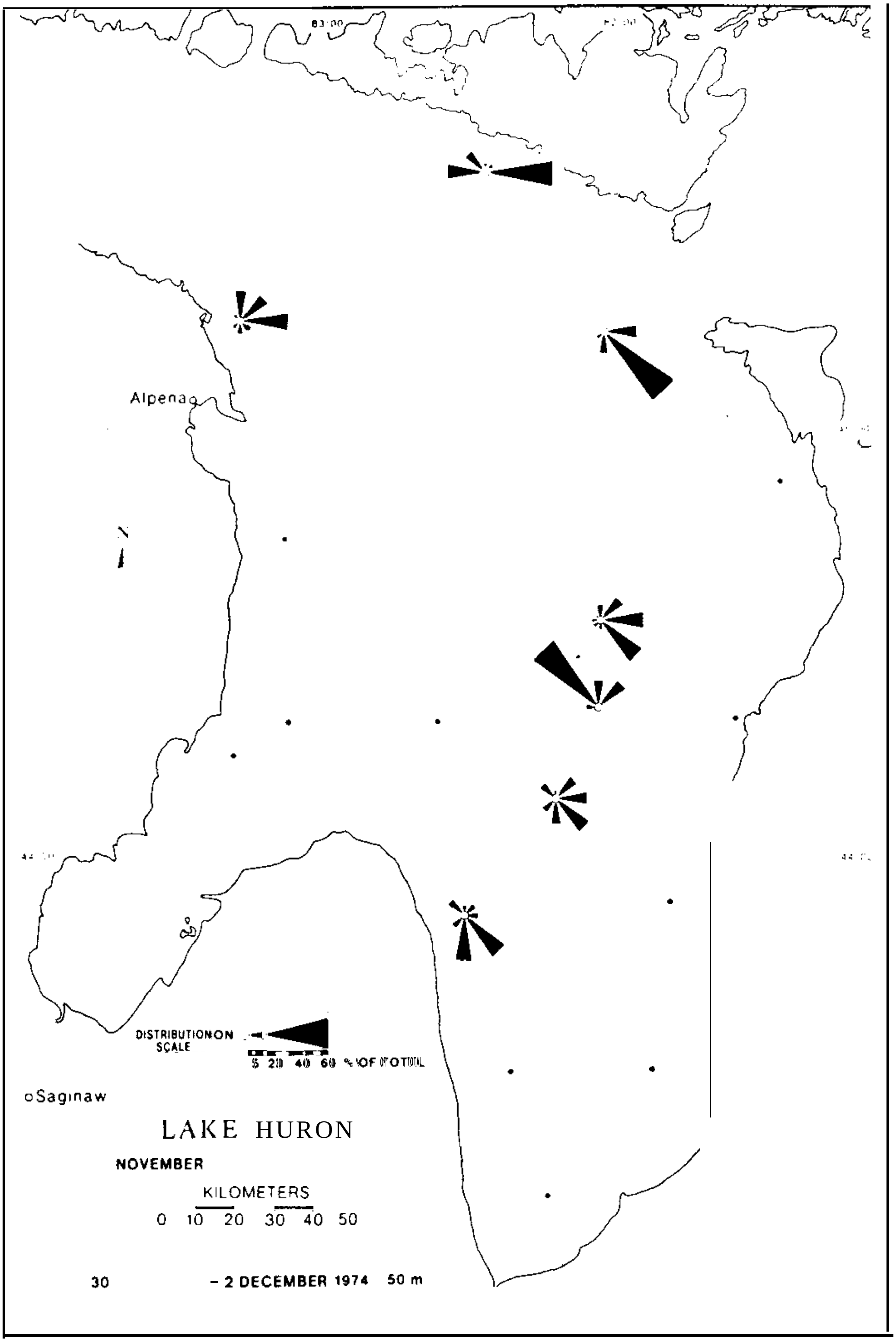

Figure B.2c. Current roses at 50 m depth for 30 November-2 December 1974.

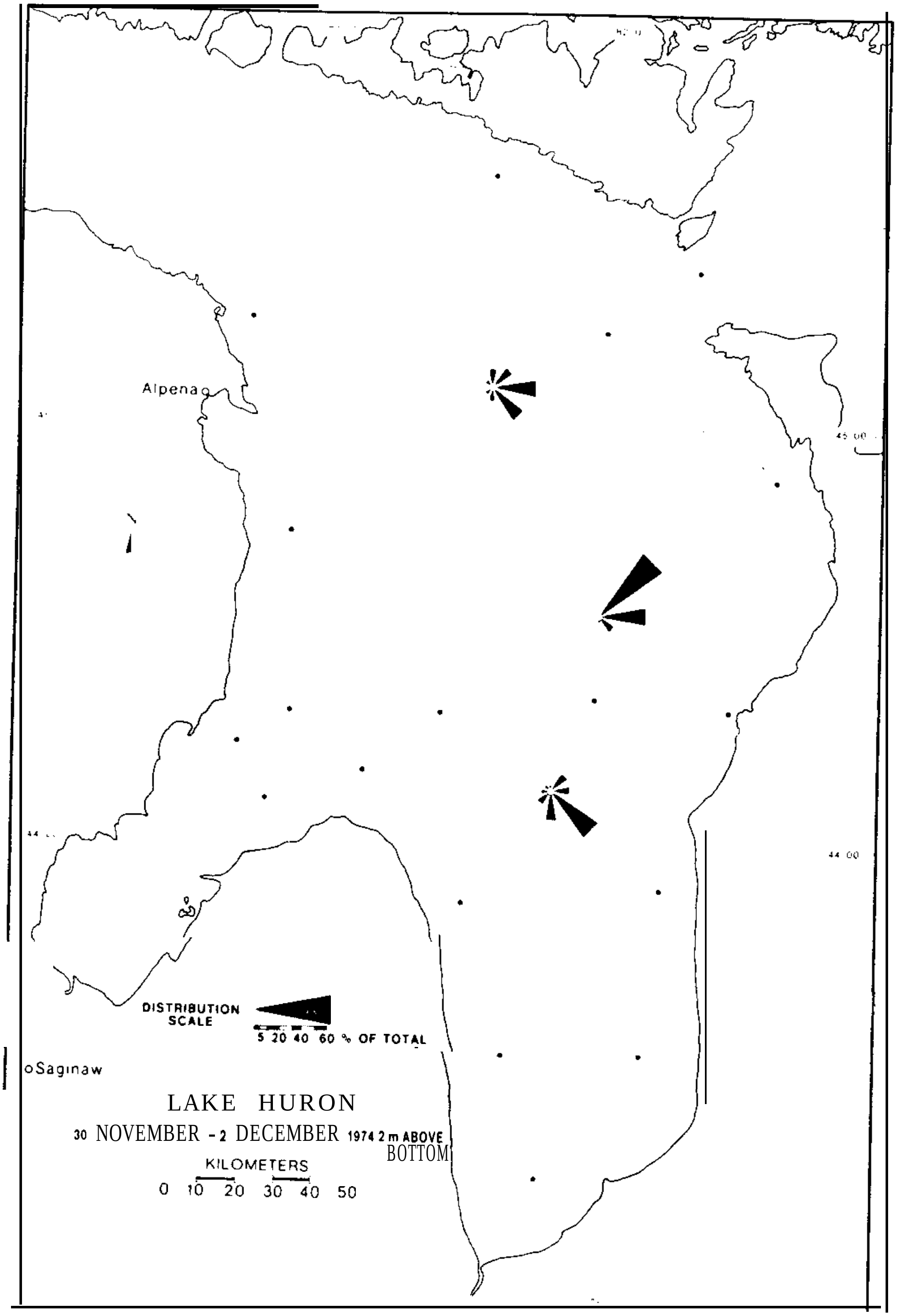

Figure B.2d. Current roses at 2 m above the bottom for 30 November-2 December 19 74.

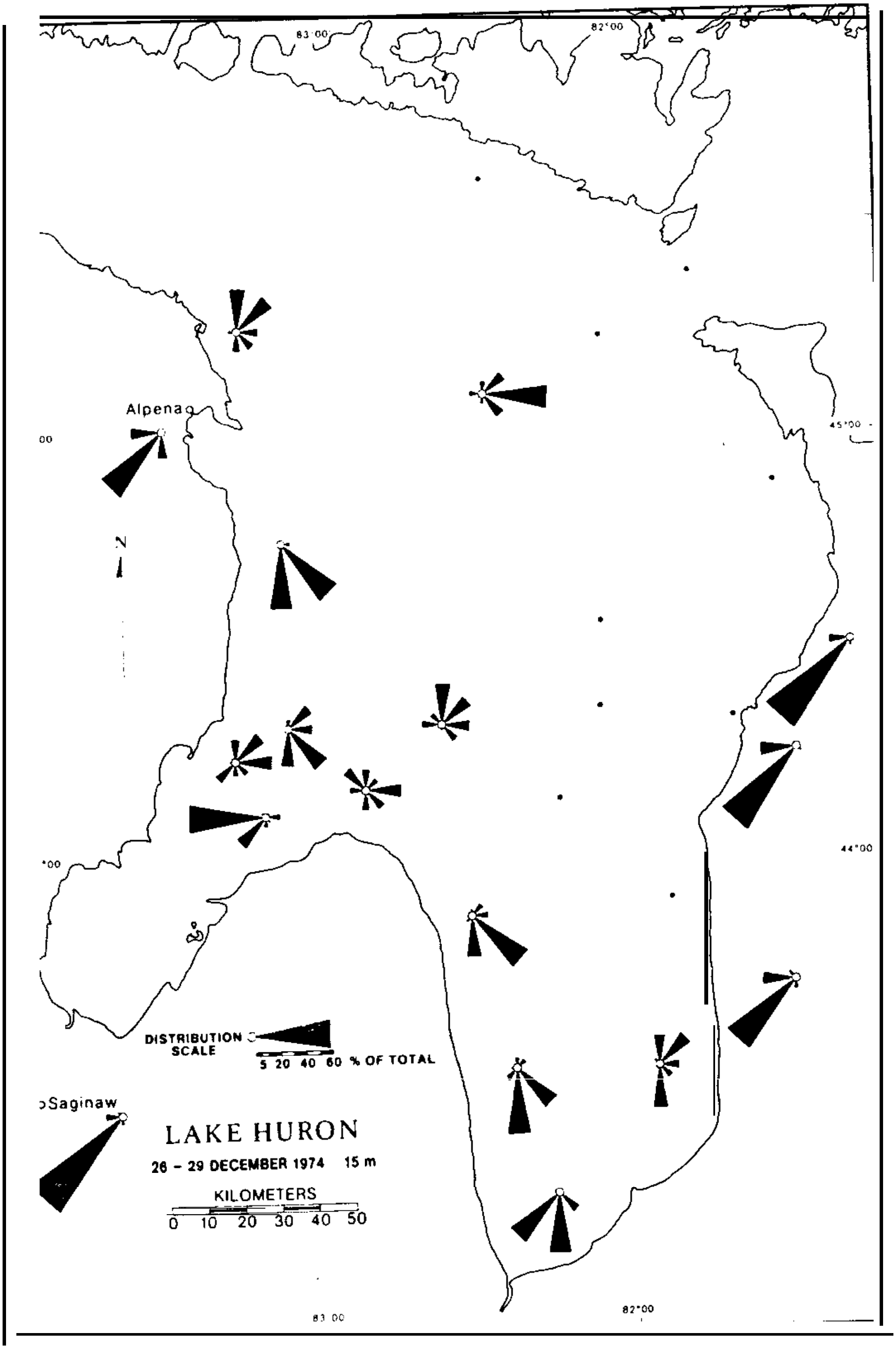

Figure B.3a. Current roses at 15 m depth and wind roses for 26-23 December 1974.

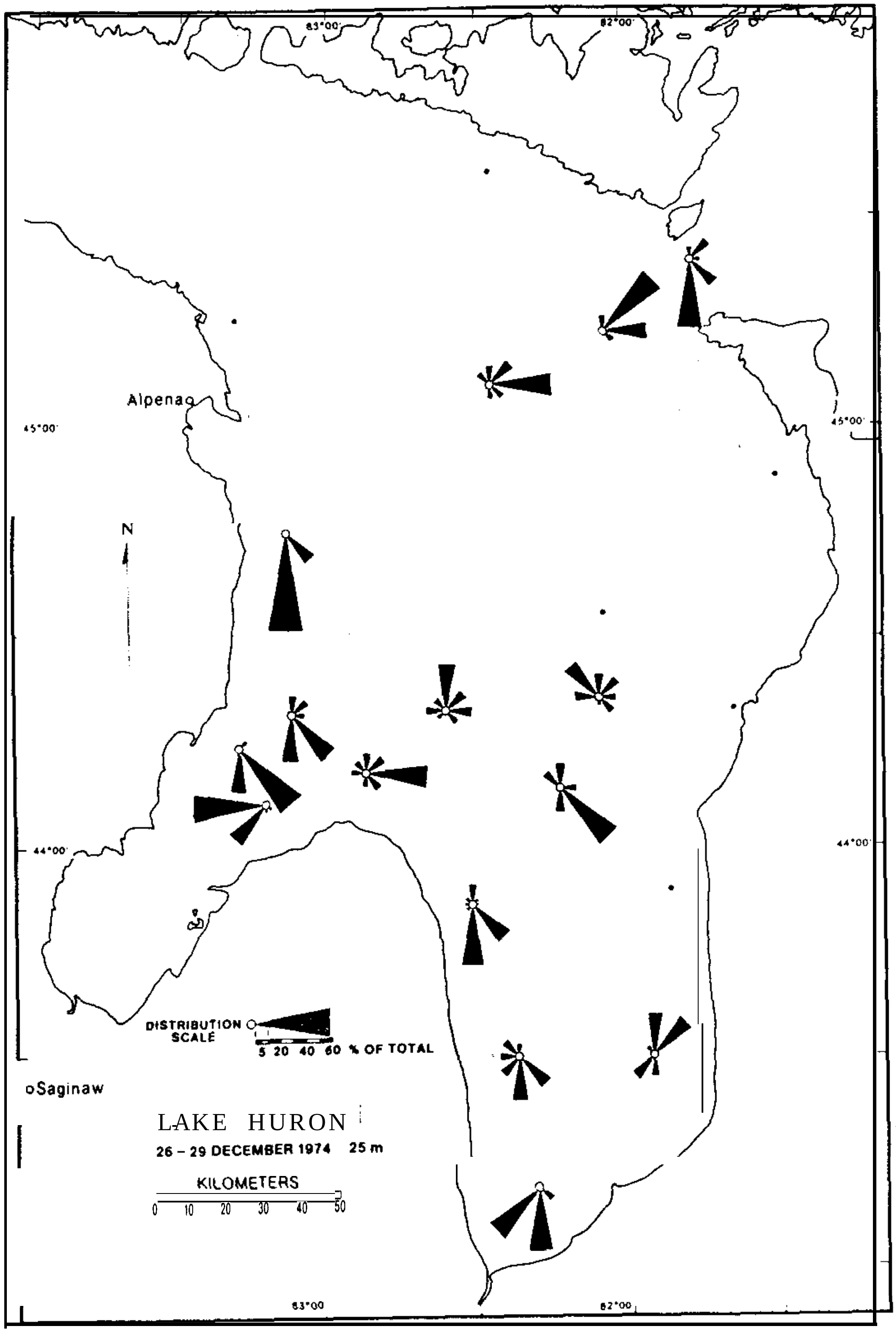

Figure B.3b. Current roses at 25 m depth for 26-29 December 1974.

