Velocity Distribution at Two Sites Within the Southern Basin of Lake Michigan

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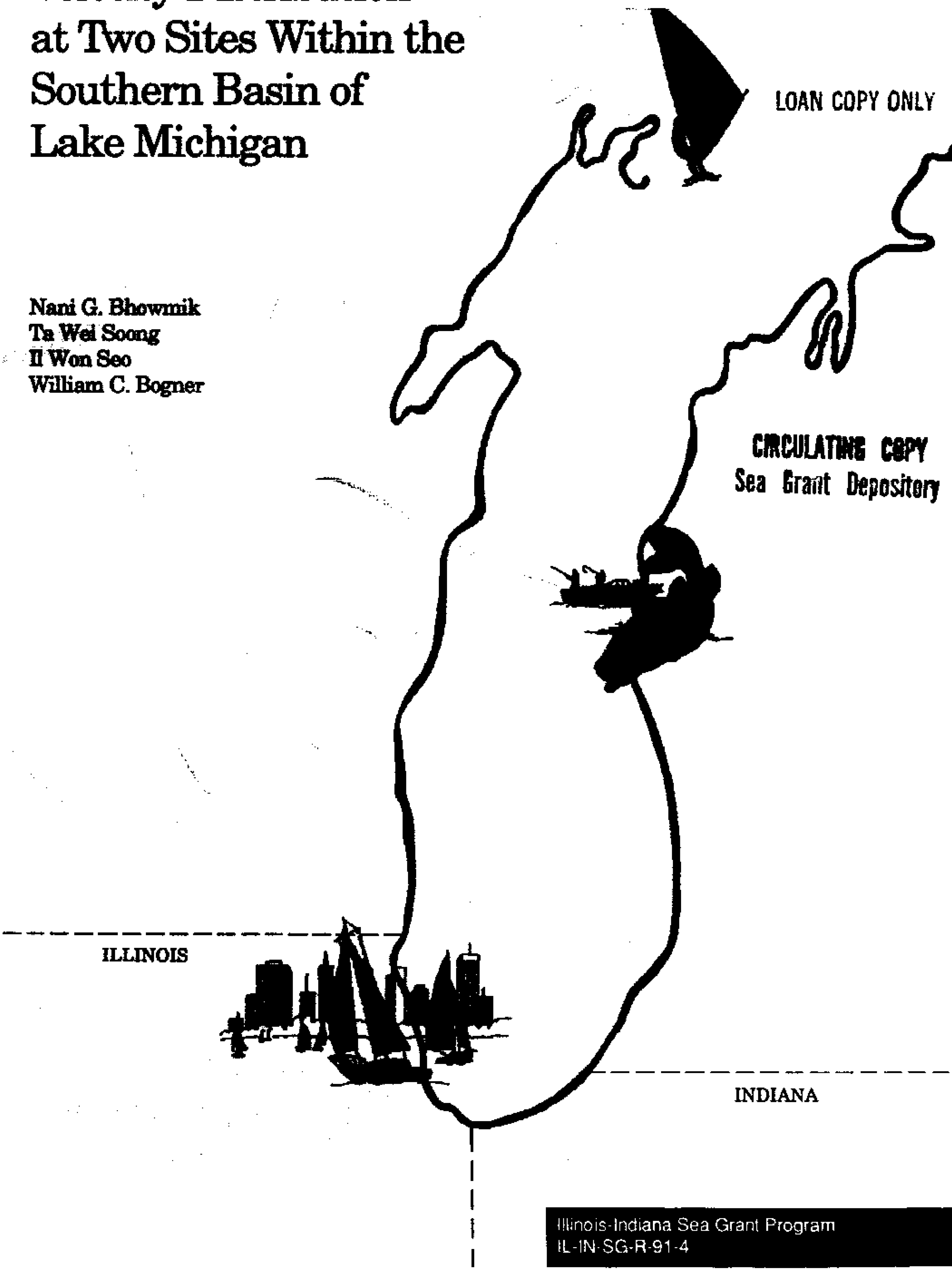

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VELOCITY DISTRIBUTION AT TWO SITES WITHIN THE SOUTHERN BASIN OF LAKE MICHIGAN

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ABSTRACT

This report summarizes data on velocity and suspended sediment characteristics near Wilmette Harbor on the southwestern shore of Lake Michigan. The report also includes analyses of velocity structure at a Lake Michigan site where 8,000-year-old tree stumps have been discovered. Data collected at the Wilmette Harbor site showed that the water normally moved in a southeasterly direction, following the shoreline. This coincides with the existence of a classical longshore current pattern. Much greater fluctuations were found at the nearshore station than at the farshore station. Suspended sediment concentrations did not show much variation over the three-day data collection period. The bed materials at the site ranged from fine to very fine sand sizes.

