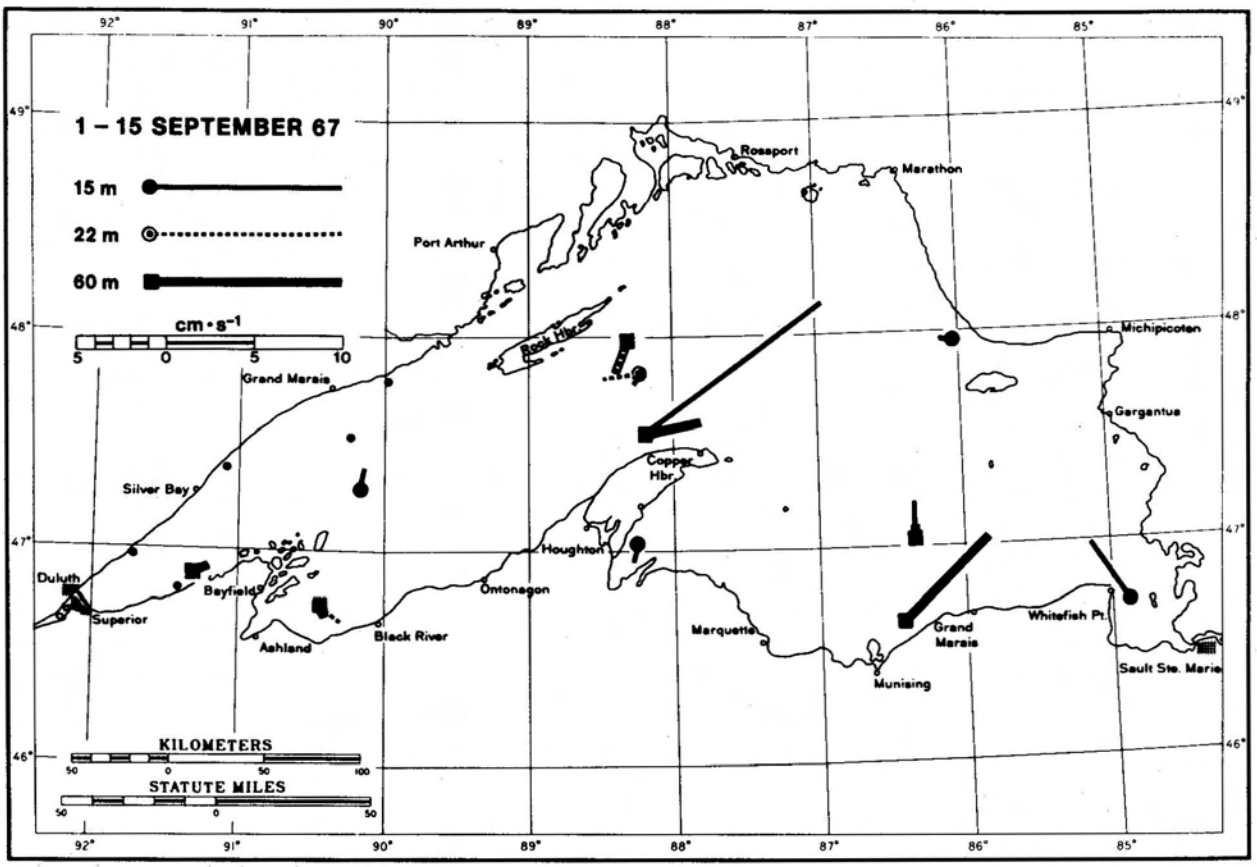

Figure 10b. (FWPCA) half-month average current vectors, 1-15 September 1967, 15, 22, and 60 m.

The second half of September (fig. 11a, b) seemed to contain a change in the flow pattern as a current flowed from the Keweenaw Peninsula toward Isle Royale at 15 m at station 9, and at 10 and 15 m at station 11. Winds were predominantly from the north. There was still evidence of a strong counterclockwise circulation west of 88°W to the tip of the lake and of another cell occupying the eastern half. The cross-lake current from station 9 may have been an artifact of the hardware used in data collection or reduction. Thus, the suggestion of two counterclockwise cells in the lake can be inferred from the data, but certainly not proved conclusively.

October (fig. 12a, b and 13a, b) was the last month in which a significant number of moorings were left; only five still reported at 10 m for 1-15 October. The late September pattern was continued. A strong northeastward coastal current was found at stations 2 and 3 at 10 and 30 m and at station 15 at 60 m. For 16-31 October four stations still reported flows at 10 m, including the suspiciously steady north-northwest flow at station 9. Deeper flows for this period were still parallel to bathymetry at stations 2, 3, and 15, but strong and divergent in direction at station 5, which showed such behavior all season. The scatter of directions at mooring 5 is probably due to its location in a confined bay and out of the mainstream of the basic counterclockwise lake circulation.

3.2 FWPCA Observations - Summer 1967, Summary

Five and one-half months of current data from a network of moorings in Lake Superior revealed a persistent counterclockwise circulation covering the whole lake once stratification had set in. Serious deficiencies in data reduction techniques and equipment during the original processing by the FWPCA and contracted data processors rendered a significant fraction of the data sample useless, so that only general features of long-term circulation patterns could be inferred. Monthly summaries of summer current components are given in table 1.

3.3 CCIW Observations - Summer 1973

Figures 14-21 display half-monthly averages of CCIW data for the period 1 June-30 September 1973. A detailed, month-by-month discussion will not be made here, since the patterns already determined from the FWPCA data are again present. There are, however, some significant differences. CCIW mooring 4 reported a consistent, strong east-northeast Keweenaw Current at speeds exceeding 30 cm s^{-1} from a location near FWPCA site 9, which showed north-northwest currents at 10 m with lower speeds for a similar season. Currents at CCIW site 3 showed an extension of the Keweenaw Current as it swept around with the bathymetry although some of the data from FWPCA site 13 showed this flow continuing to the south-southwest.

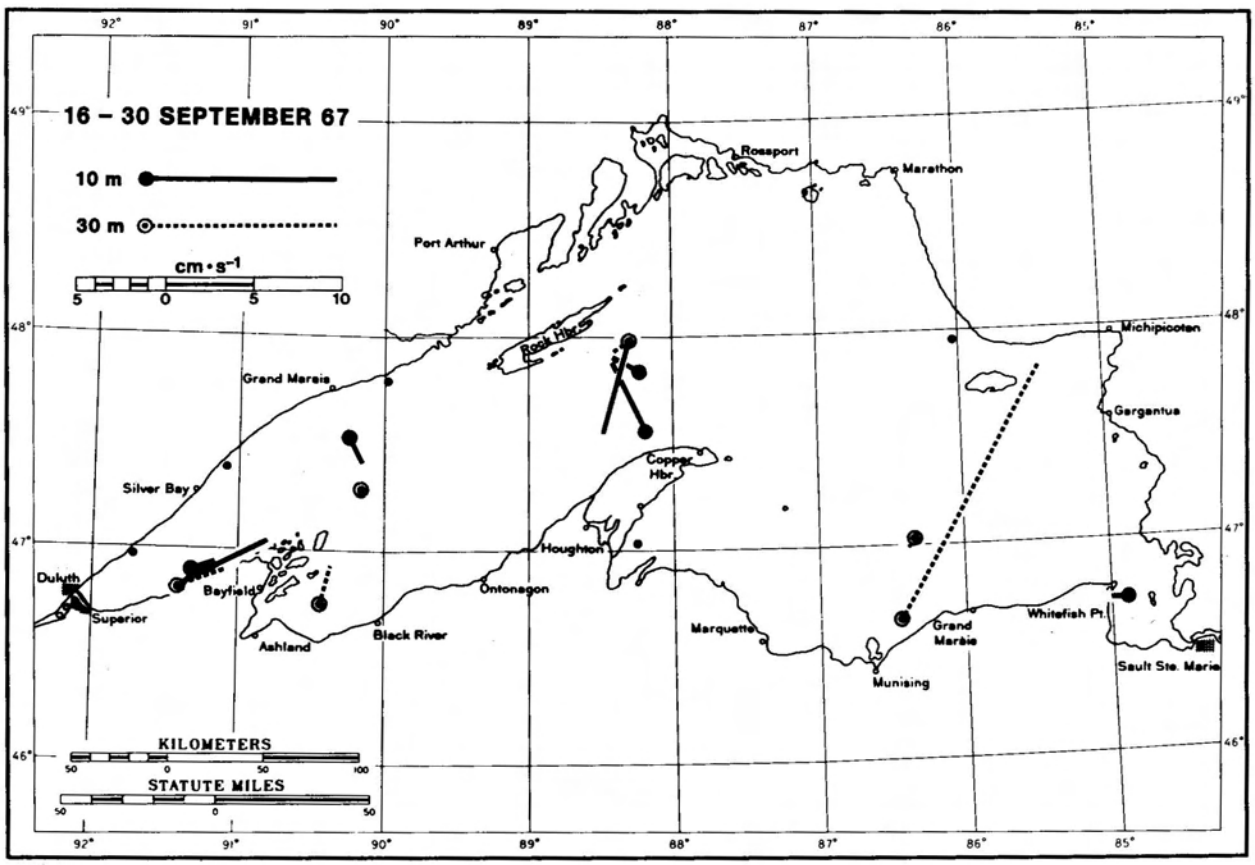

Figure 11a. (FWPCA) half-month average current vectors, 16-30 September 1967, 10 and 30 m.