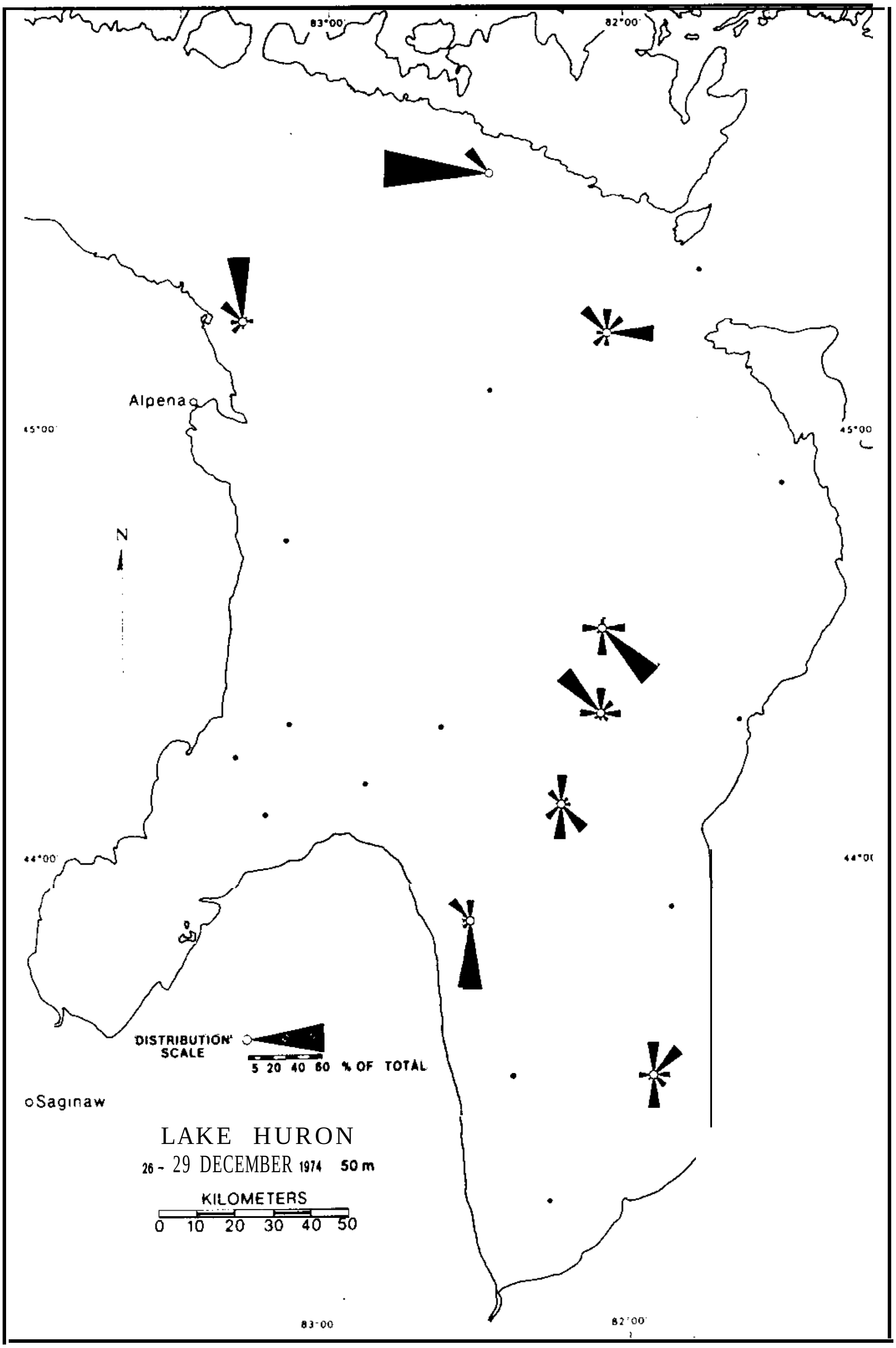

Figure B.3c. Current roses at 50 m depth for 26-29 December 1974.

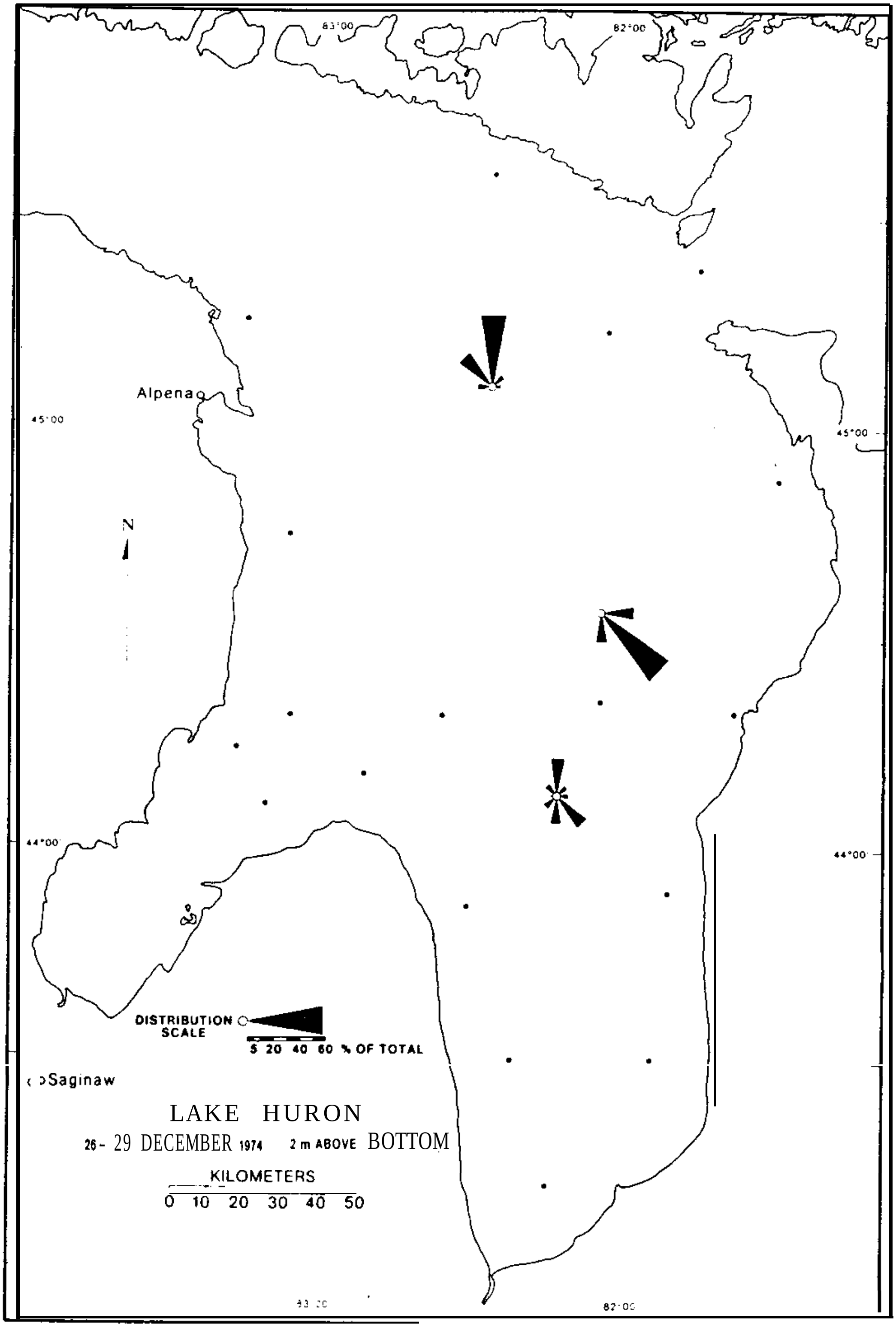

Figure B.3d. Current roses at 2 m above the bottom for 26-29 December 1974.

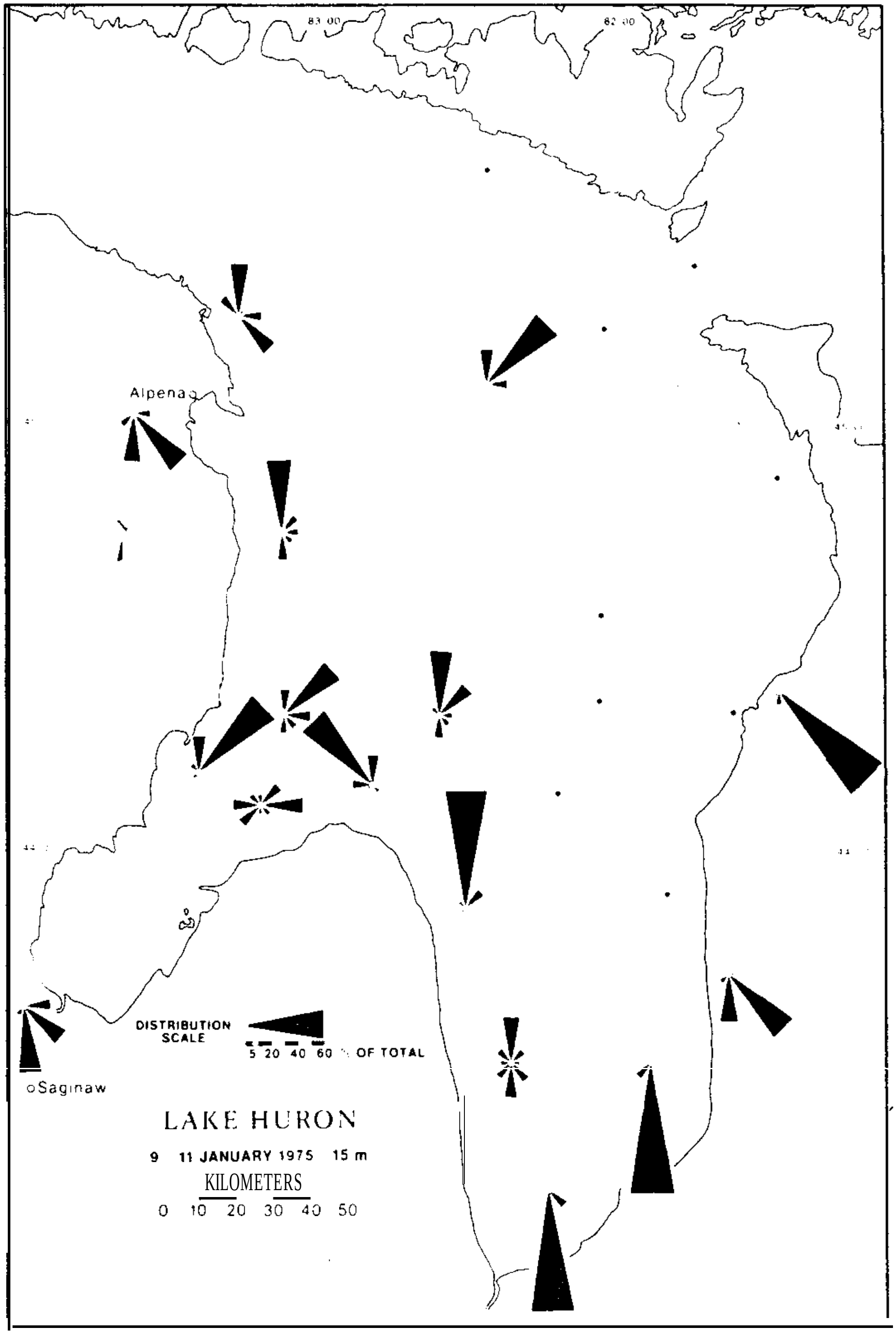

Figure B.4a. Current roses at 15 m depth and wind roses for 9-11 January 1975.

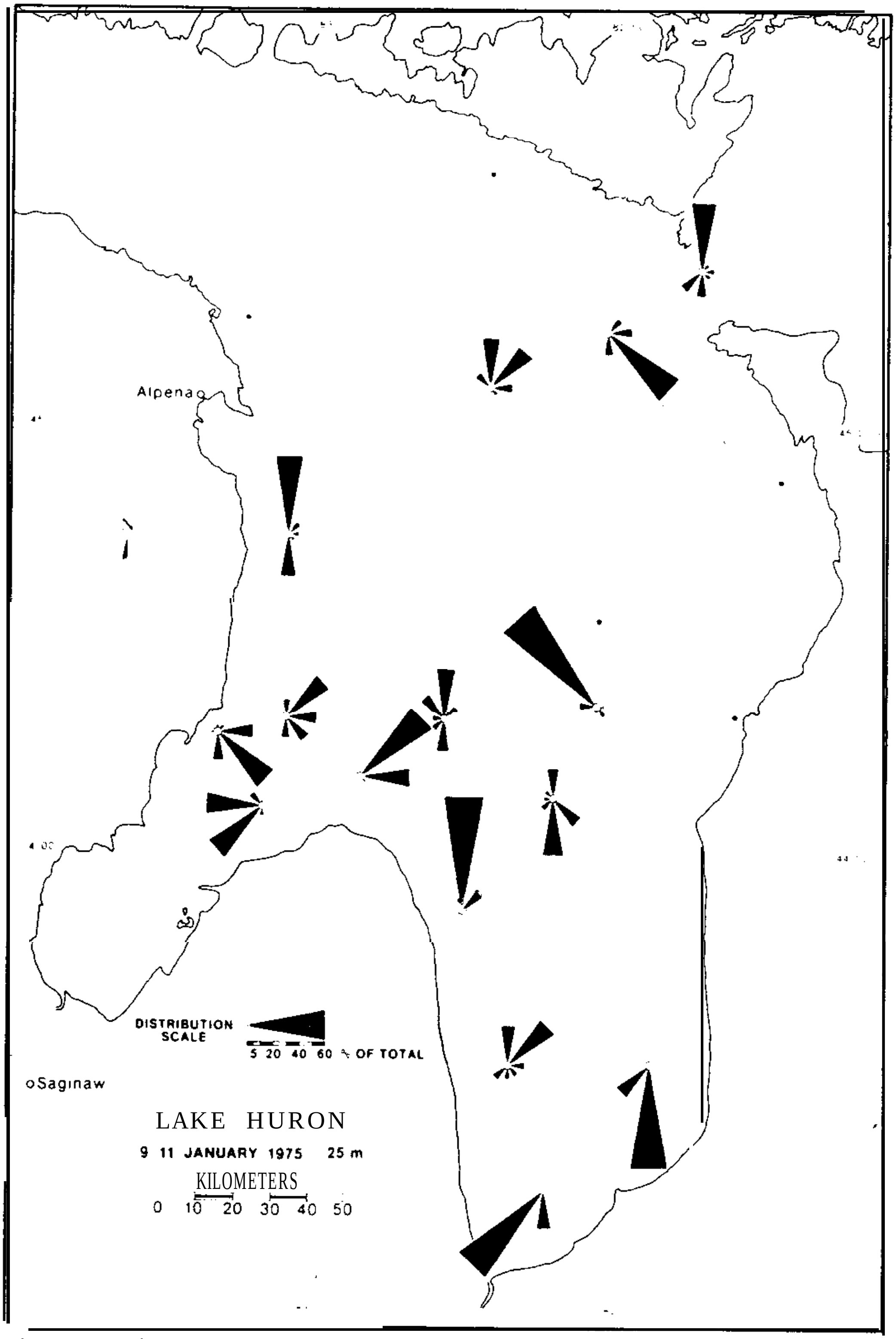

Figure B. 4b. Current roses at 25 m depth for 9-11 January 1975.