Data from the tree stump site, collected during a four-week period, showed at least three peaks in water temperature. The average velocity was about 2.6 centimeters per second, and the current rotated by about 360° within a period of four to five days. It appears that eddies with longitudinal diameters of several kilometers may occur at this site on a regular basis. However, no further generalized statements can be made because of the unavailability of detailed long-term velocity data for the site.

KEYWORDS: Lake Michigan, Suspended Sediments, Tree Stump Site (Lake Michigan), Velocity, Water Circulation

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INTRODUCTION

The southwestern basin of Lake Michigan has been subjected to extreme stresses because of its close proximity to large population centers. A variety of conflicting demands are made on the lake waters and shores by the citizens living near the area. Uses include water supply, real estate development, industry, recreation, boating, commerce, waste dilution and disposal, and drainage. About 8 million people living along approximately 105 miles of Illinois-Indiana shores may also be responsible for inadvertent alteration of natural processes in this area.

The conflicting demands placed on the lake are threatening this irreplaceable resource. Lake management should be designed so that Lake Michigan's resources are used in the most effective way. Management designs would benefit tremendously from a thorough and detailed evaluation of the physical processes associated with the southwestern basin of the lake. But while information is available on wave-induced current inside the surf zone and on mid-lake circulation, adequate information is not available on the longshore current pattern in the nearshore zone. Longshore currents can transport and disperse sediment and other pollutants. Evaluations of excessive beach erosion, shore stability, transport of organic and inorganic materials, dilution and dispersion of inflows, and enhancement or deterioration of aquatic habitats (including habitats for both macro- and microinvertebrates) all require a clear understanding of the longshore transport processes in this basin.

Waves, wind, and density differences are the major forces in the development of nearshore currents. Storm episodes can introduce short-term changes in the current field, but long-term persistent longshore circulation may also exist, as evidenced by Blanton's (1974) study on Lake Ontario. Csanady (1972a,b) investigated nearshore currents in Lake Ontario and concluded that stratification, inertial acceleration, bottom topography, and friction may all be important in the boundary region. However, very little solid data and information are available on the actual magnitude, duration, and direction of longshore currents within the southwestern basin of Lake Michigan. Even though some theoretical work has been done on the prediction of longshore currents, the discrepancies between mathematical and physical descriptions of wave- and wind-generated circulation should be resolved with measured data.

In recognition of these needs, the Illinois State Water Survey proposed a pilot research project involving collection and analyses of a basic set of data on velocities, suspended sediments, and bed materials. Subsequently, the Illinois-Indiana Sea Grant Program office supported this pilot project with funding of $11,820 for a period of two fiscal years. With this support, a set of data was collected near Wilmette Harbor in September 1989. Subsequent to this project, other researchers studying Lake Michigan asked the Water Survey researchers to collect additional data on circulation patterns near the site of recently discovered 8,000-year-old tree stumps. With the assistance of researchers from Northeastern Illinois University and the Illinois State Geological Survey, Water Survey engineers collected velocity data from the tree stump site for about four weeks in June and July 1990. All the data for the two sites have been analyzed, and this report has been prepared to present the data. Some generalized conclusions were drawn on the basis of this limited amount of data. However, seasonal and spatial variations in velocity structure could not be determined from the limited amount of available data. To understand the patterns, distribution, and magnitudes of current/circulation within the southern basin of Lake Michigan and to develop a predictive mathematical model, an additional comprehensive data collection program must be implemented for a longer period. Only after such a database has been generated can an existing or modified hydrodynamic model be calibrated and verified for application within this basin.