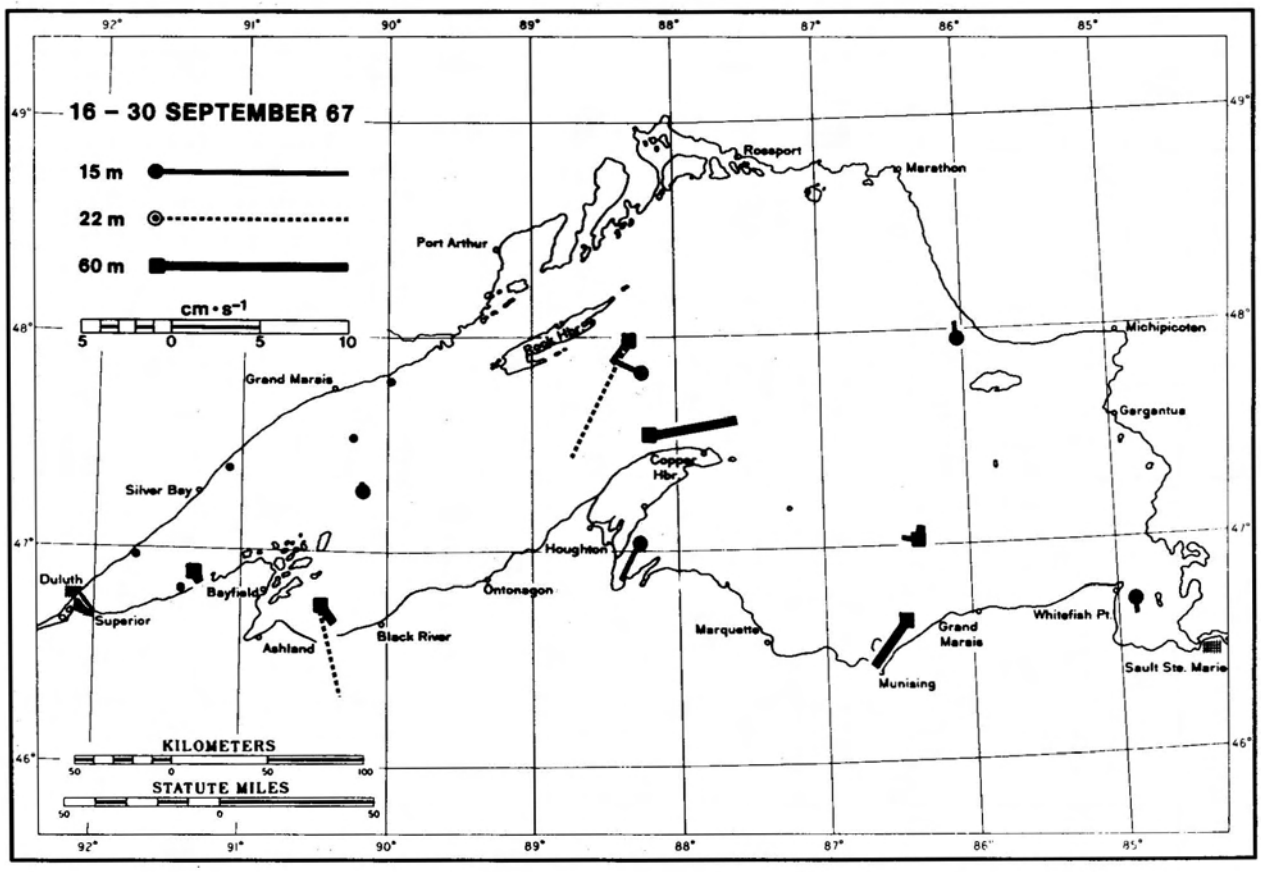

Figure 11b. (FWPCA) half-month average current vectors, 16-30 September 1967, 15, 22, and 60 m.

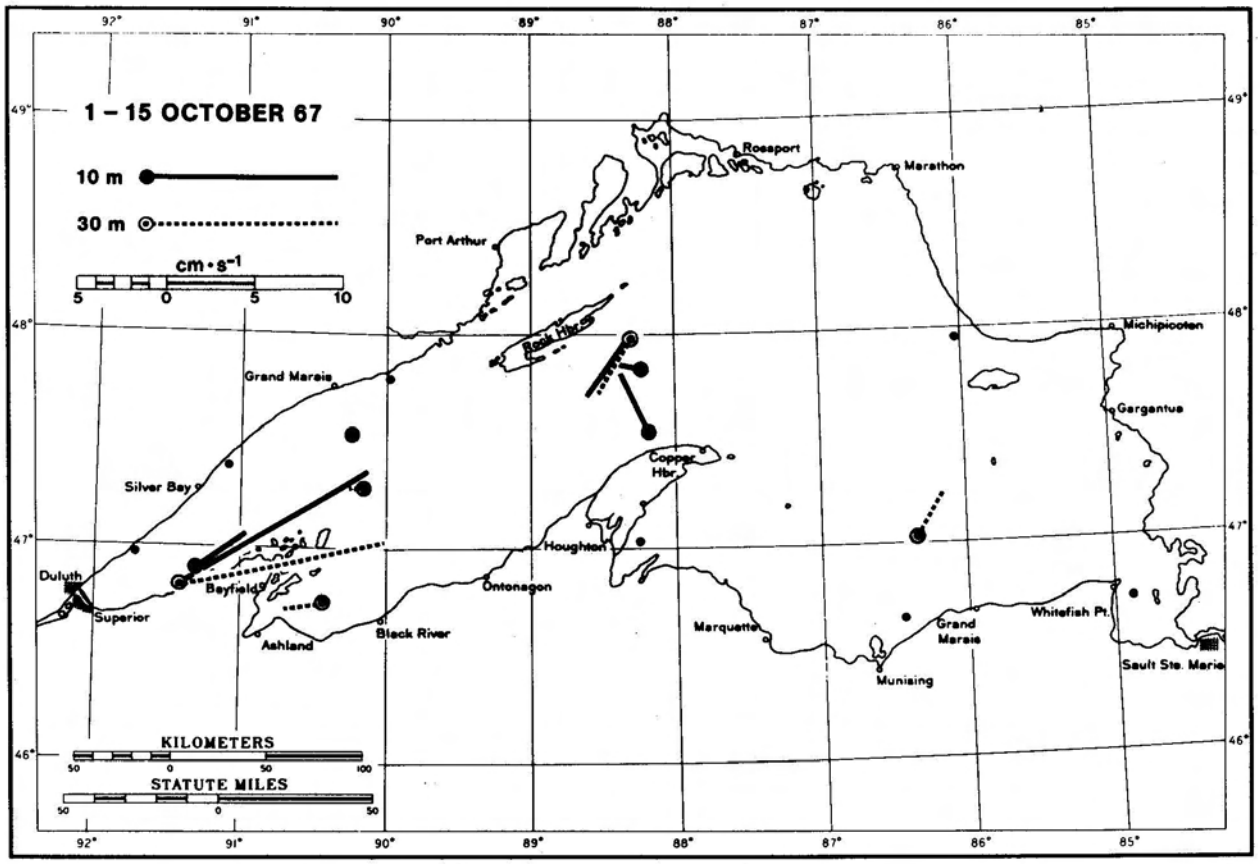

Figure 12a. (FWPCA) half-month average current vectors, 1-15 October 1967, 10 and 30 m.

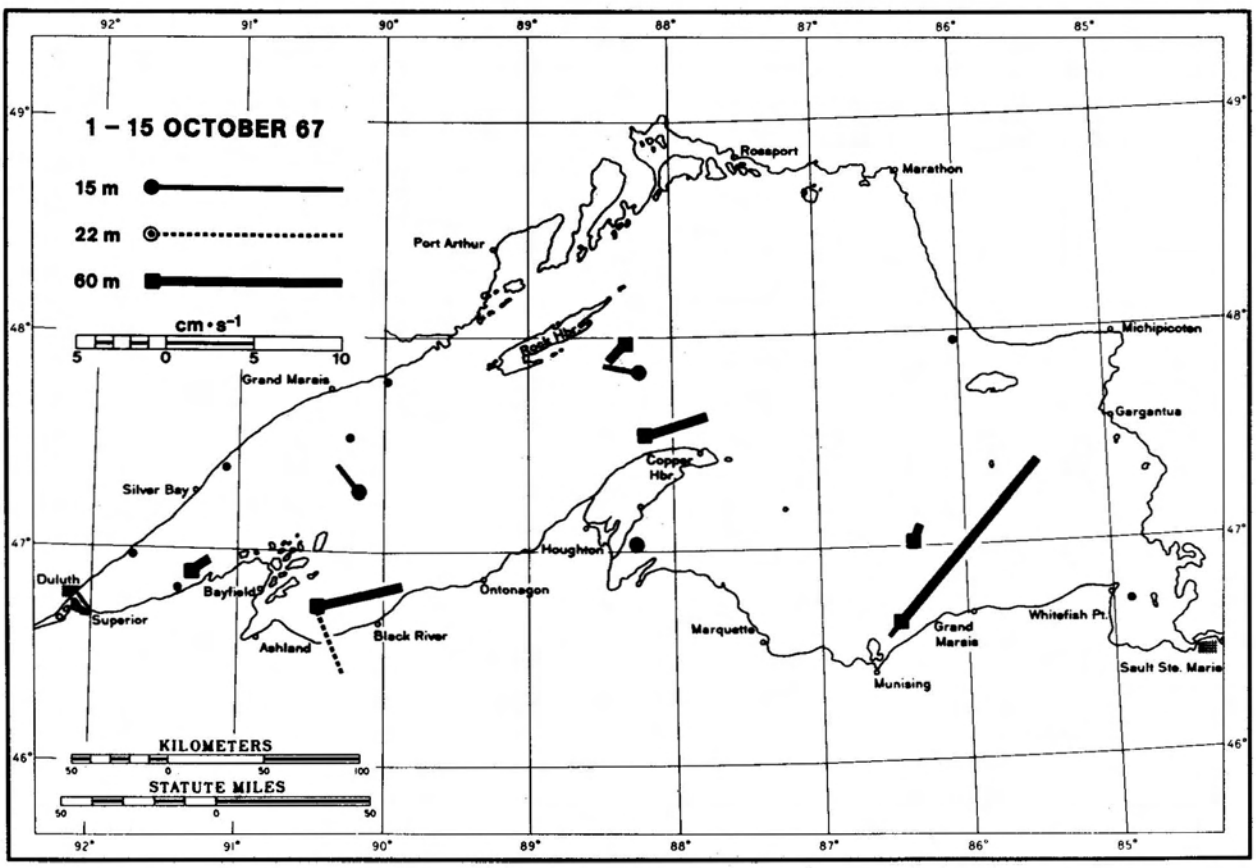

Figure 12b. (FWPCA) half-month average current vectors, 1-15 October 1967, 15, 22, and 60 m.