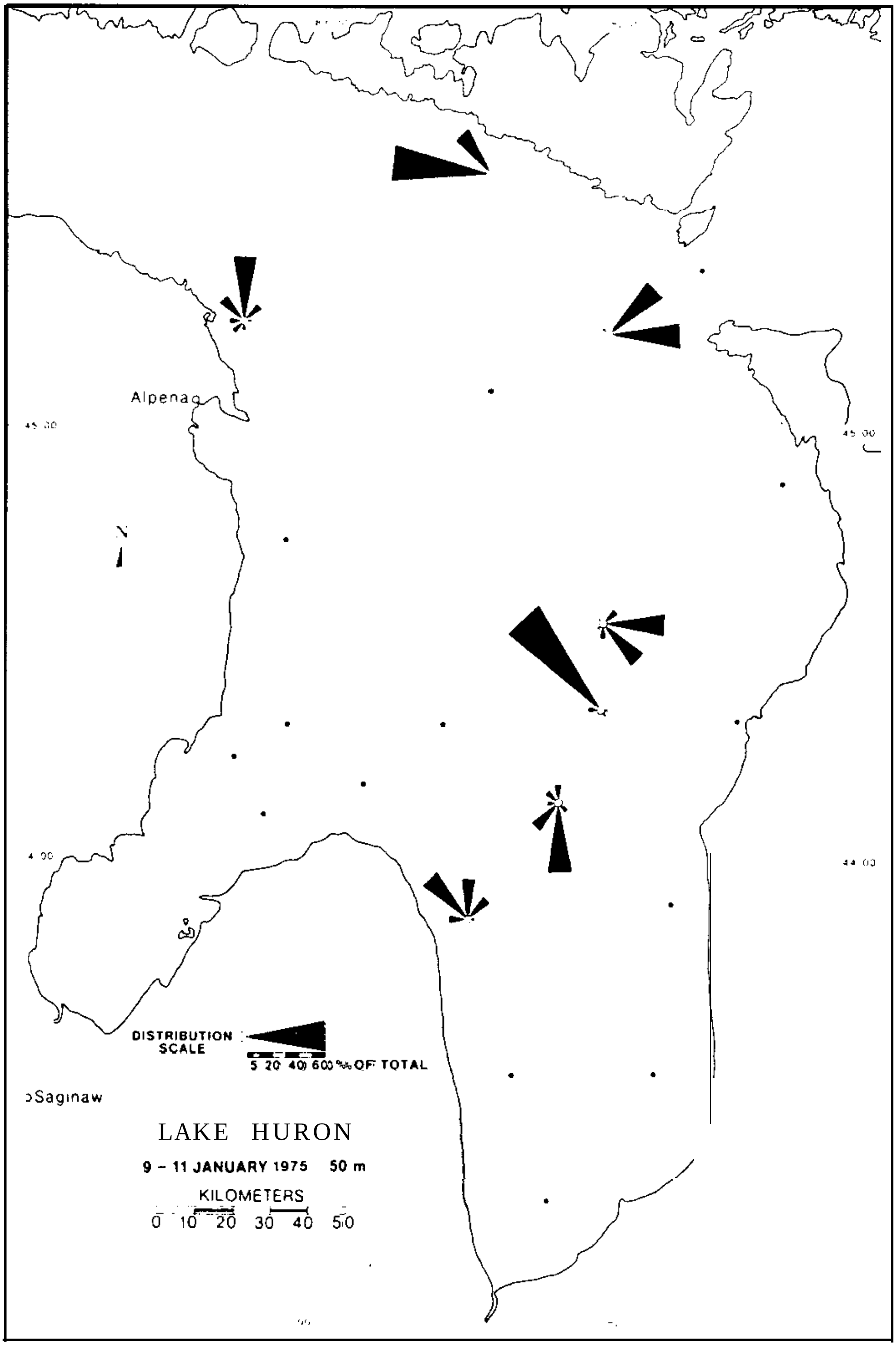

Figure B.4c. Current roses at 50 m depth for *9-11* January 1975.

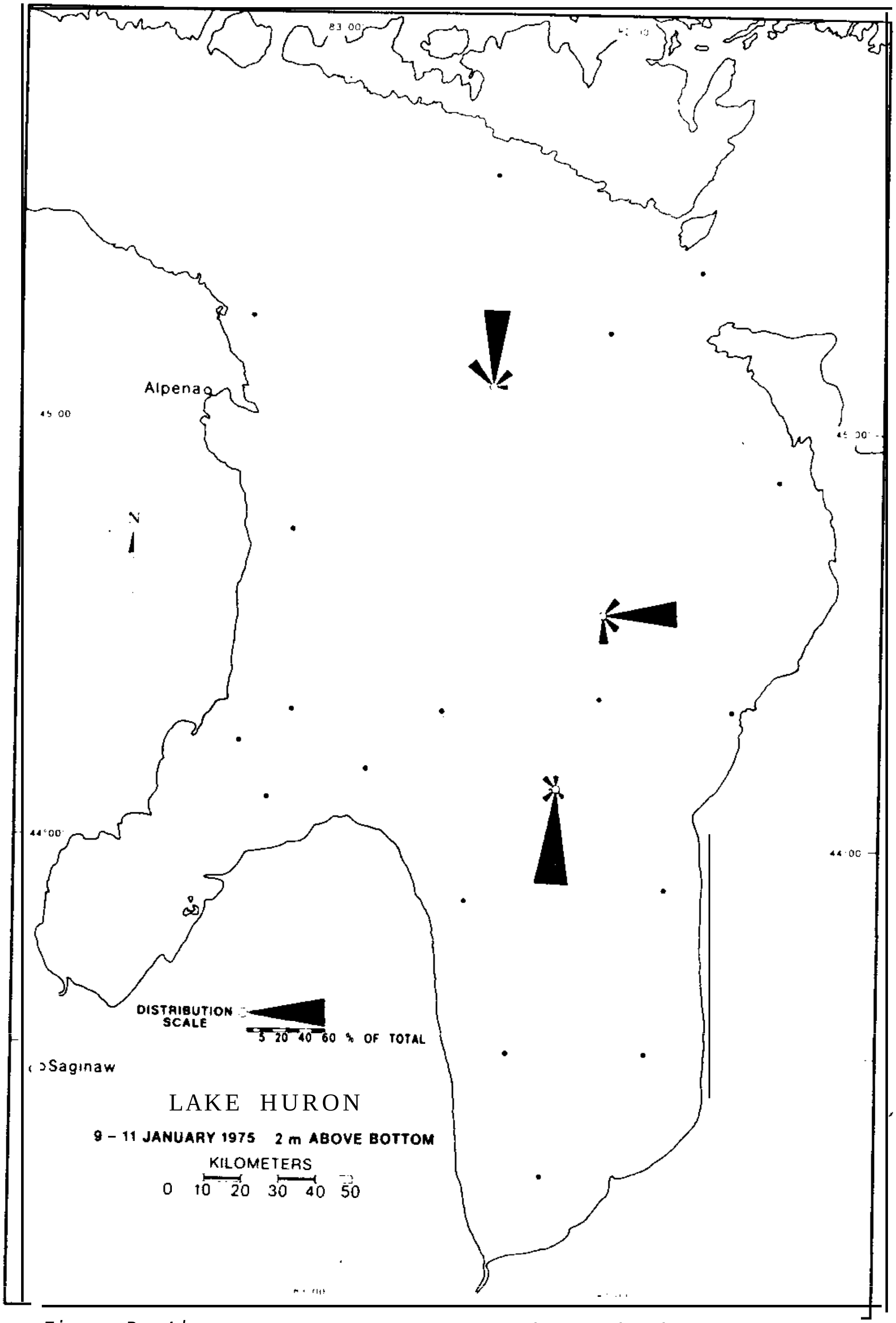

Figure B. 4d. Current roses at 2 m above the bottom for 9-11 January 1975.

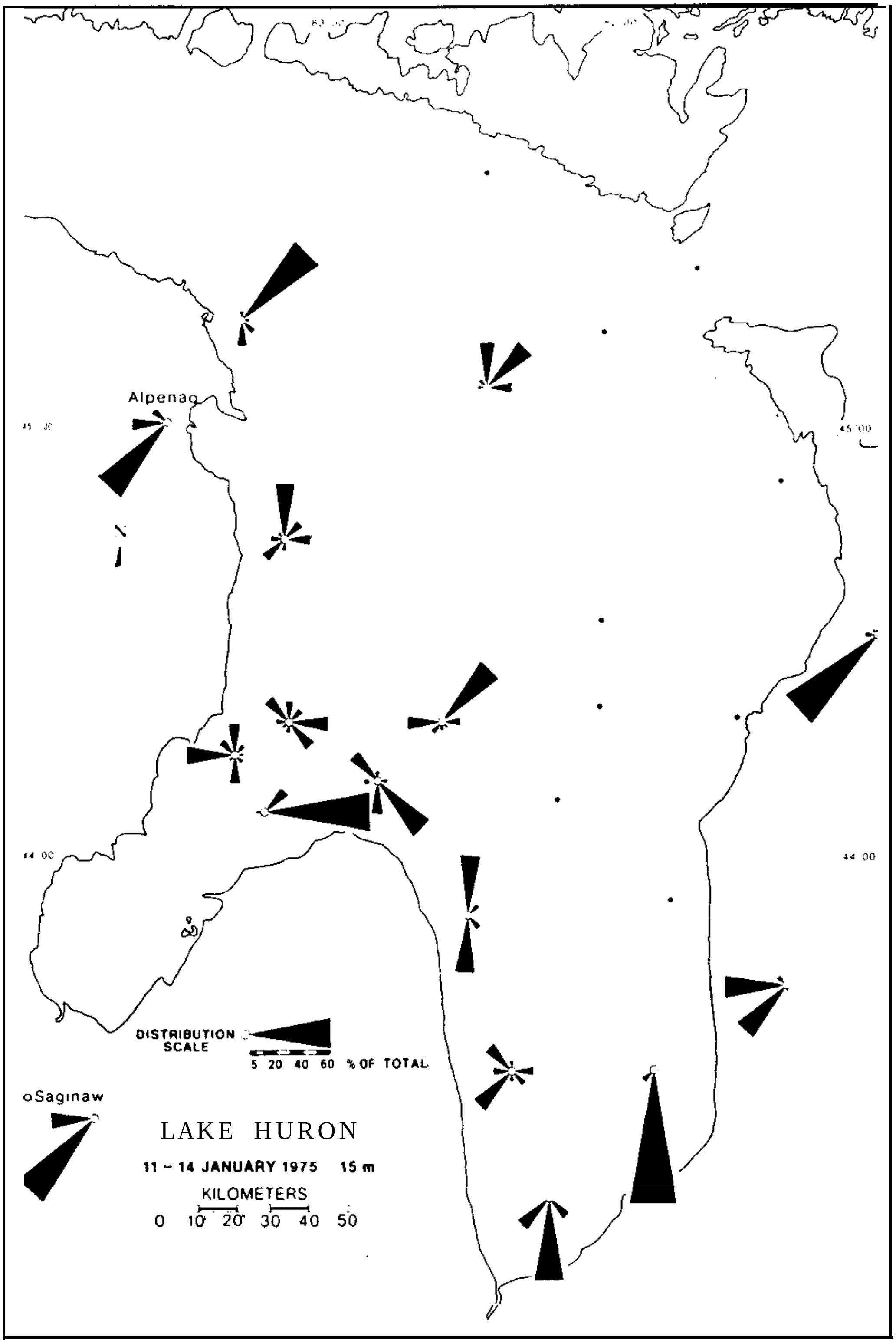

Figure B.5a. Current roses at 15 m depth and wind roses for 11-14 January 1975.

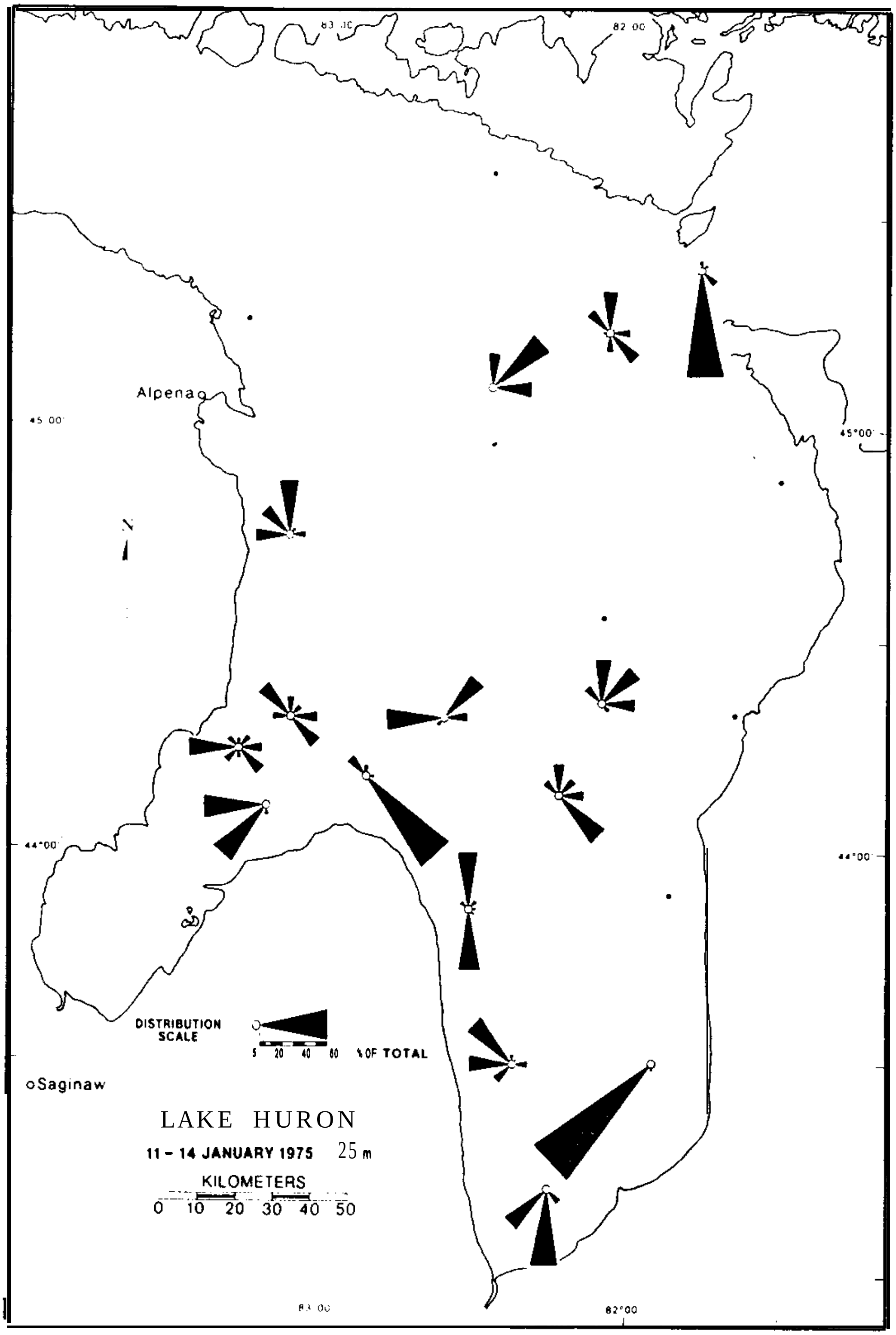

Figure B. 5b. Current roses at 25 m depth for *11-14 January 1975.*

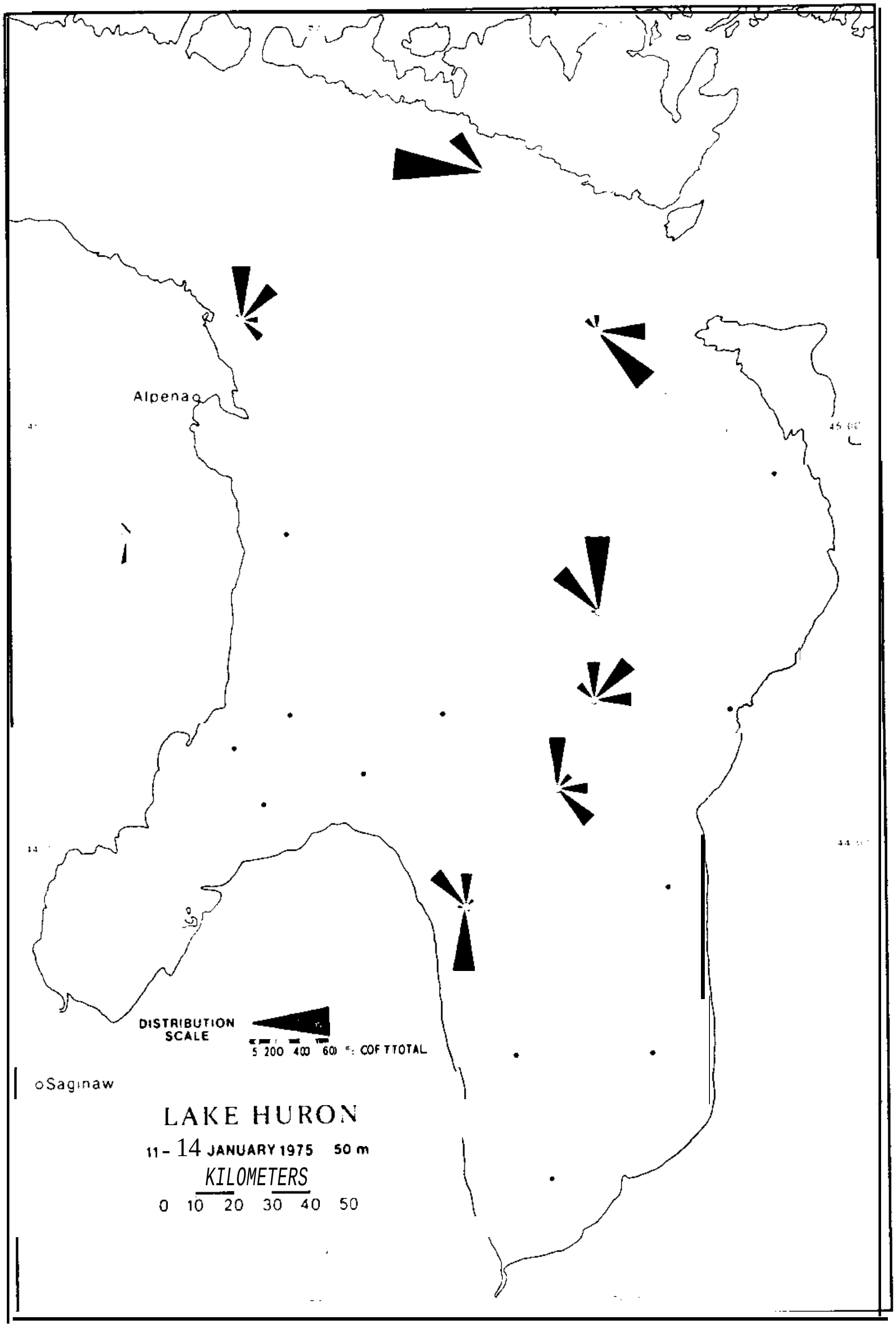

Figure B.5c. Current roses at 50 m depth for 11-14 January 1975.

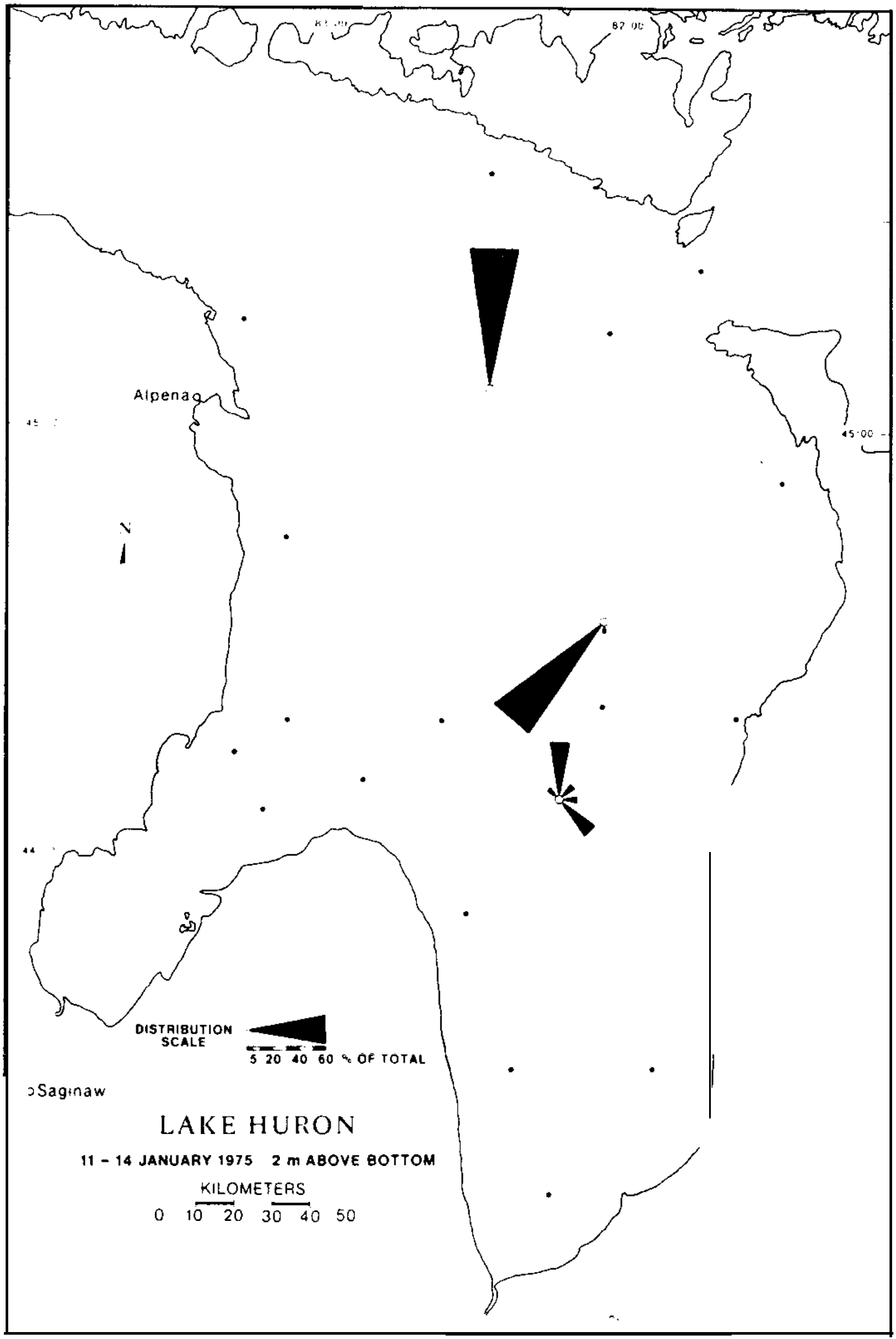

Figure B. 5d. Current roses at 2 m above the bottom for 11-14 January 1975.

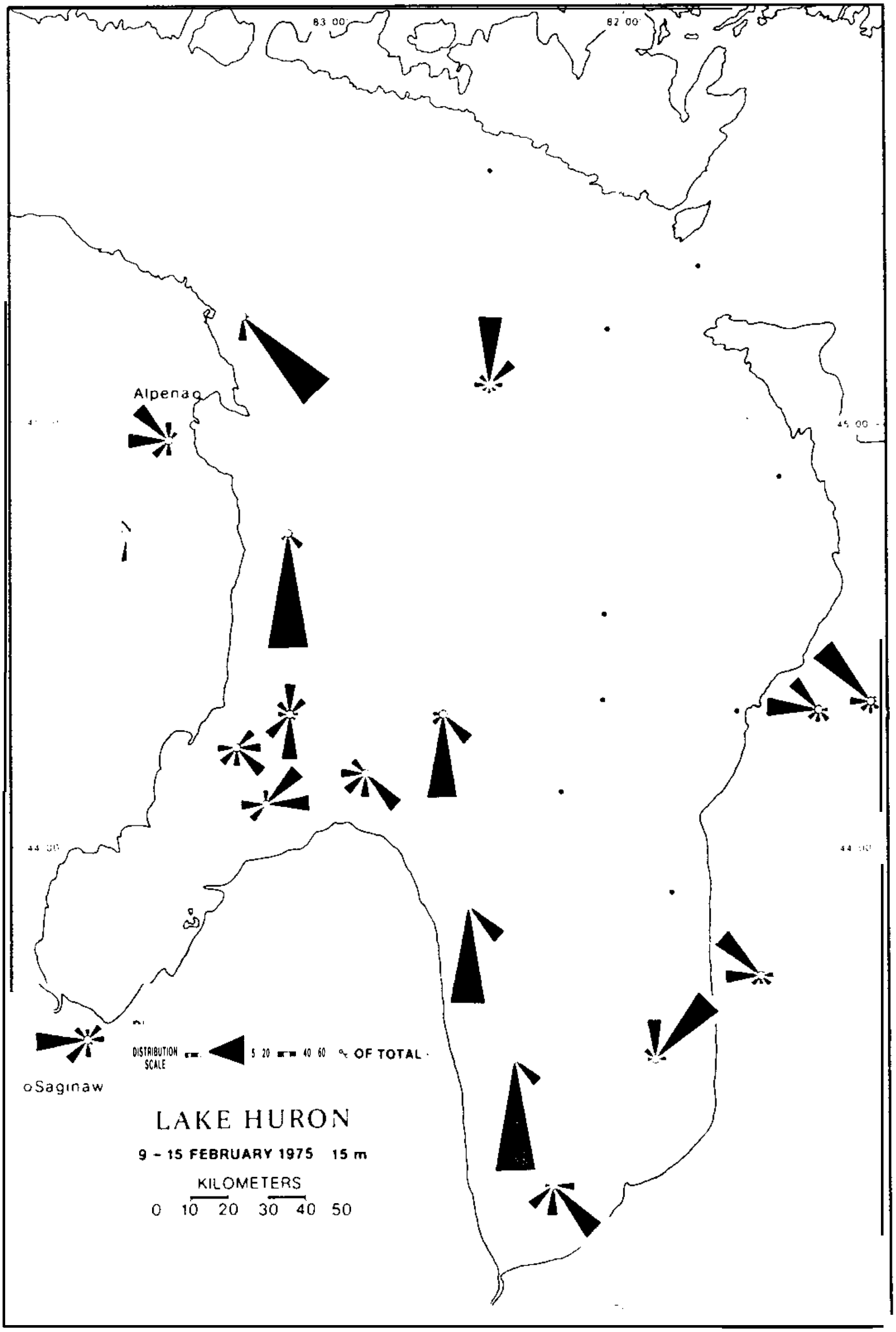

Figure B.6a. Current roses at 15 m depth and wind roses for 9-15 February 1975.

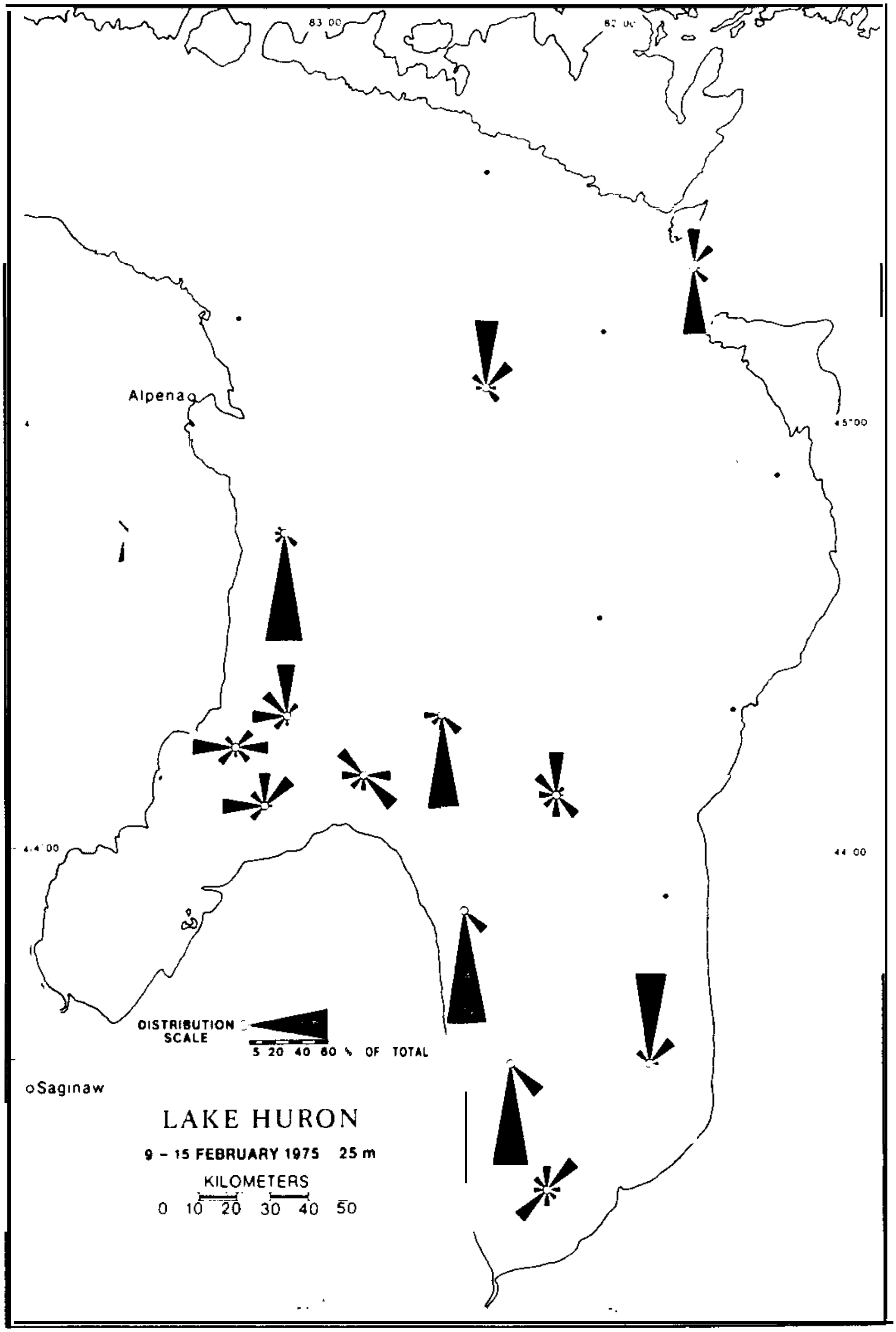

Figure B.6b. Current roses at 25 m depth for 9-15 February 1975.

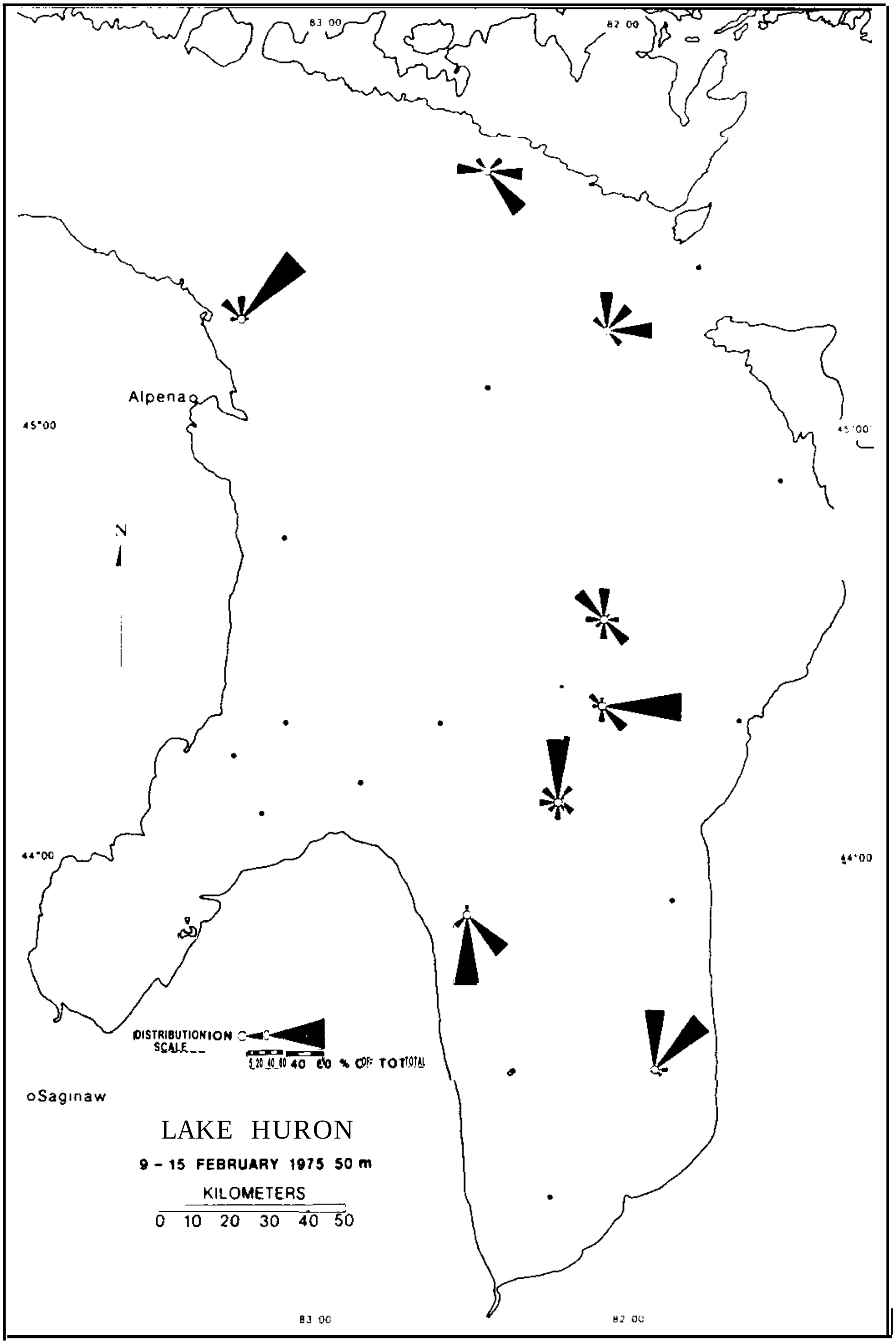

Figure B.6c. Current roses at 50 m depth for 9-15 February 1975.