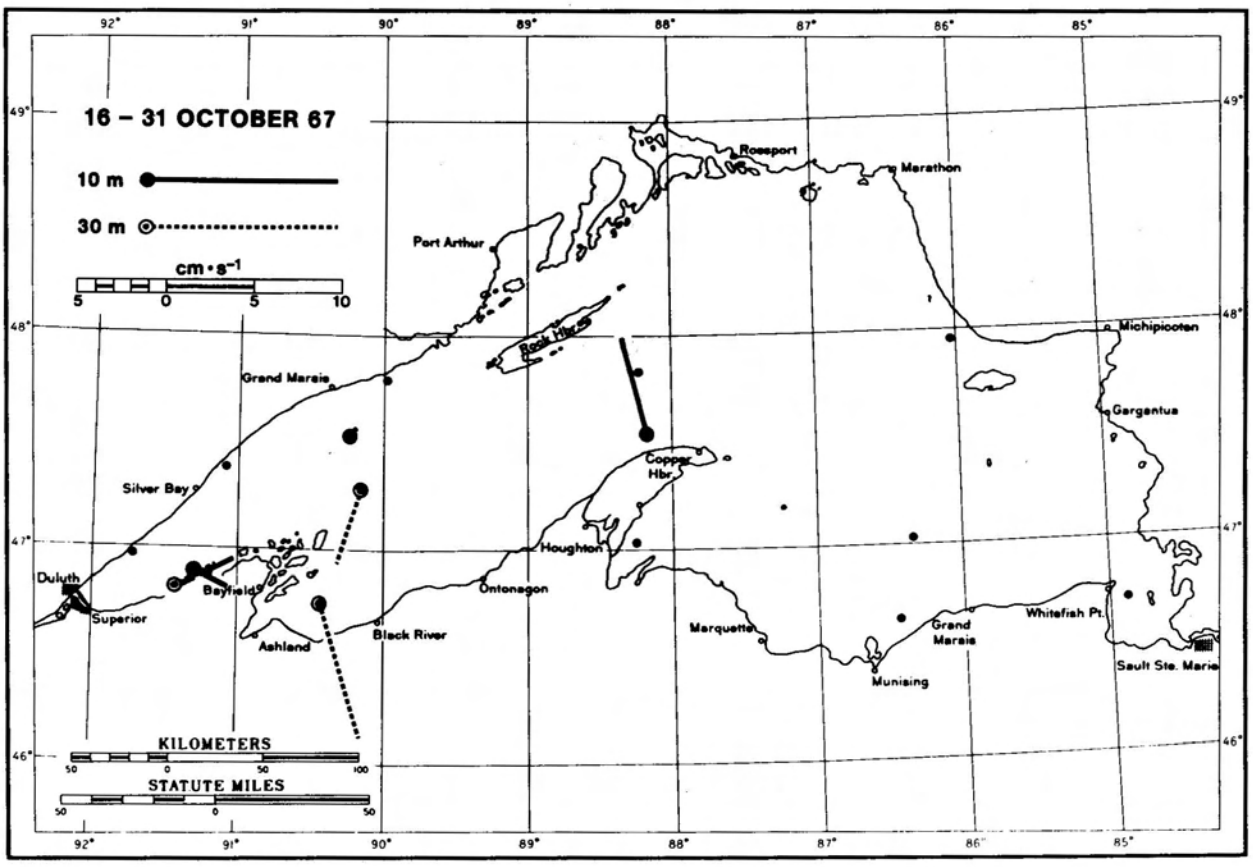

Figure 13a. (FWPCA) half-month average current vectors, 16-31 October 1967, 10 and 30 m.

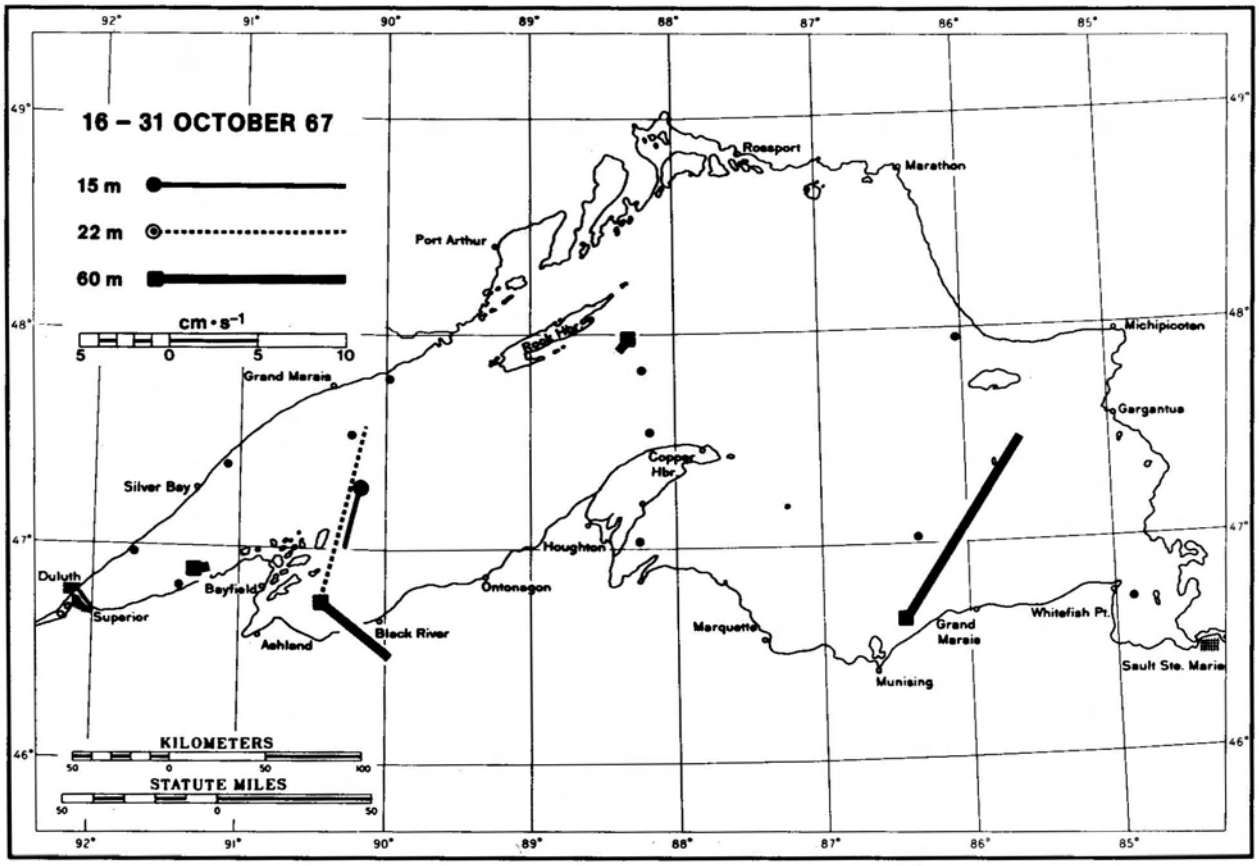

Figure 13b. (FWPCA) half-month average current vectors, 16-31 October 1967, 15, 22, and 60 m.

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1})

Date	Station	Depth 10 m	15 m	22 m	30 m
June 1967	1	----	----	----	----
	2	-0.33, 1.15	----	----	-0.20, -1.35
	3	0.80, 0.08	----	----	----
	4	-3.30, -3.10	----	----	----
	5	----	----	-4.42, -2.08	0.36, 1.35
	6	1.66, 1.80	-0.34, -0.76	----	-0.88, -1.31
	7	0.01, 0.01	----	----	----
	8	----	----	----	----
	9	0.39, 2.69	4.70, 6.50	----	----
	11	0.68, 0.86	-0.95, 0.12	-0.72, 0.02	----
	12	0.17, -0.89	----	-0.55, 0.01	-0.65, -2.63
	13	----	-0.96, -0.33	-0.72, -1.06	----
	14	----	----	----	----
	15	----	----	----	----
	16	----	----	----	----
	17	----	----	----	----
July 1967	1	----	----	----	----
	2	0.46, 0.62	----	----	0.52, 0.74
	3	-0.44, -0.36	----	----	----
	4	----	----	----	----
	5	----	----	-3.78, -6.60	-0.44, 2.42
	6	----	-1.10, 1.40	----	----
	7	0.00, 0.00	----	----	----
	8	----	----	----	----
	9	0.57, 2.64	6.41, 2.20	----	----
	11	-3.90, -3.00	-0.40, -0.17	-0.62, -0.08	----
	12	-0.02, -1.88	----	-0.24, -1.12	-0.92, -1.95
	13	----	-1.45, -2.82	-0.94, -2.67	----
	14	----	-0.08, 2.30	----	----
	15	----	----	----	-1.46, -1.38
	16	-2.69, -1.08	-1.90, -1.66	----	----
	17	----	-0.98, 0.05	----	----
August 1967	1	----	----	----	----
	2	1.87, 1.10	----	----	0.64, 0.61
	3	-0.30, 0.47	----	----	----
	4	----	----	----	----
	5	----	----	1.02, -0.91	-0.35, 0.03
	6	----	0.10, 0.30	----	-0.30, 0.00
	7	-0.17, -0.44	----	----	----
	8	----	----	----	----
	9	-0.94, 2.47	8.36, -0.24	----	----
	11	-1.12, -0.20	-1.30, -0.24	-0.87, 0.06	----
	12	-0.92, -2.91	----	-0.64, -0.70	-1.54, -2.46
	13	----	0.12, -0.54	-0.17, -1.32	----
	14	----	-0.32, 2.59	----	0.05, -0.66
	15	----	----	----	0.16, 2.80
	16	-4.06, -1.20	-2.72, -1.56	----	----
	17	----	-1.19, 0.88	----	----

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1}) (continued)