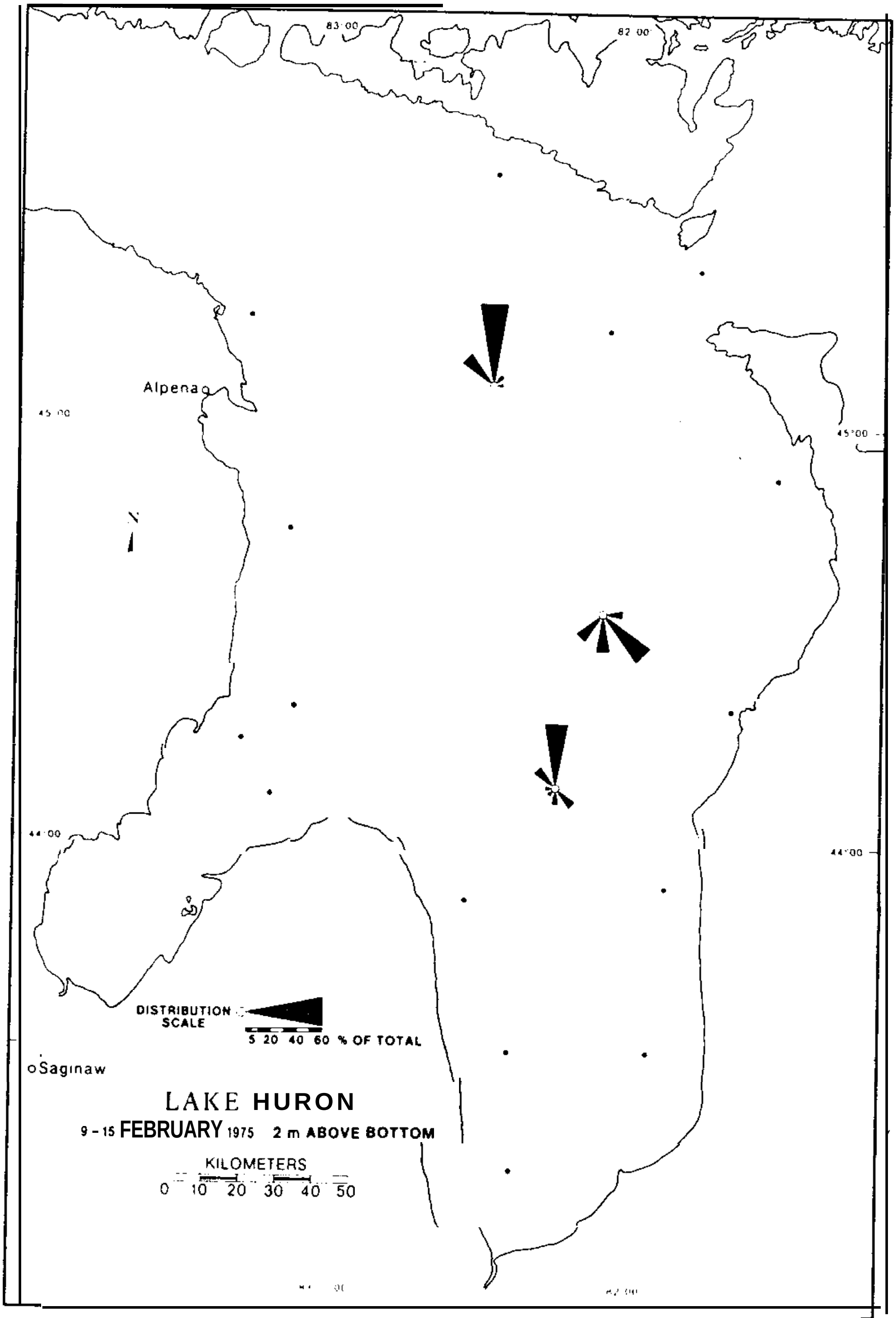

Figure B.9a. Current roses at 2 m above the bottom for 9-15 February 1975.

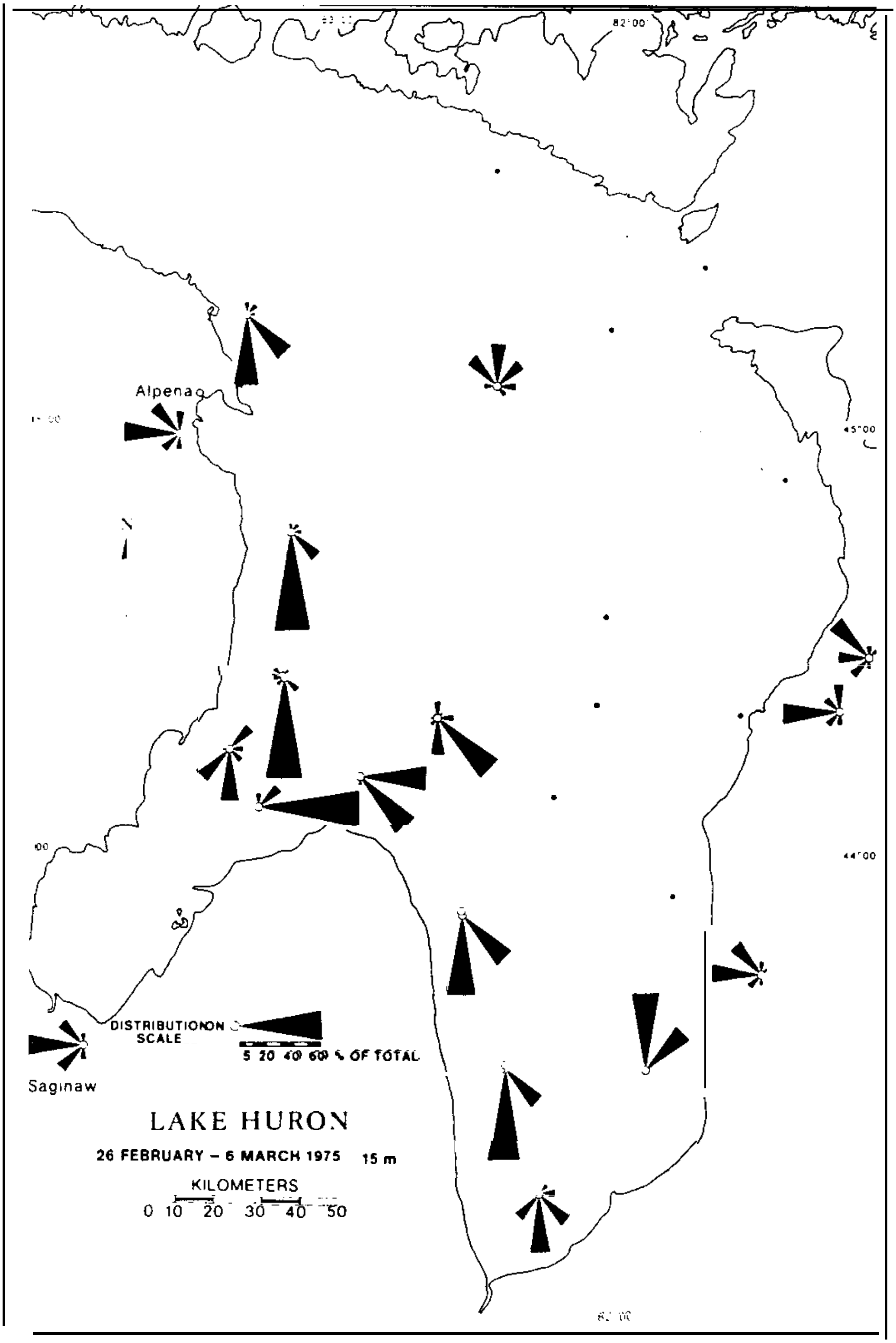

Figure B.7a. Current roses at 15 m depth and wind roses for 26 February-6 March 1975.

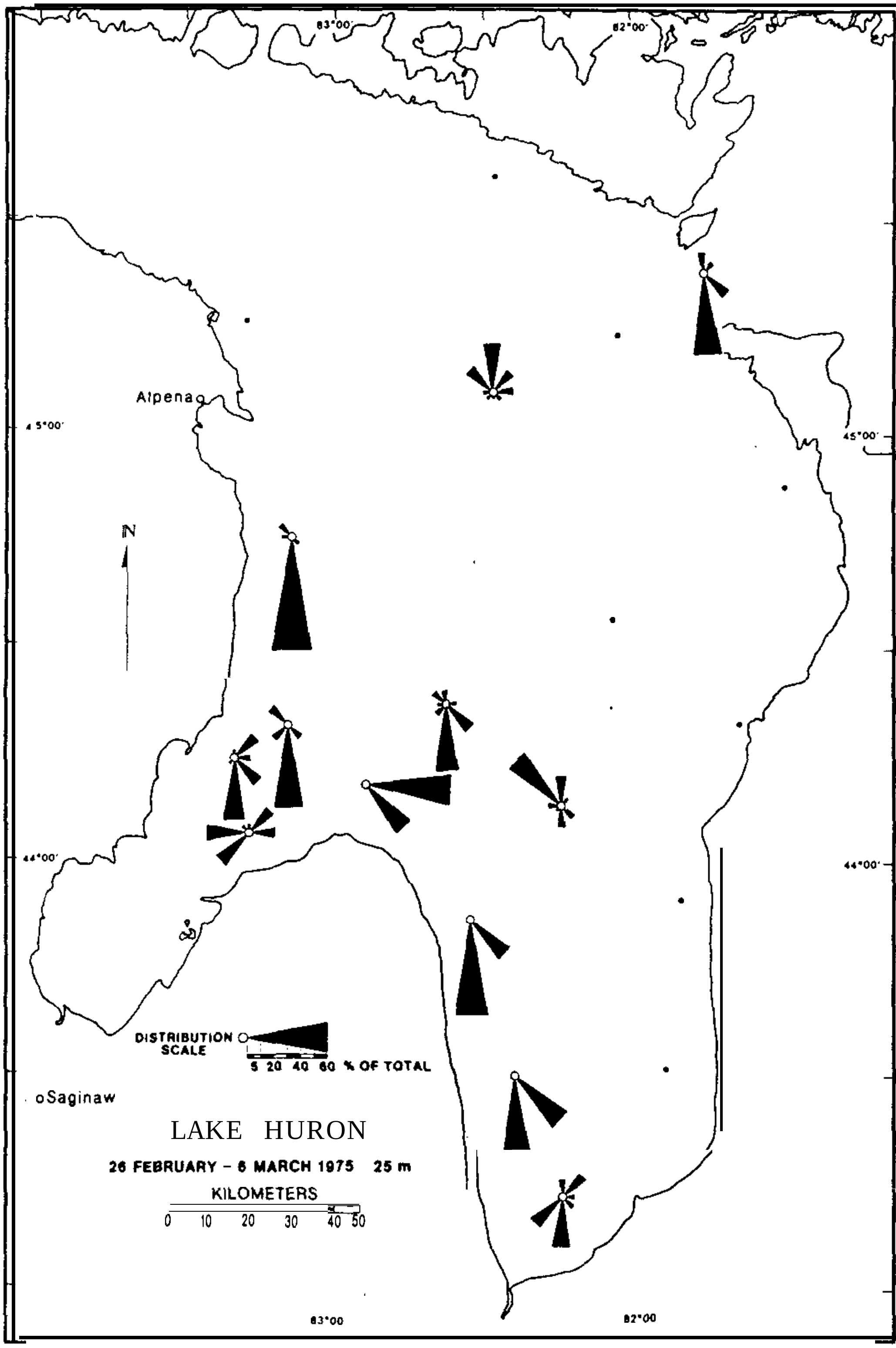

Figure B. 7b. Current roses at 25 m depth for 26 February-6 March 1975.

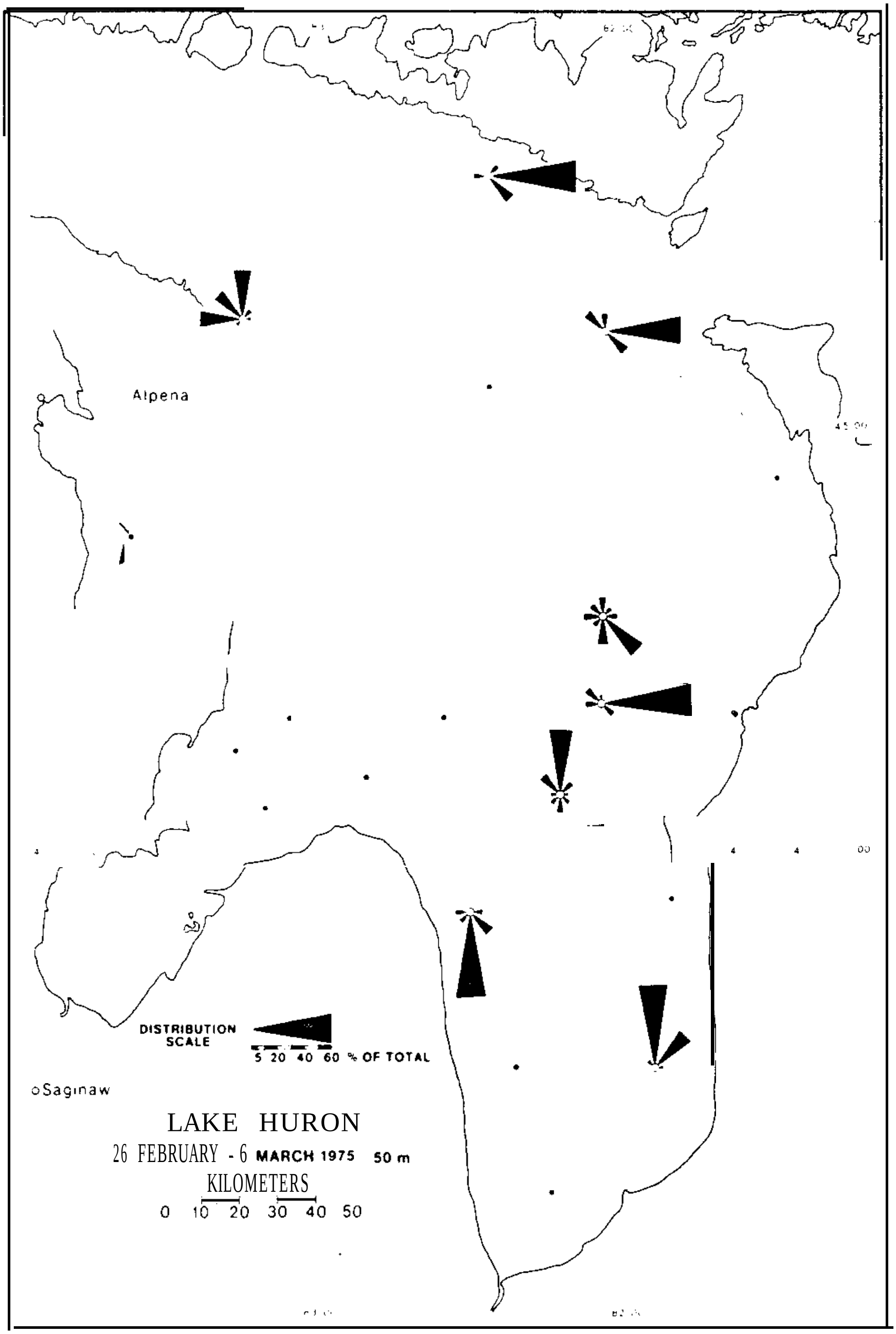

Figure B.7c. Current roses at 50 m depth for 26 February-6 March 1975.

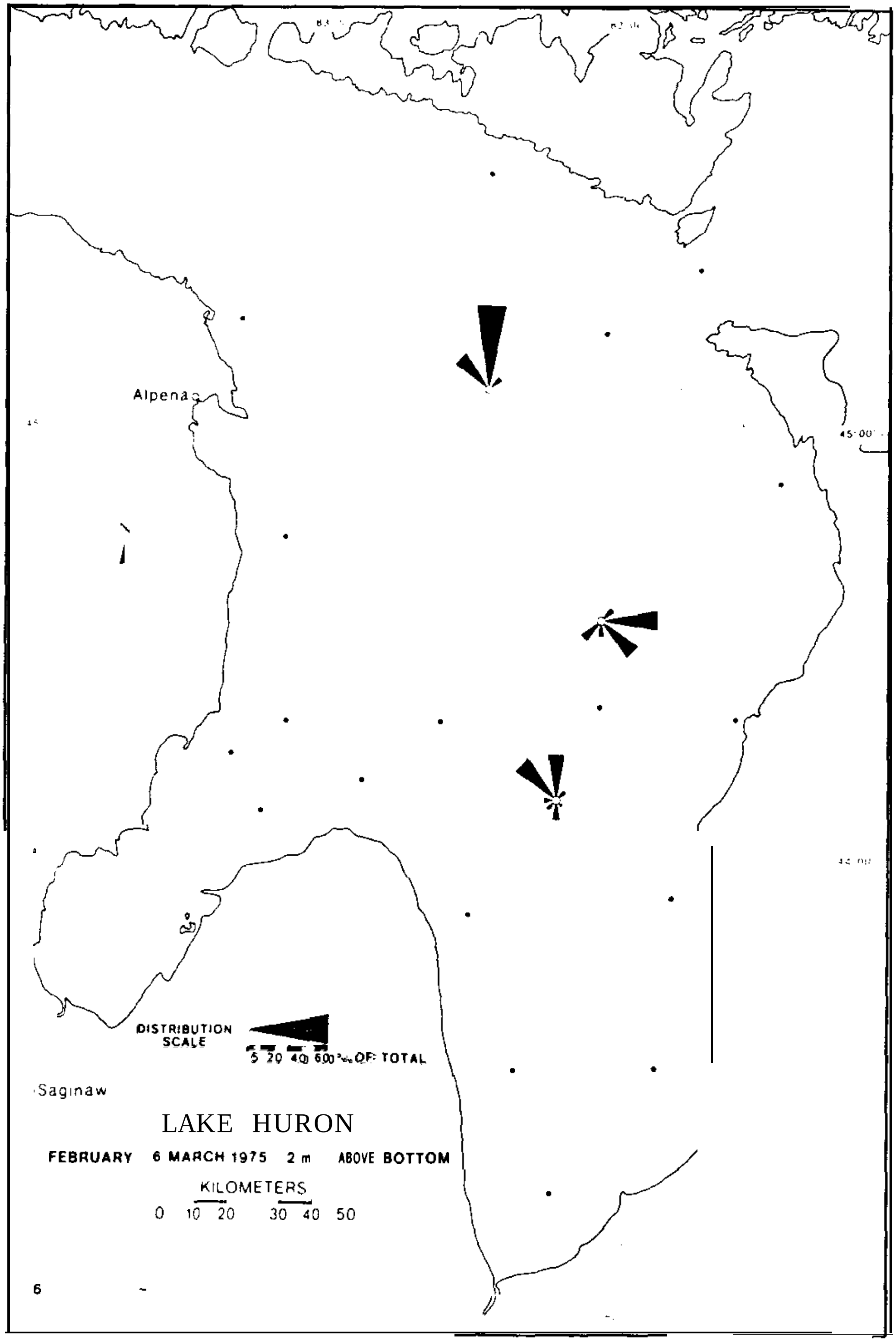

Figure B. 7d. Current roses at 2 m above the bottom for 26 February-6 March 1975.

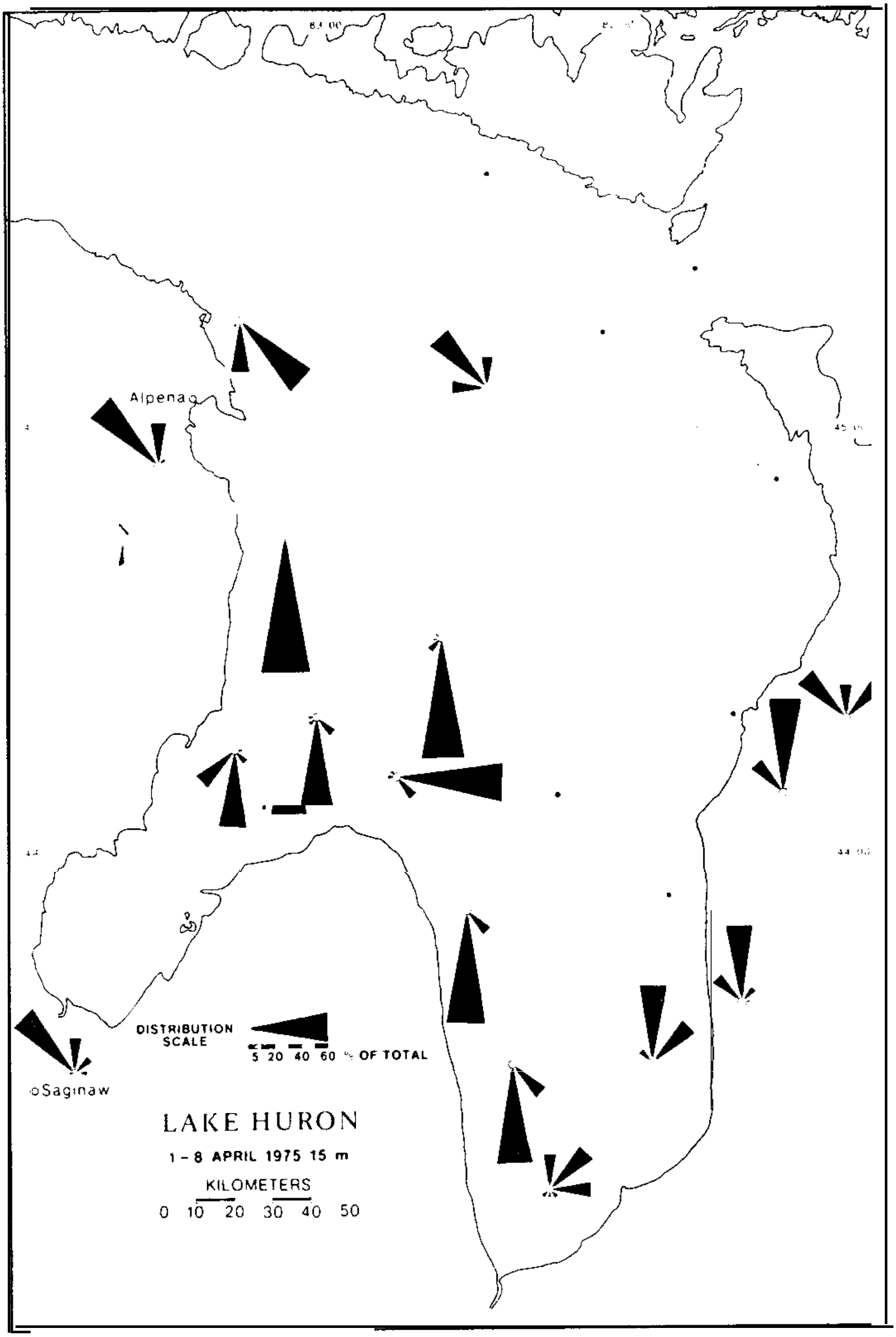

Figure B.8a. Current roses at 15 m depth and wind roses for 1-8 April 1975.

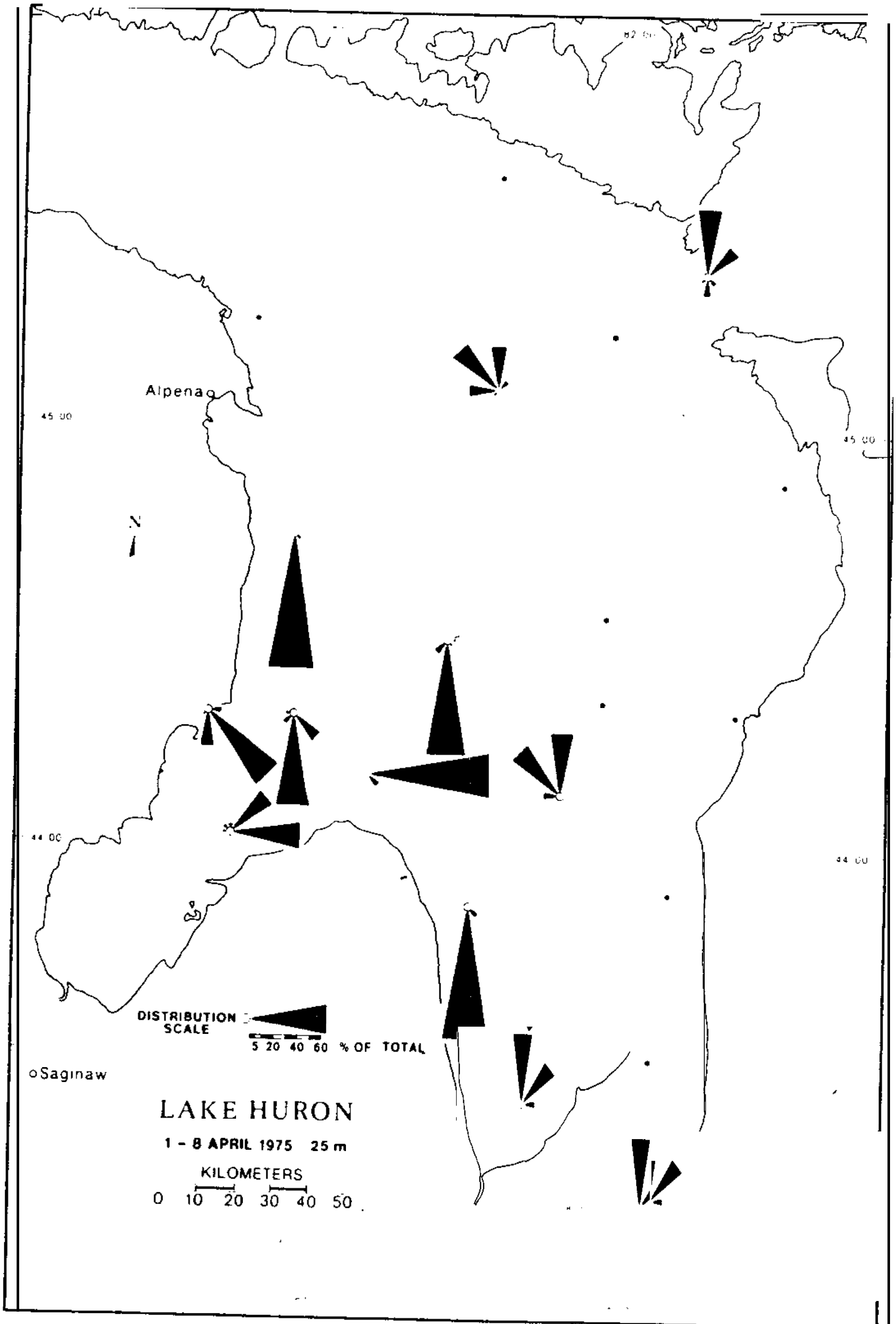

Figure B.8b. Current roses at 25 m depth for 1-8 April 1975.