Date	Station	Depth 60 m	90 m	120 m	150 m
June 1967	1	----	----	----	----
	2	----	----	----	----
	3	-0.25, -0.12	----	----	----
	4	----	----	----	----
	5	-0.20, 0.28	----	----	----
	6	----	----	----	----
	7	----	-0.22, -0.24	----	0.96, 0.24
	8	----	----	----	----
	9	4.56, 0.92	6.95, 2.08	7.16, 1.46	-0.38, 3.21
	11	----	----	----	----
	12	-0.76, -1.07	-0.89, 0.16	----	----
	13	----	----	----	----
	14	----	----	----	----
	15	----	----	----	----
	16	----	----	----	----
	17	----	----	----	----
July 1967	1	----	----	----	----
	2	----	----	----	----
	3	-0.79, -2.65	----	----	----
	4	----	----	----	----
	5	0.02, 0.00	----	----	----
	6	----	----	----	----
	7	----	0.92, 0.16	0.74, 0.07	----
	8	----	----	----	----
	9	4.50, 0.39	6.28, 1.74	3.93, 2.36	4.80, 1.25
	11	----	-0.37, -0.08	----	----
	12	-0.54, -0.76	----	----	----
	13	----	----	----	----
	14	-0.30, 1.62	----	----	----
	15	5.00, 1.74	----	----	----
	16	----	----	----	----
	17	----	----	----	----
August 1967	1	----	----	----	----
	2	----	----	----	----
	3	-1.61, -0.92	----	----	----
	4	----	----	----	----
	5	0.38, -0.54	----	----	----
	6	----	----	----	----
	7	----	0.23, 0.09	----	0.02, 0.19
	8	----	----	----	----
	9	3.10, 1.08	4.08, 2.26	2.65, 0.80	-1.08, 0.90
	11	----	-0.41, -0.07	----	----
	12	----	----	----	----
	13	----	----	----	----
	14	-0.16, 1.54	----	----	----
	15	3.98, 7.34	----	----	----
	16	----	----	----	----
	17	----	----	----	----

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1}) (continued)

Date	Station	Depth 10 m	15 m	22 m	30 m
September 1967	1	----	----	----	----
	2	3.61, 2.07	----	----	1.32, 0.66
	3	1.36, 0.76	----	----	----
	4	----	----	----	----
	5	----	----	1.16, -2.96	0.02, 1.28
	6	----	0.14, 0.77	----	-0.34, -0.30
	7	0.24, -1.62	----	----	----
	8	----	----	----	----
	9	-1.50, 2.90	----	----	----
	11	-1.94, -0.01	-0.68, 0.11	----	----
	12	-1.04, -3.78	----	-1.70, -3.73	-1.24, -1.76
	13	----	-0.59, -1.60	----	----
	14	----	-0.67, 1.14	----	-0.30, -0.09
	15	----	----	----	4.47, 8.20
	16	-1.72, 2.72	-1.14, 1.20	----	----
	17	----	-0.36, 0.42	----	----
October 1967	1	----	----	----	----
	2	7.12, 4.02	----	----	7.17, 1.98
	3	2.42, 0.68	----	----	----
	4	----	----	----	----
	5	----	----	2.28, 3.14	0.08, -3.84
	6	----	-0.90, -0.96	----	-0.82, -1.94
	7	0.11, 0.22	----	----	----
	8	----	----	----	----
	9	-1.54, 4.18	----	----	----
	11	----	----	----	----
	12	----	----	----	----
	13	----	----	----	----
	14	----	----	----	----
	15	----	----	----	----
	16	----	----	----	----
	17	----	----	----	----

Table 1. (FWPCA) Current Components (East Component Followed by North Component; Both in cm/s^{-1}) (continued)

Date	Station	Depth 60 m	90 m	120 m	150 m
September 1967	1	----	----	----	----
	2	----	----	----	----
	3	0.67, -0.15	----	----	----
	4	----	----	----	----
	5	0.52, -0.74	----	----	----
	6	----	----	----	----
	7	----	0.84, -0.11	----	-0.29, -0.04
	8	----	----	----	----
	9	4.18, 0.92	4.33, 1.76	4.28, 0.60	-1.16, 0.48
	11	----	-0.70, -0.02	----	----
	12	-0.72, -1.56	----	----	----
	13	----	----	----	----
	14	-0.03, 1.10	----	----	----
	15	1.50, 1.29	----	----	----
	16	----	----	----	----
	17	----	----	----	----
October 1967	1	----	----	----	----
	2	----	----	----	----
	3	1.12, 0.51	----	----	----
	4	----	----	----	----
	5	4.36, -0.79	----	----	----
	6	----	----	----	----
	7	----	0.94, 0.60	----	0.76, 0.28
	8	----	----	----	----
	9	----	----	----	----
	11	----	----	----	----
	12	-0.54, -0.69	----	----	----
	13	----	----	----	----
	14	----	----	----	----
	15	7.20, 10.14	----	----	----
	16	----	----	----	----
	17	----	----	----	----

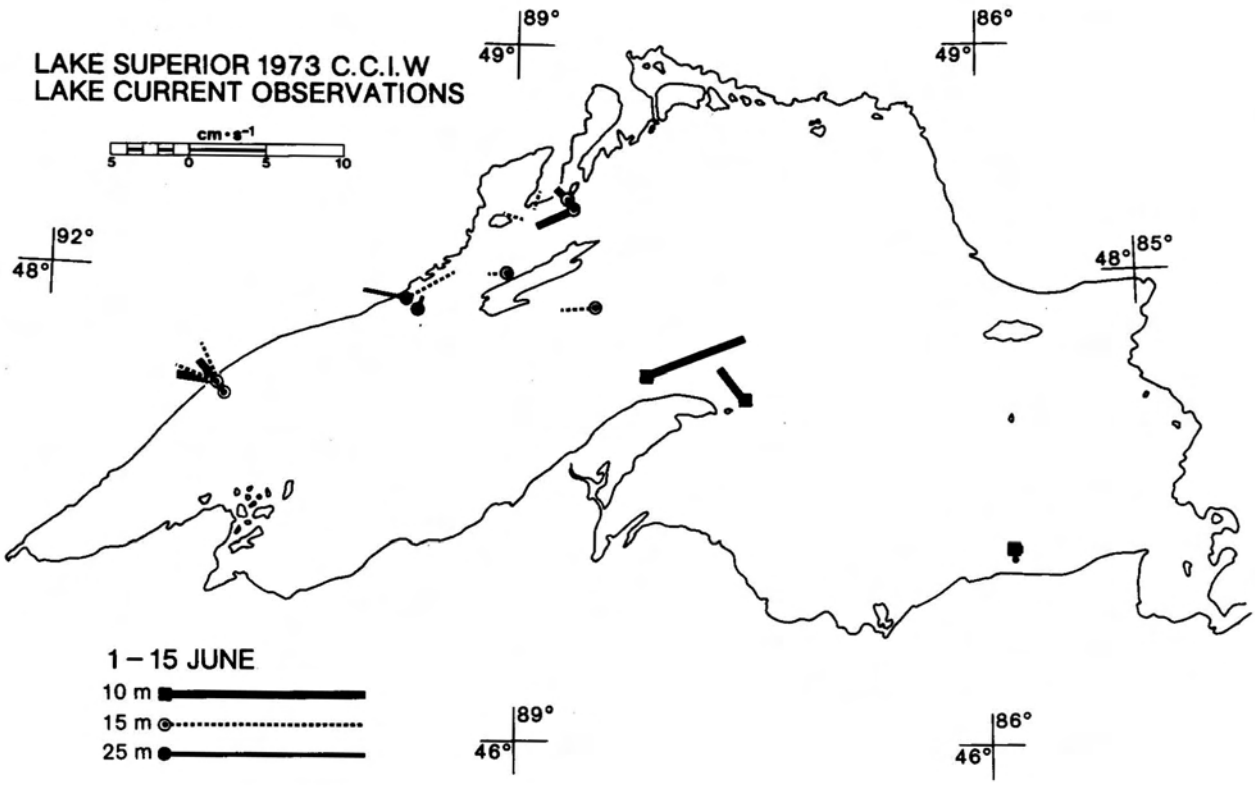

Figure 14. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-15 June 1973.

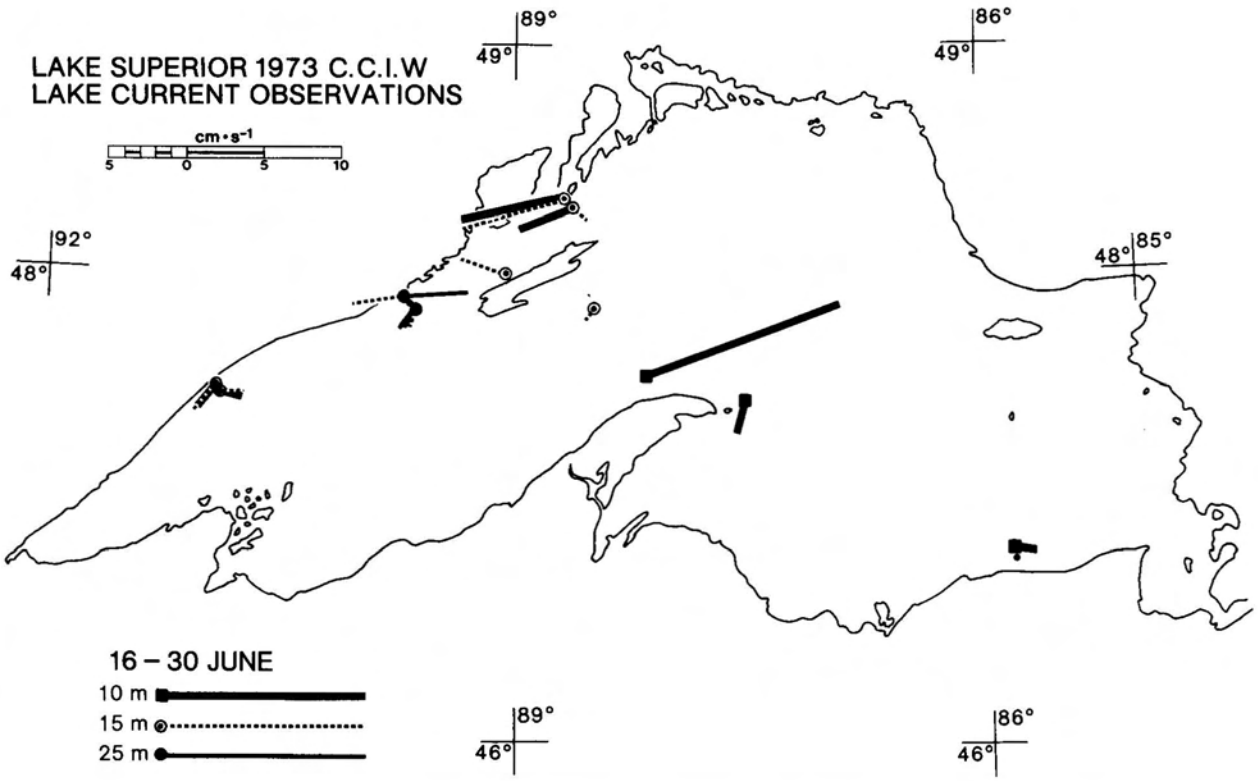

Figure 15. (CCIW) half-month average current vectors at 10, 15, and 22 m, 16-30 June 1973.