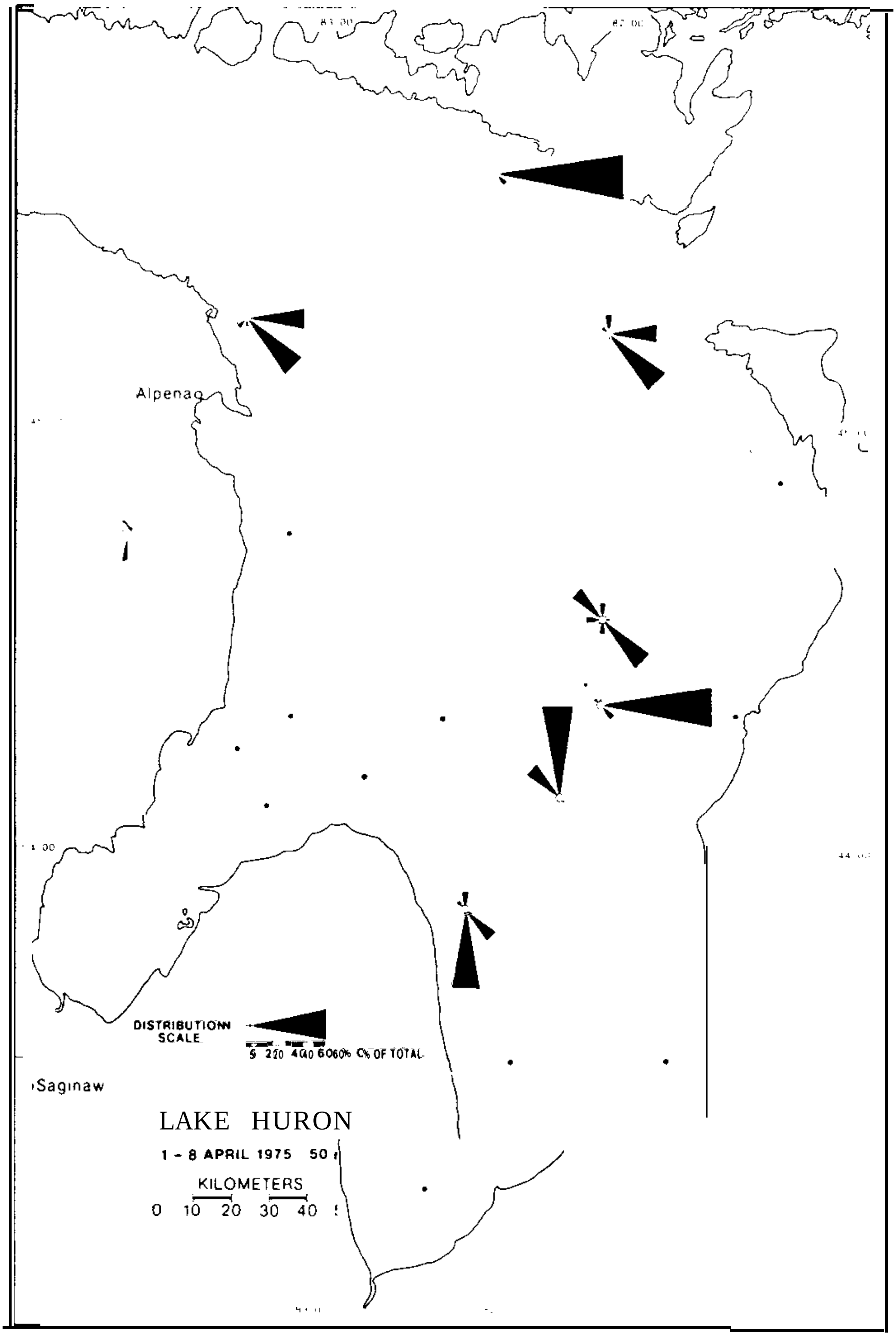

Figure B. 8c. *Current roses at 50 m depth* for *l-8 April 1975.*

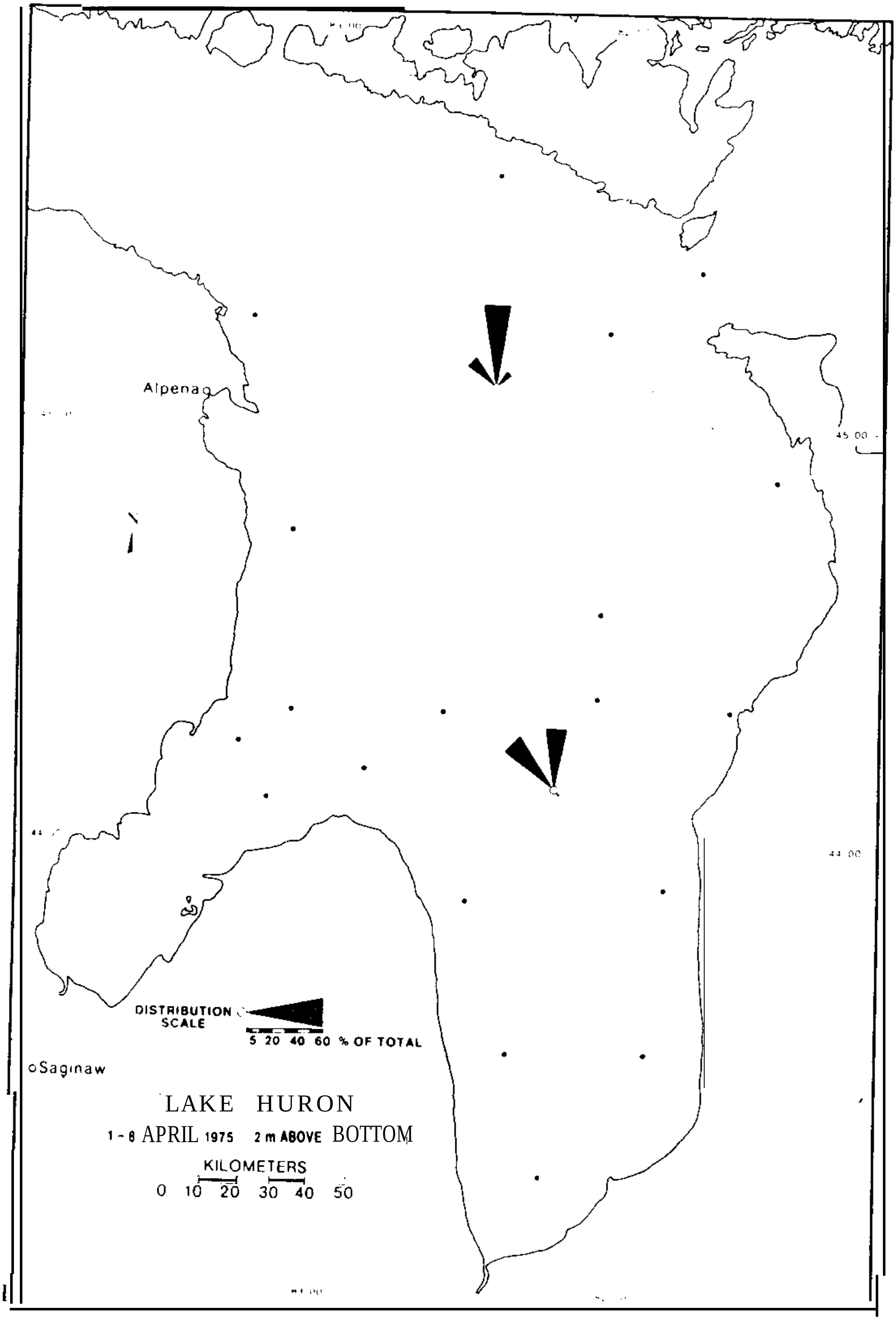

Figure B. 8d. Current roses at 2 m above the bottom for 1-8 April 1975.

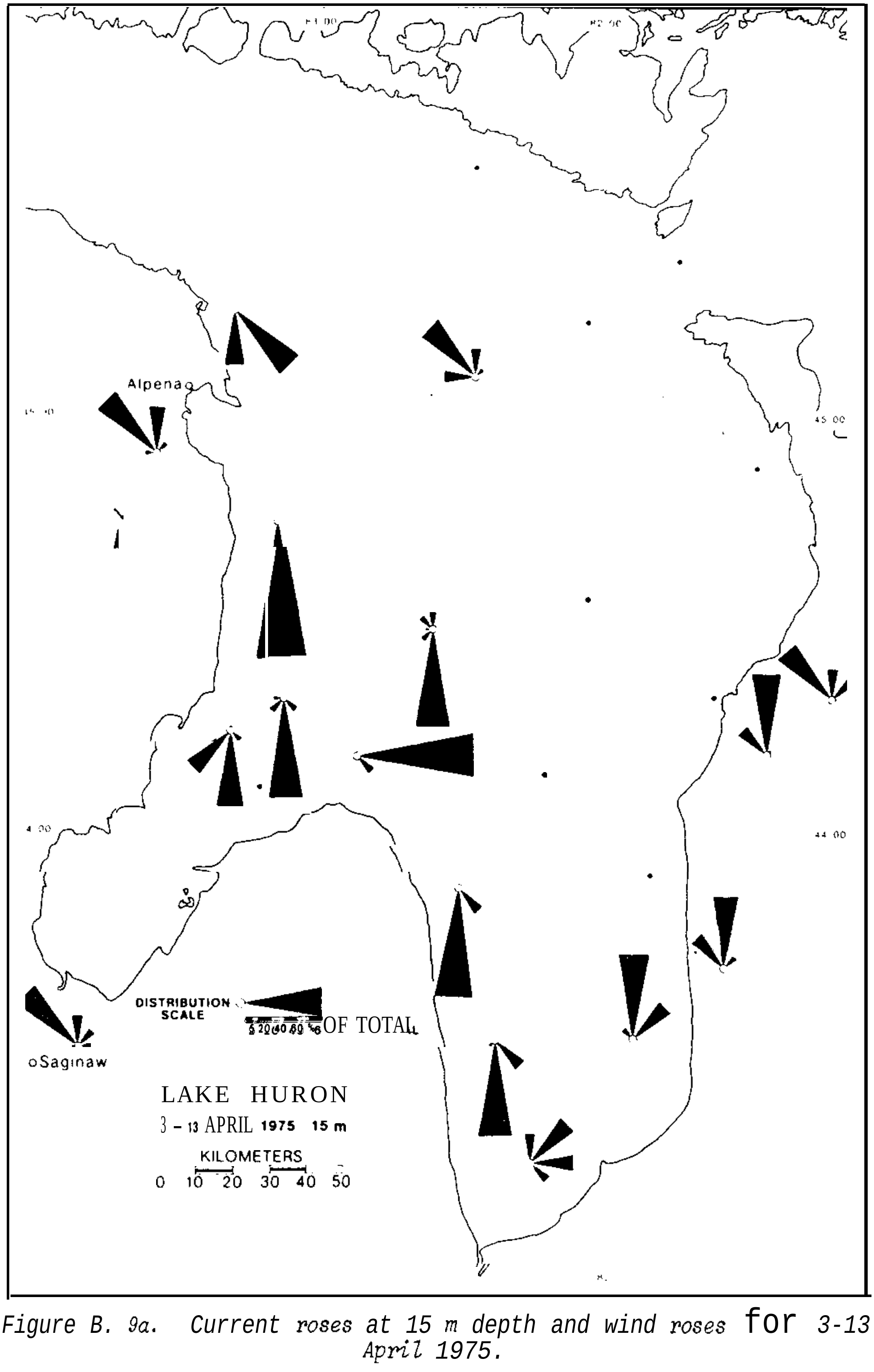

Figure B. 9a. Current roses at 15 m depth and wind roses for 3-13 April 1975.

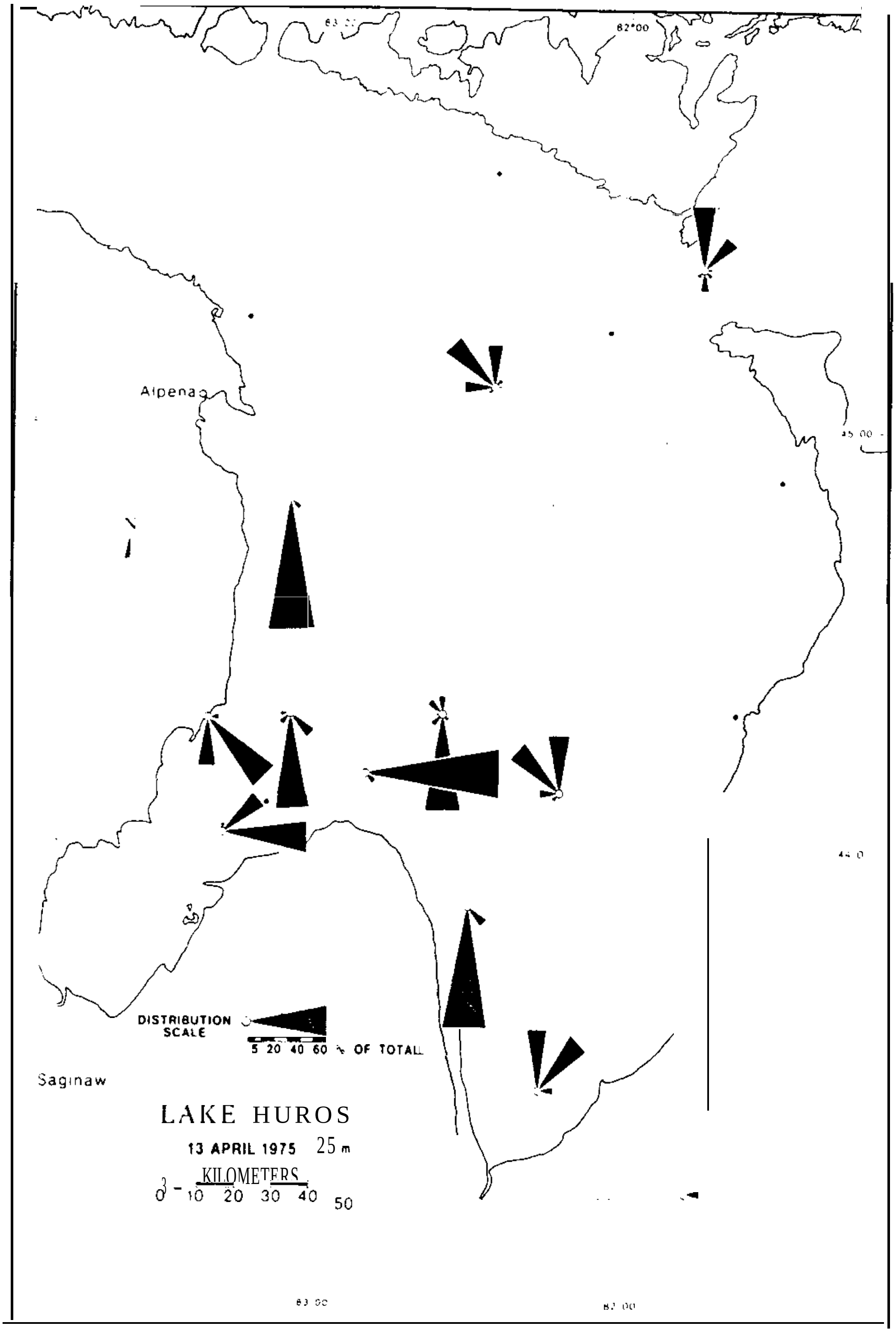

Figure B.9b. Current roses at 25 m depth for 3-13 April 1975.

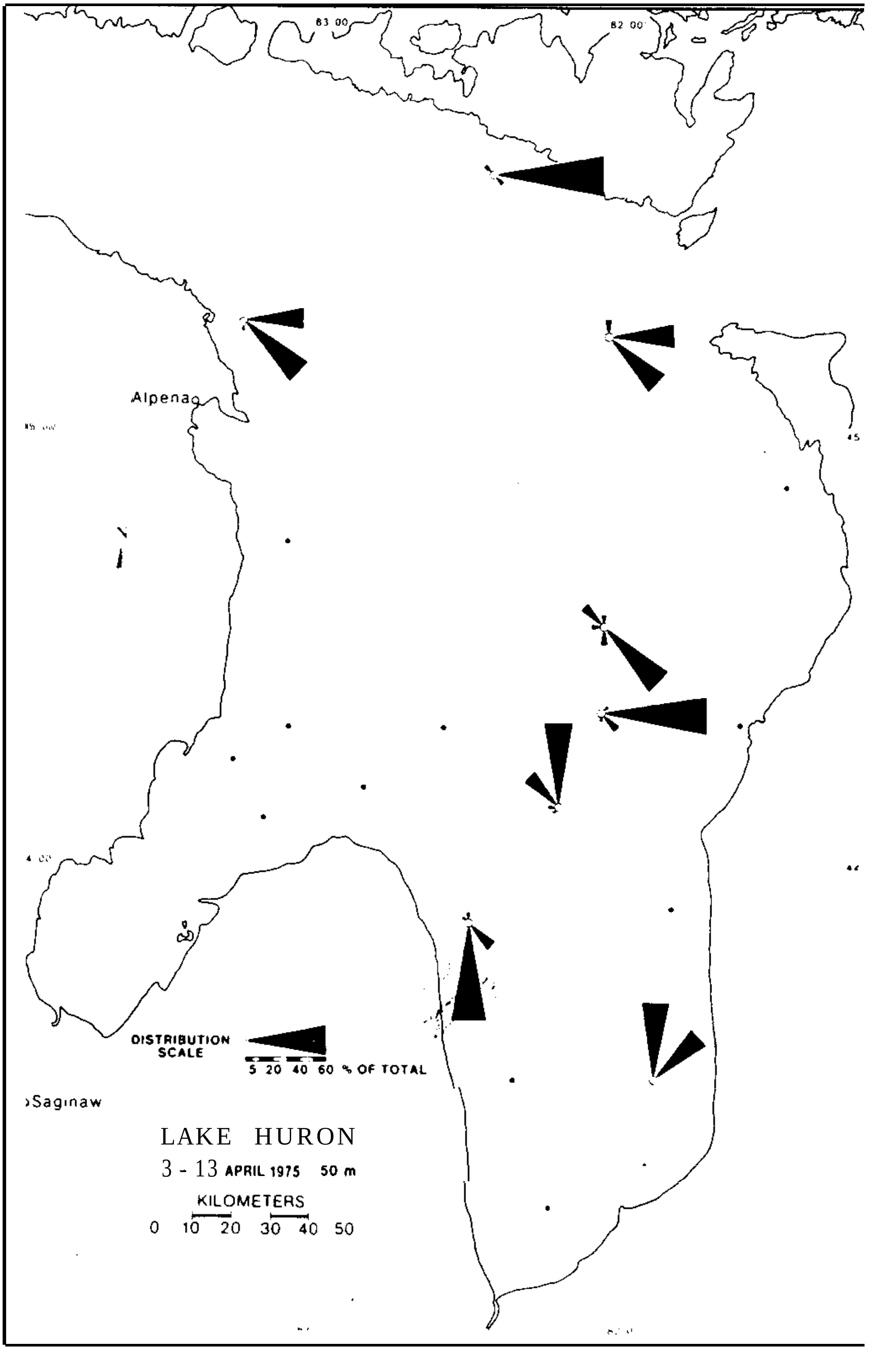

Figure B. 9c. Current roses at 50 m depth for 3-13 April 1975.