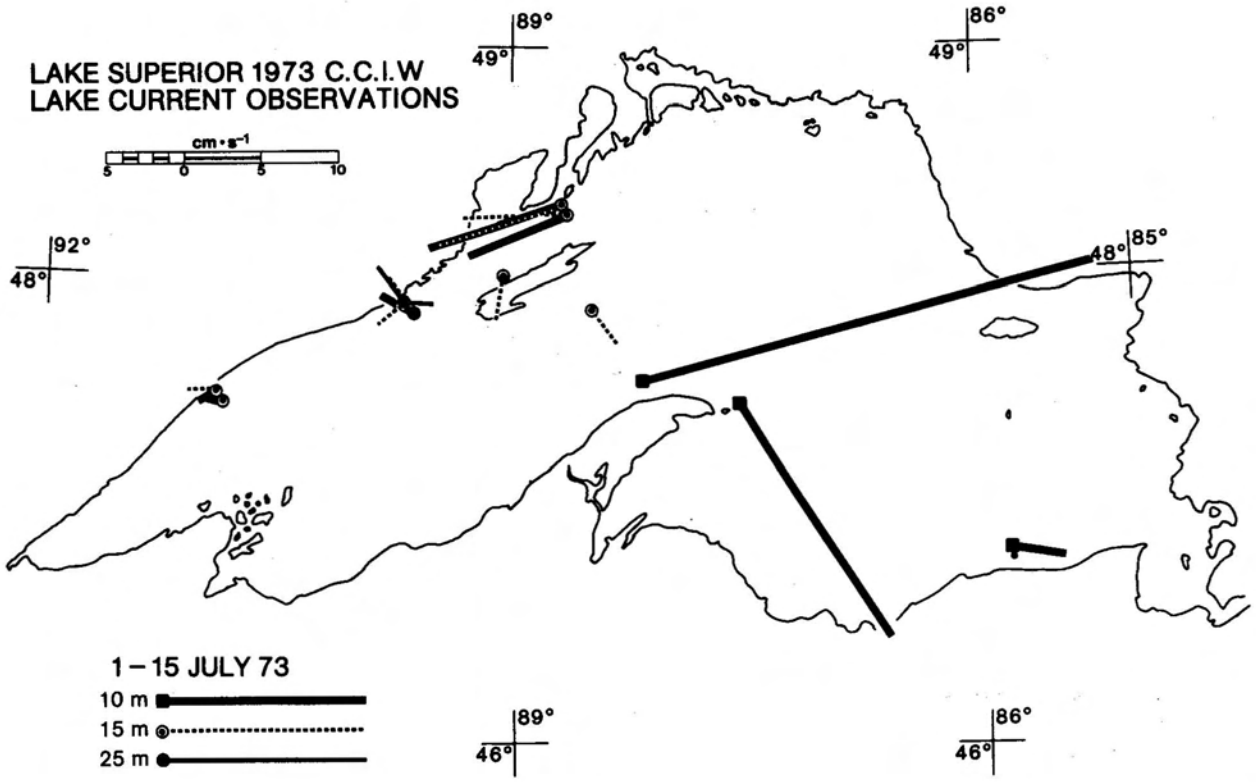

Figure 16. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-15 July 1973.

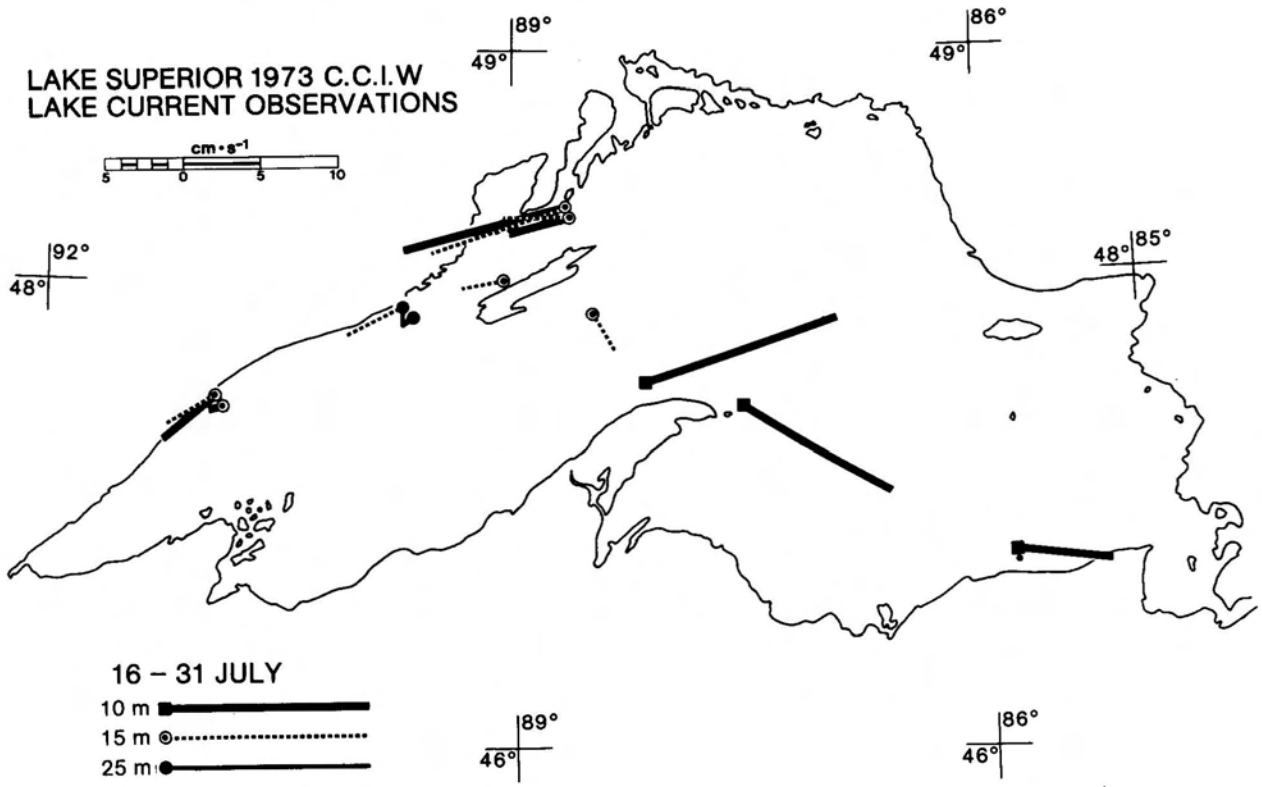

Figure 17. (CCIW) half-month average current vectors at 10, 15, and 22 m, 16-31 July 1973.

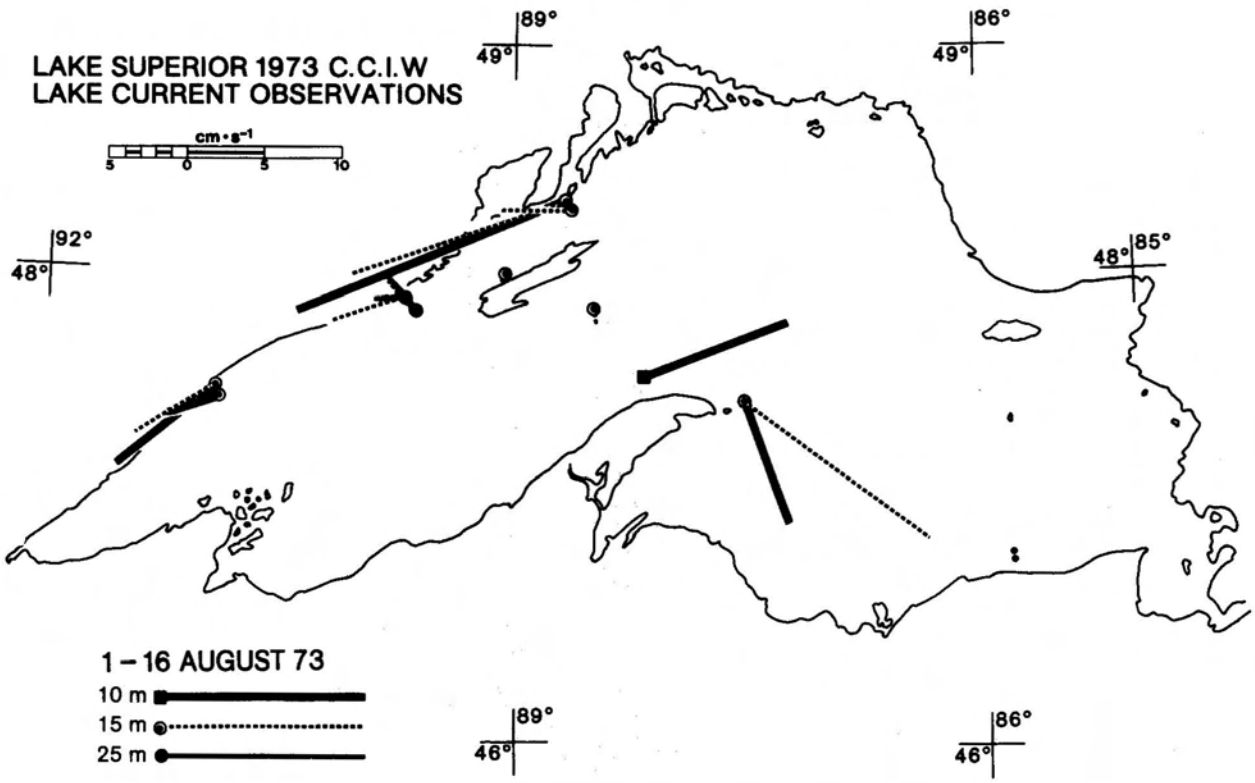

Figure 18. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-16 August 1973.

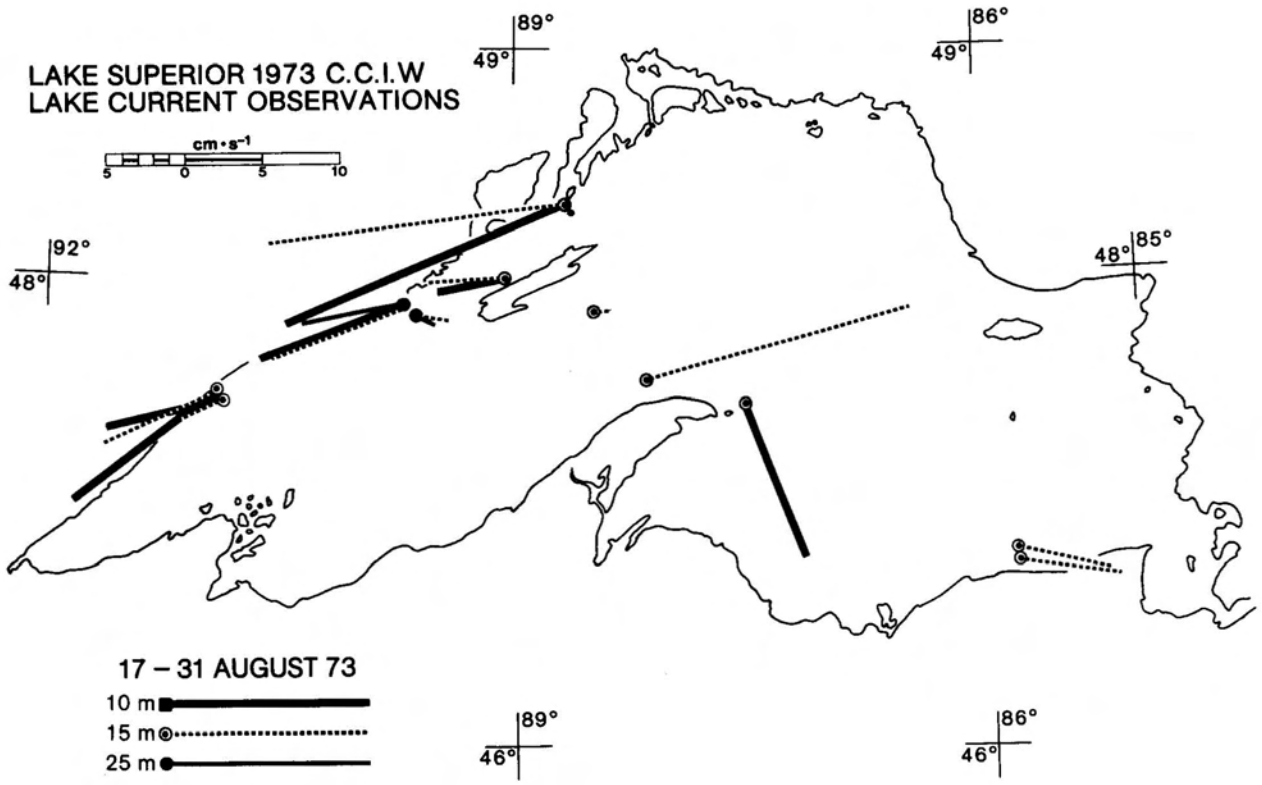

Figure 19. (CCIW) half-month average current vectors at 10, 15, and 22 m, 17-31 August 1973.

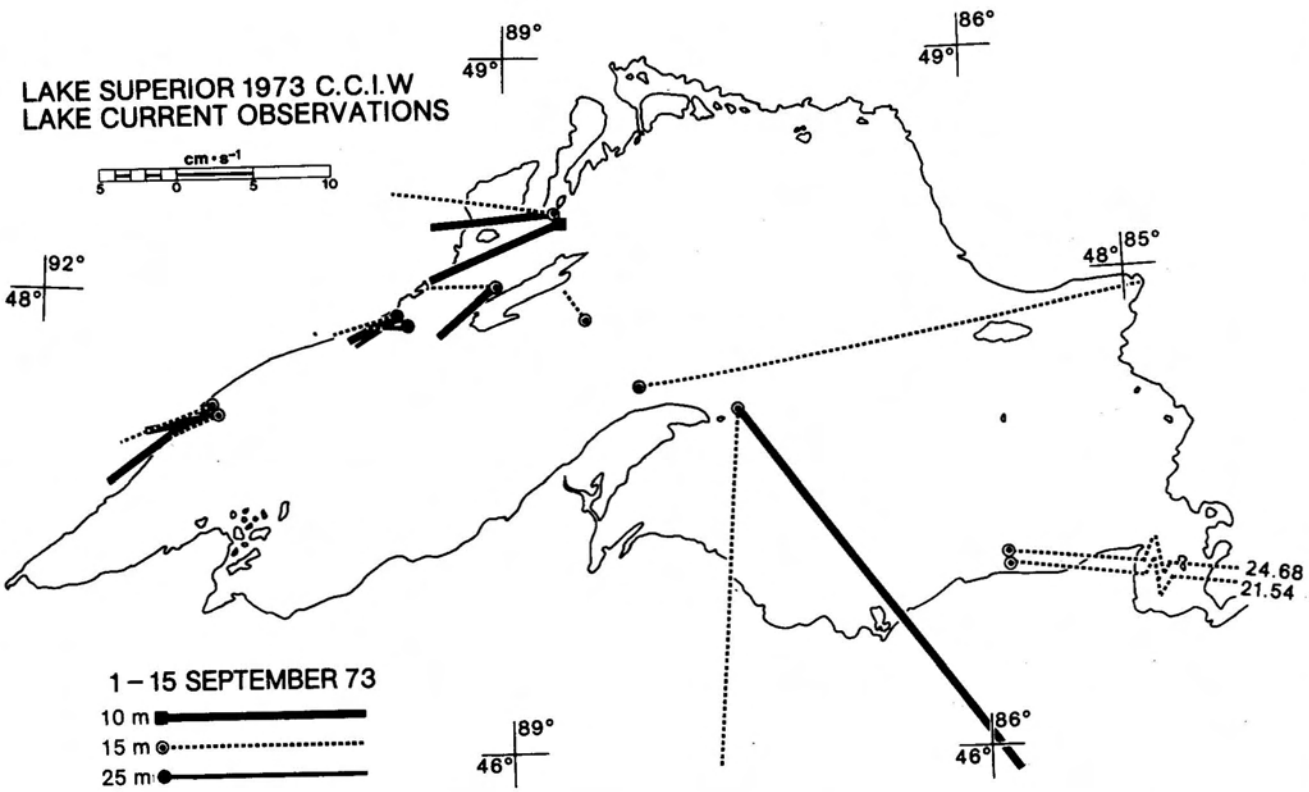

Figure 20. (CCIW) half-month average current vectors at 10, 15, and 22 m, 1-15 September 1973.

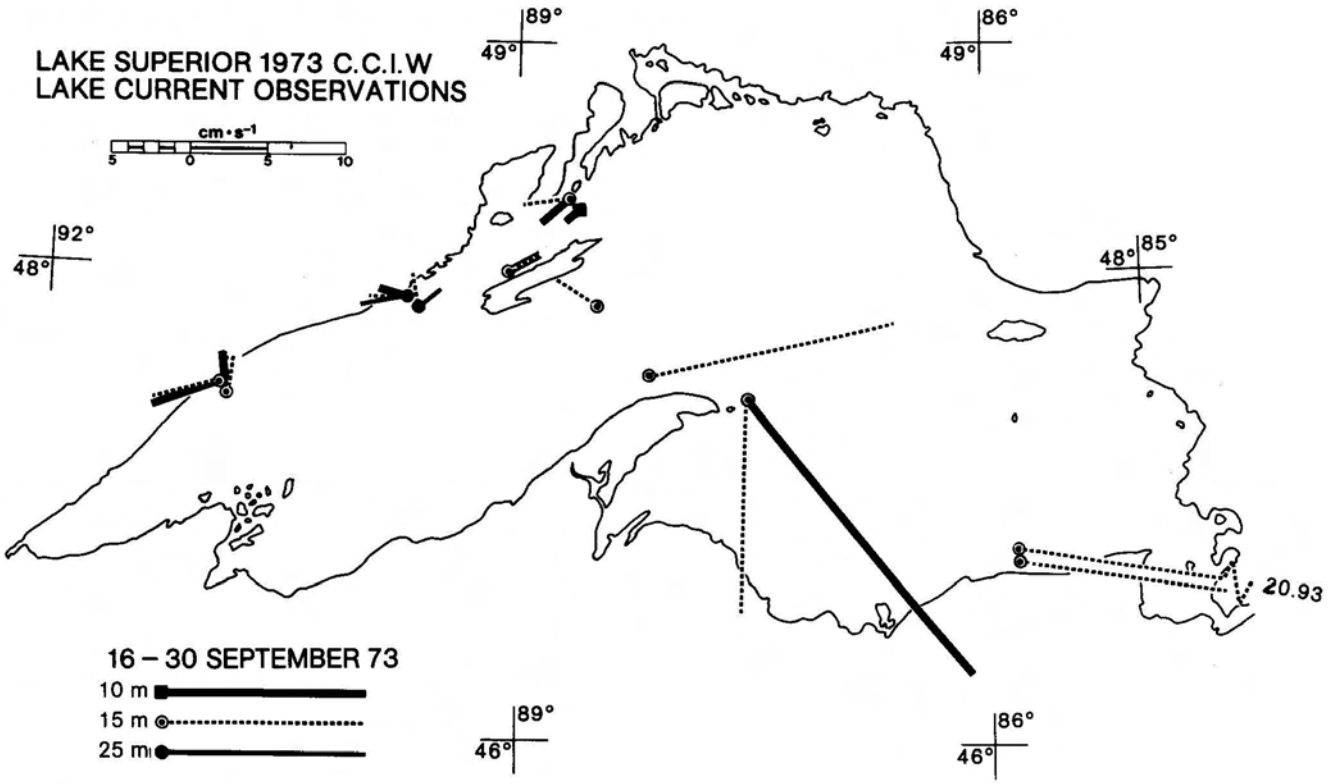

Figure 21. (CCIW) half-month average current vectors at 10, 15, and 22 m, 16-30 September 1973.