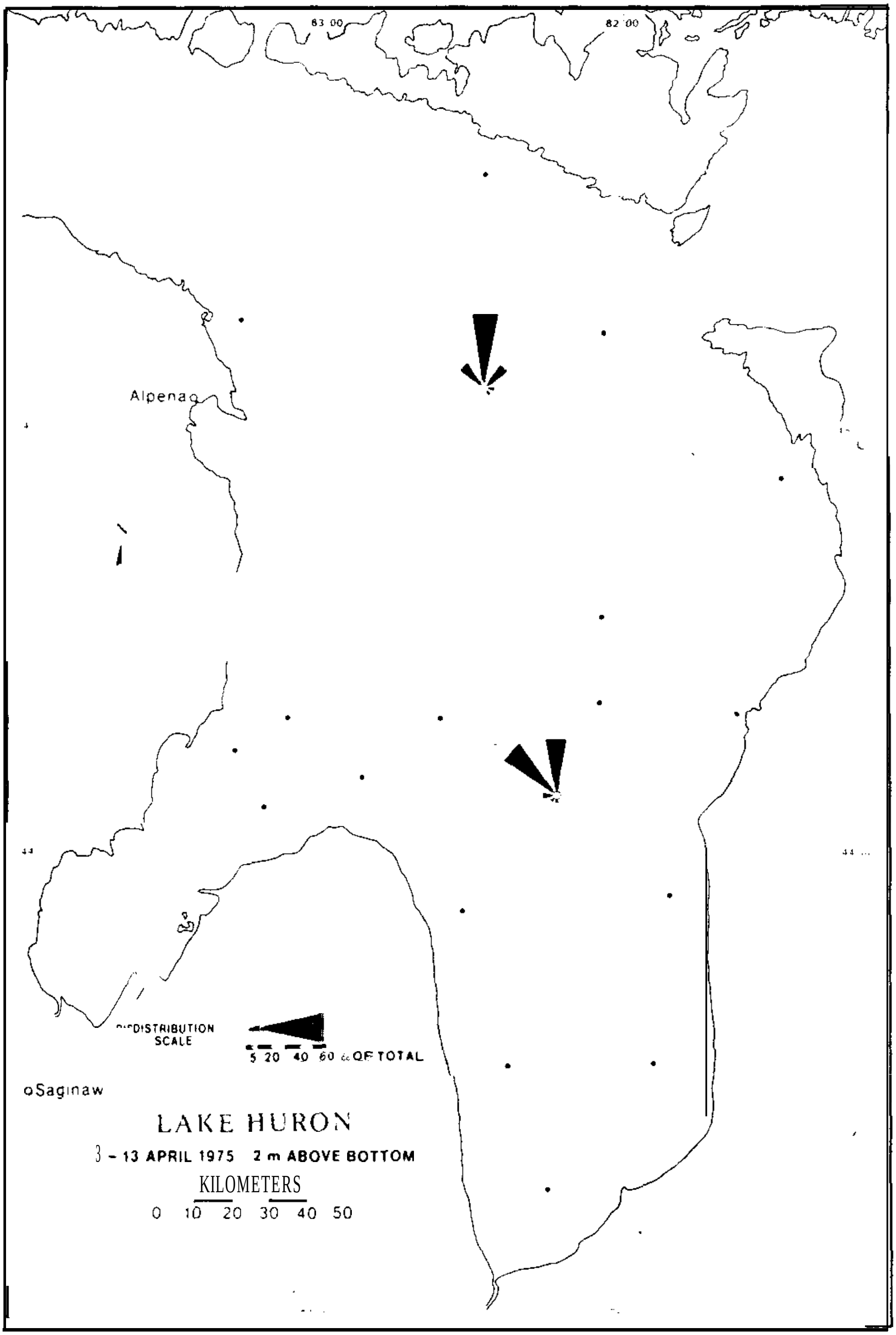

Figure B.9d. Current roses at 2 m above the bottom for 3-13 April 1975.

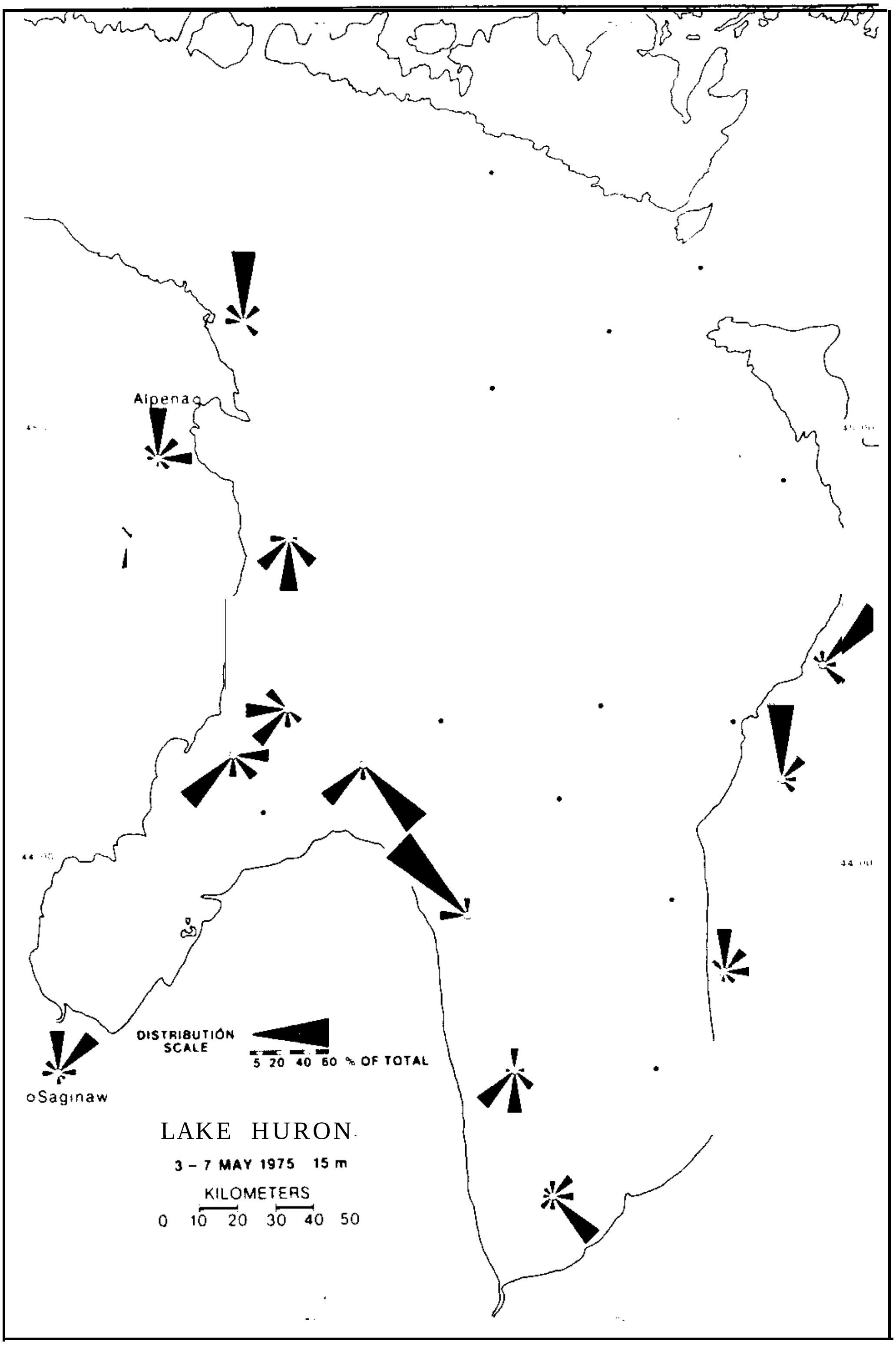

Figure B.10a. Current roses at 15 m depth and wind roses for 3-7 May 1975.

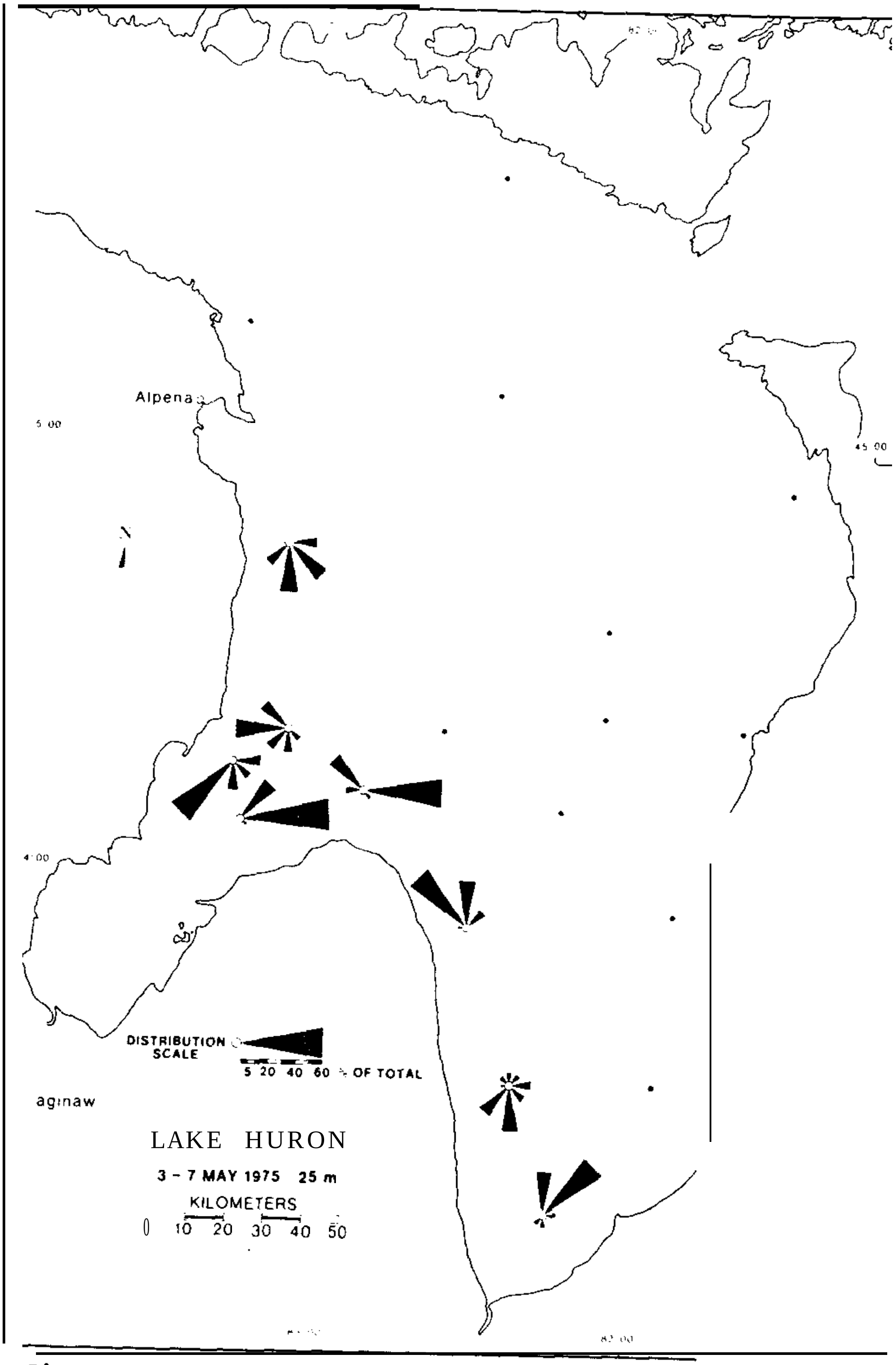

Figure B. 10b. Current roses at 25 m depth for 3-7 May 1975.

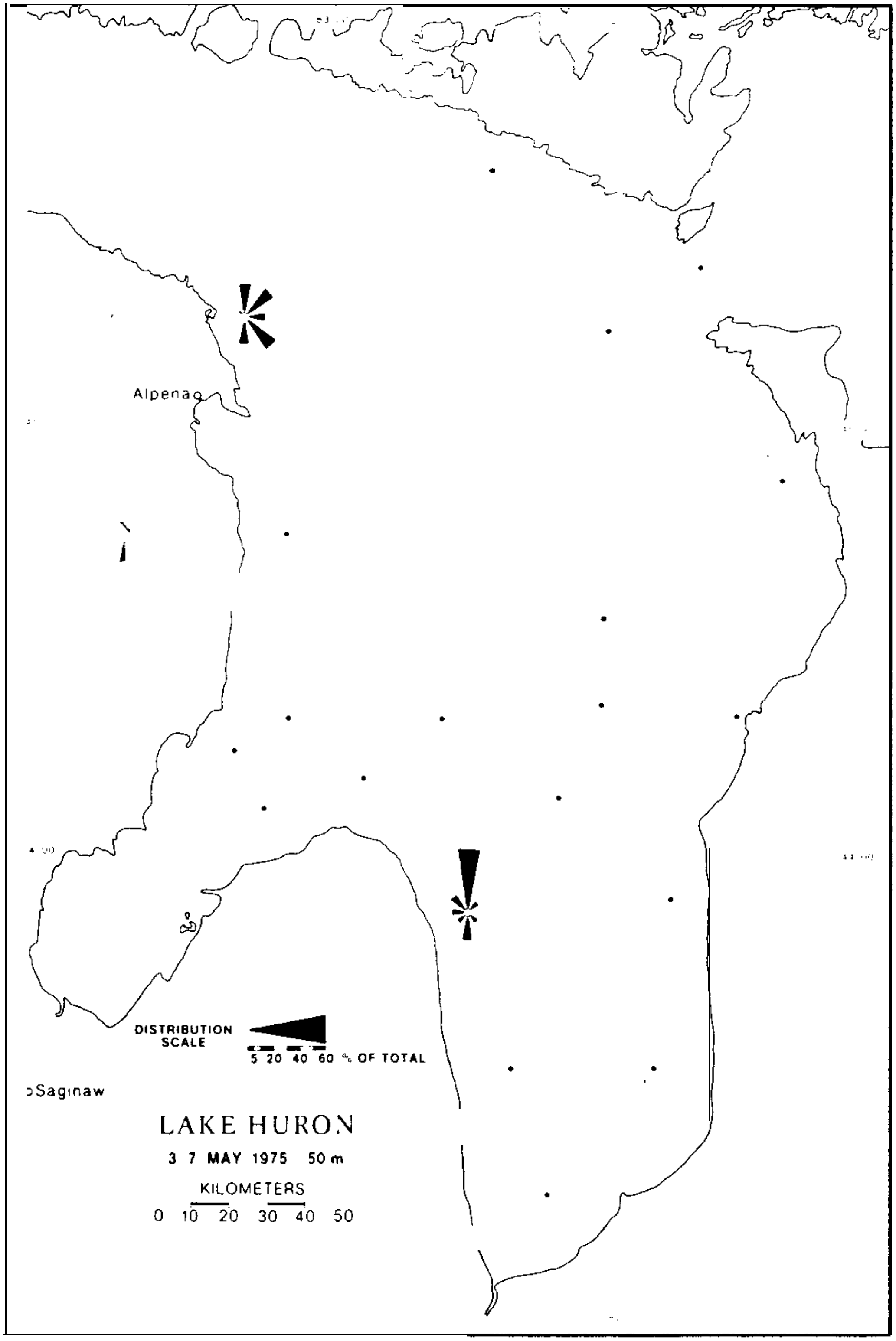

Figure B.10c. Current roses at 50 m depth for 3-7 May 1975.

No current data received from 2 m off the bottom for May 1975.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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16. ABSTRACT

Twenty-one current meter moorings were deployed in Lake Huron during winter 1974-75. The moorings were set in November 1974 and retrieved approximately 6 months later. The stations were configured on a coarse grid to measure the lake-scale circulation during winter. Water temperature "as also recorded in nearly all of the 65 current meters deployed. Results reveal a strong cyclonic flow pattern in the Lake Huron Basin persisting throughout the winter. The observed winter circulation "as in essence very similar to what is no" believed to be the summer circulation of epilimnion water, although the winter currents penetrated to deeper levels in the water column and were more intense. Winter cyclonic flow persisted in a nearly homogeneous water mass, while summer currents exhibited an almost geostrophic balance with observed water density distributions. This suggests that the current field driven by prevailing wind stresses across the lake's water surface may be largely responsible for establishing the horizontal gradients of water density observed in the lake during summer. Analyses of energetic wind stress impulses reveal the prevailing wind directions that drive the dominant circulation?. The winter studies permit a description of the annual cycle of horizontal current speed variation with depth in Lake Huron, and in the other Great Lakes as well. The effects of the ice cover are examined and the distribution and movement of the ice cover with respect to lake current and temperature fields are discussed.

17. KEY WORDS AND DOCUMENT ANALYSIS

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