Flows along the northwest shore follow the bathymetry and are stronger than those measured by the FWPCA. Early in the season (through mid-July) the flows at CCIW station 10 were in near opposition between 15 and 25 m, indicating probable downwelling. This is particularly clear in July (fig. 16-17) when flow at station 8 was onshore while flow at station 10 divided to flow parallel to shore, westward at 15 m, but eastward at 25 m. Note also the strength measured for the Keweenaw Current.

The entire CCIW data set supports the existence of the counterclockwise circulation of the whole lake, but wide spacing and absence of data from the northeastern lake (also not well covered by FWPCA) makes verification difficult.

The relatively small current at station 5 is a residual of averaged inertial currents, which are a nearly constant phenomenon during the stratified season. For example, while the net resultant current at 15 m for station 5 averaged 2.1 cm s^{-1} for 1-15 September (fig. 20), the current speed for the same period ranged from 8 to 11 cm s^{-1} and the direction rotated clockwise through 360° each 16 hr. The average speed was thus more than four times the vector resultant average.

A possible period of downwelling is shown in figure 21, the current map for 16-30 September. Flow was toward shore at stations 6 and 8 and parallel to shore at 7 and 10. Currents between Isle Royale and Thunder Bay at stations 12 and 13 are westward, while flow at 11 is eastward.

In summary, the CCIW data show a lakewide counterclockwise flow which generally averages 5-10 cm s^{-1} and as fast as 35 cm s^{-1} in the Keweenaw Current. Flow near shore paralleled the bathymetry, while deepwater flow was dominated by inertial currents during stratified conditions.

3.4 Oscillatory Currents at Isle Royale

Interesting periodicities occurred also in the currents at stations 11, 12, and 13. These periodic components were directed parallel to bathymetry and corresponded to predicted oscillations and seiches of the lake (Rockwell, 1966; Mortimer and Fee, 1976; Rao and Schwab, 1976).

Flows in the channel between Isle Royale and the north shore of the lake oscillated in two distinct patterns. During the early part of the measurement season, the lake was thermally unstratified and spectral analysis of flows measured at stations 12 and 13 showed strong coherence between 10- and 15-m levels at periods corresponding to the uninodal longitudinal seiche, the lunar semidiurnal tide, and all periods greater than about 20 hr. The effects of surface oscillations are not generally detectable in currents, except where amplified by some sort of constriction through which an oscillatory flow is driven. The periodic current driven by the uninodal seiche is also strongly coherent between measured east-west flows at 10 m at stations 12 and 13.

Figure 22 shows the spectra of east-west oscillations for 22 May-11 August 1973 for stations 12 and 13 at 10 m. The coherence spectrum comparing the two stations clearly shows significant correlations between the measured oscillations only at line 21 (about 12.5 hr, the lunar tidal period), line 33 (about 7.9 hr, the uninodal seiche), and line 92 (about 2.8 hr). Rao and Schwab (1976) computed a period of about 2.6 hrs for a sixth mode of Lake Superior; this mode has a significant amplitude only behind Isle Royale, and no other mode except the first strongly affects that region. Rao and Schwab (personal communication) stated that their computations provided better spatial than temporal resolution and that the period of 2.8 hrs was probably correct for the sixth mode. Mortimer and Fee (1976) observed in Lake Superior water levels normal modes which had periods a few percent longer than those Rao and Schwab computed, so the observations described in the present study appear to fit the actual situation.

Figure 23 shows east-west current spectra for stations 12 and 13 at 10 m for 12 August-3 October 73. The lake had become stratified and a different oscillatory pattern dominated the currents. Inertial oscillations prevailed with an order of magnitude more energy than the seiche-driven motions. There is a suggestion of a hump in the spectrum from station 13 (closer to shore) at the 7.8-hr seiche period, but there is no coherence between stations 12 and 13 at that period. The strong coherence at the 16-hr inertial period and a relative phase of 3° between the two meters indicates that both meters were in the same rotating current cell. Inertial motions at station 12 were nearly circular; with a phase angle of 91° between northward and eastward components at a coherence of 0.949, magnitudes of the two spectral components were equal within 10 percent. Similar flows existed at station 13, which in spite of its proximity to shore was in water 142-m deep. Depth at station 12 was 195 m.

3.5 FWPCA Observations - Winter 1966-67

Monthly resultant currents were calculated for six winter meters on four moorings (locations shown on fig. 24) at winter stations 1, 2, 7, and 8. Other records were of insufficient duration or quality to be used. The data, summarized in table 2, spanned mid-October 1966 through mid-May 1967. Measured speeds were small, generally around 1 to 3 cm s^{-1}, although the monthly peak was 8.32 and a half-month value of 11.17 cm s^{-1} was recorded at station 1 at 10 m. These data were too sparse to define a circulation pattern, but the resultants generally paralleled the bathymetry, and station 1 tended to indicate a prevailing counterclockwise pattern of general circulation. The locations of moorings 7 and 8 in particular were placed out of the expected general circulation pattern and seemed to respond to eddies shed by the main flow.

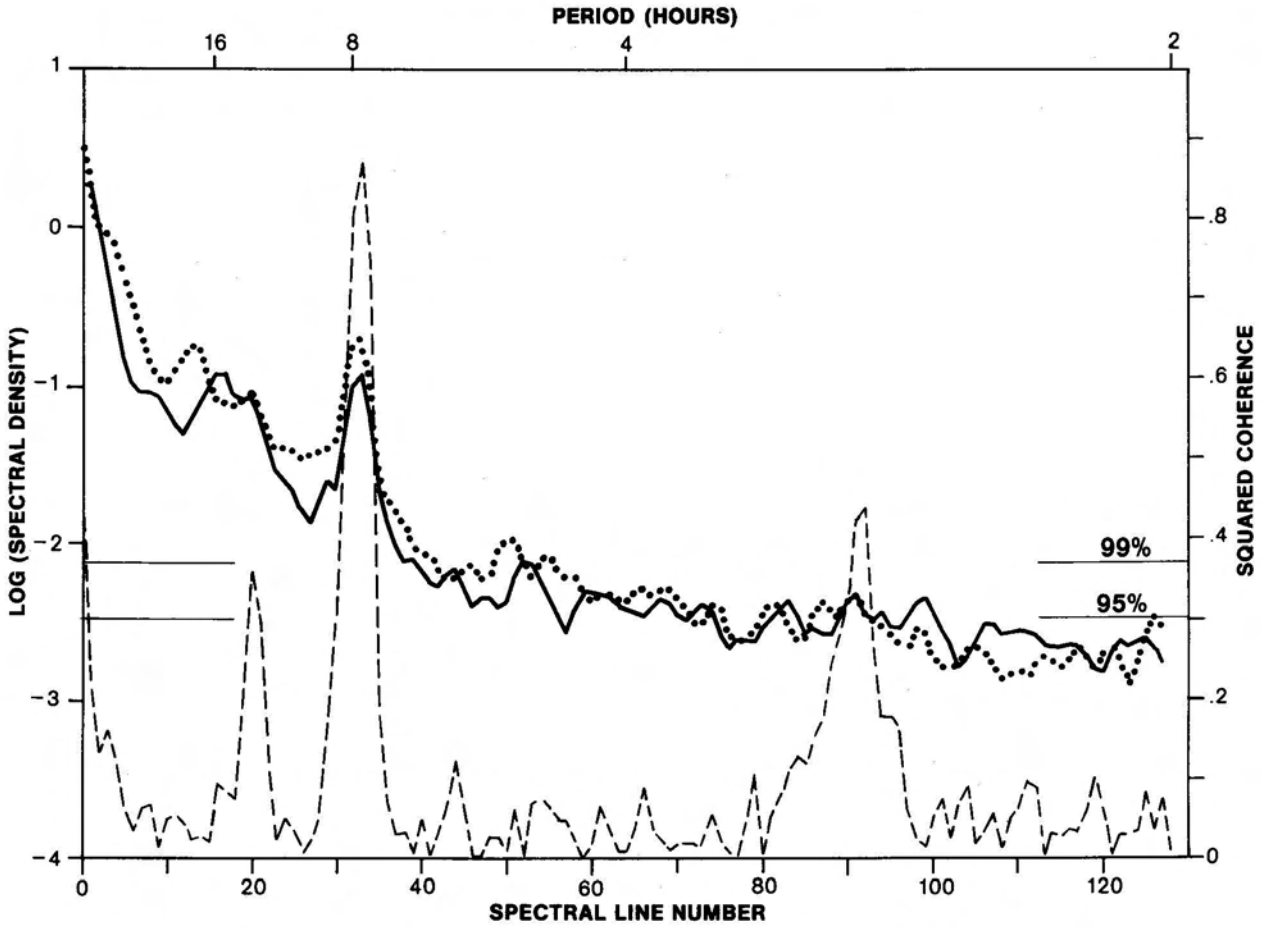

Figure 22. Spectra of the east-west current components at CCIW moorings 12 (solid line) and 13 (dotted line), depth 10 m, 22 May-11 August 1973. Broken light line is squared coherence between the two stations. Peak in coherence at 8-hr period is due to first longitudinal seiche of the lake; the peak at 2.8 hr (line 92) may be due to sixth free mode.

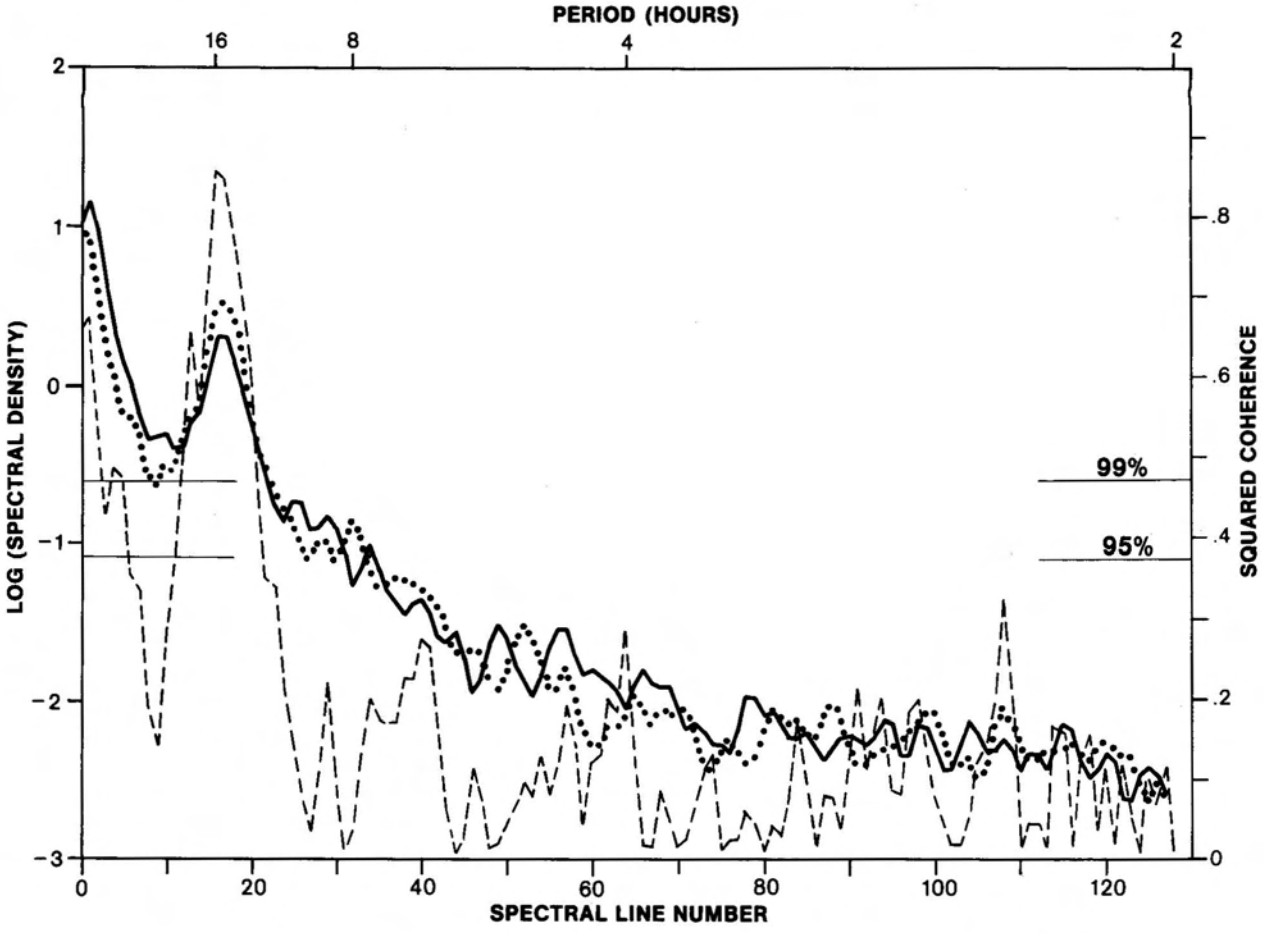

Figure 23. Same notation as figure 22, stations 12 and 13 at 10 m, east-west components, 12 August-3 October 1973. Coherence peak at 16 hr is due to inertial oscillation.

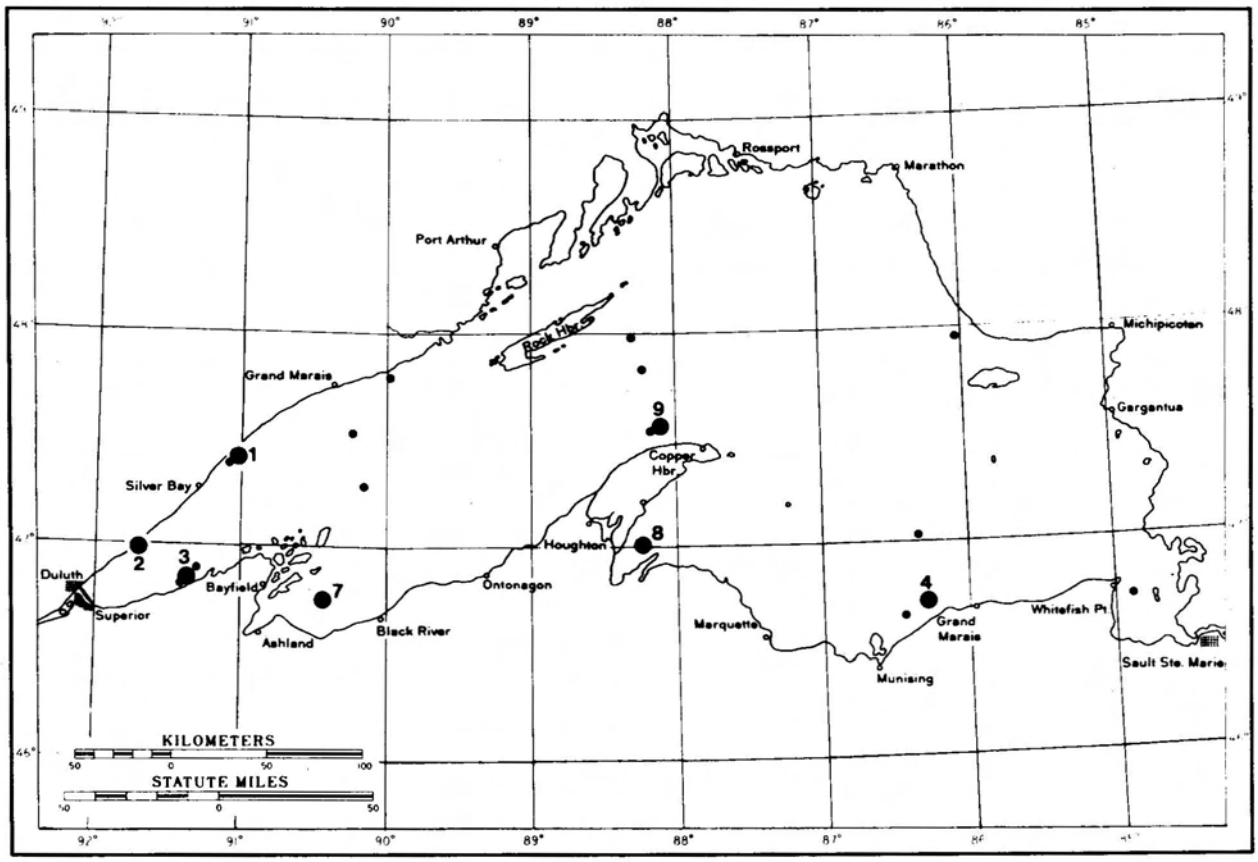

Figure 24. FWPCA winter 1966-67 mooring sites.

Table 2. (FWPCA) Current Components at Four Selected Stations (East Component Followed by North Component; Both in cm/s^{-1}; Half-Month Data in Brackets)

Date	Station	Depth 15 m	22 m	30 m	60 m
17-31 Oct. 1966	1	[-5.54, -6.37]	----	[-0.46, 4.96]	----
	2	----	----	[0.95, 2.55]	[-0.23, 2.32]
	7	----	----	----	----
	8	----	----	----	----
Nov. 1966	1	-1.02, -1.39	----	0.56, -0.28	----
	2	----	----	-0.50, 1.26	0.27, 0.55
	7	----	-0.72, 0.32	----	----
	8	----	----	-0.60, 2.85	----
Dec. 1966	1	0.22, -0.68	----	1.48, 0.90	----
	2	----	----	-0.70, 0.72	-1.11, -1.56
	7	----	0.91, -2.08	----	----
	8	----	----	-0.32, 0.19	----
Jan. 1967	1	-3.18, -4.40	----	-2.30, 1.28	----
	2	----	----	0.30, 0.42	-1.04, -1.92
	7	----	3.23, -1.76	----	----
	8	----	----	0.26, 0.72	----
Feb. 1967	1	-6.12, -5.64	----	-1.44, -0.51	----
	2	----	----	-1.99, 0.16	----
	7	----	1.00, 0.57	----	----
	8	----	----	0.02, 1.35	----
March 1967	1	-2.16, -2.08	----	-1.78, -1.48	----
	2	----	----	0.15, 2.47	----
	7	----	-0.39, 2.16	----	----
	8	----	----	----	----
April 1967	1	-1.82, -2.50	----	-1.69, -1.40	----
	2	----	----	----	----
	7	----	0.90, -0.96	----	----
	8	----	----	----	----
1-16 May 1967	1	[-4.92, -10.03]	----	[-1.08, -2.01]	----
	2	----	----	----	----
	7	----	[0.01, -0.16]	----	----
	8		----	----	----

4. REFERENCES

FWQA (Federal Water Quality Administration), 1968: Report on the water movements and temperature structure in Lake Superior based on 1966-67 field study. U.S. Dept. of the Interior, FWQA, Great Lakes Region, Chicago, IL., 66 pp.

Millar, F. G., 1952: Surface temperatures of the Great Lakes. *Jour. Fish. Res. Bd., Canada* 9:329-376.

Mortimer, C. J., and E. J. Fee, 1976: The free surface oscillations and tides of Lakes Michigan and Superior. *Phil. Trans. Roy. Soc. Lond. (A)* 281:1-62.

Rao, D. B., and D. J. Schwab, 1976: Two-dimensional normal modes in arbitrary enclosed basins on a rotating earth: Application to Lakes Ontario and Superior. *Phil. Trans. Roy. Soc. Lond. (A)* 281:63-96.

Rockwell, D. C., 1966: Theoretical free oscillations of the Great Lakes. *Proc. 9th Conf. Great Lakes Research*, Pub. No. 11, Great Lakes Res. Div., Univ. Michigan, 362-368.

Sloss, P. W., and J. H. Saylor, 1975: Measurements of current flow during summer in Lake Huron, NOAA Tech. Report *ERL 353-GLERL 5*, National Oceanic and Atmospheric Administration, Boulder, Colorado, 39 pp.

Smith, N. P., 1972: Summertime temperature and circulation patterns in Lake Superior. Ph.D. Dissertation, Univ. of Wisconsin. Univ. Microfilms, Ann Arbor, Mich., 205 pp.

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