Such a model or models, once calibrated and verified, will enable management authorities to formulate decisions and management criteria related to lakeshore protection methodologies; locations, sizes, and patterns of jetties and breakwaters; and patterns, distribution, and movements of fish and other aquatic organisms dependent upon the longshore currents.

BACKGROUND

Water uses in the nearshore zone of the southwestern Lake Michigan basin include public water supply, recreation, fishing, boating, and navigation. In some areas the nature and quantity of incoming pollutants are unknown, as are the physical processes that transport these materials. Water quality managers must understand the patterns, distribution, and movement of water in this area in order to develop strategies that can protect this important natural resource from existing and potential contamination. Until now, however, data and engineering findings have been scattered. Many contaminant transport studies have been based on hypothetical flow patterns because physical processes in this area have not been adequately investigated. The current status of our knowledge is revealed in the following review of physical measurements and theoretical developments.

Many physical measurements and mathematical modeling efforts have been carried out in an attempt to reveal the complex circulation patterns in the Great Lakes. These efforts have focused on lakewide circulation; however, nearshore currents are dynamic and can have different structures from lakewide circulation patterns. Data from Lake Ontario showed a rather clear separation between "wave-like" circulation offshore and the more "current-like" circulation in the nearshore zone (Csanady, 1972a,b). On the basis of such data, Csanady has characterized a zone extending approximately 10 kilometers (km) offshore as a coastal boundary layer. Blanton (1974) conducted measurements in the same area and found that variations in flow tended to decrease with depth and with distance offshore; the nearshore current responded to wind with less time lag than offshore current; current in the nearshore zone was more or less rectilinear and contained little energy in rotary-type motion; and there was a predominant westward flow. Because of variations in basin shapes and orientations to the prevailing wind direction, research results from other Great Lakes cannot easily be generalized to Lake Michigan circulation patterns (Pickett, 1983). Moreover, current in the nearshore zone is further modified by topographical features and by the shoreline geometry.

Investigators such as Allender et al. (1981) and Schwab (1979) have studied aspects of nearshore flow patterns. Other research studies on the contaminant transport processes of Lake Michigan include those of Harrsch and Rea (1982) on suspended sediment composition and distribution during summer stratification; Rossmann (1980a) on soluble element concentrations; Rossmann (1980b) on the inorganic chemistry of particulate matter; Quigley and Robbins (1984) on silica regeneration processes; Parker et al. (1982) on sorption and sedimentation of zinc and cadmium; Bell and Eadie (1983) on suspended particles during an upwelling event; Eadie et al. (1984) on resuspension and chemical flux; Lauritsen et al. (1985) on distribution of oligochaetes; and McCown et al. (1978) on transport of oily pollutants. Linking the derived flow-field data with the sediment transport process will enable resource managers to conduct numerical simulations and use the results for a multitude of applications. However, a previous attempt by Paddock and Ditmars (1981) to link a sediment model with a model for wave-induced nearshore circulation (Allender et al., 1981) was not successful because the required computational time prevented the use of an adequate simulation period.

Argonne National Laboratory has carried out several measurement efforts to determine longitudinal variations of velocity in the nearshore zone of Lake Michigan between Chicago and Milwaukee (Saunders, 1977a,b,c, 1978a,b,c; Saunders and Van Loon, 1976; Saunders et al., 1976). Transverse current data were also measured at Waukegan, Illinois, by Allender et al. (1981). However, the emphasis of this measurement was the circulation patterns inside the breaker zone. Velocity, temperature, and wave characteristics were measured within 200 meters (m) offshore. The only other solid data that are available are those collected by the present researchers.

DATA COLLECTION

WILMETTE HARBOR SITE

The initial set of data on nearshore current, suspended sediment, and bed material characteristics was collected from a site near Wilmette Harbor in Lake Michigan (Figure 1). Velocity data were collected by using a pair of S4 two-dimensional current meters manufactured by InterOcean Systems. As described by the manufacturer, the InterOcean Systems Model S4 current meter is intended for measurement and recording of horizontal water currents. The unit is self-contained, small, and has a spherical shape, with no protruding sensors. This simplicity results in a low-drag instrument suitable for use on shipboard while providing ruggedness and ease of handling for the user. The mounting rod allows for taut-line mooring or mounting to a fixed structure. It is suited to any freshwater or saltwater environment at depths to 1,000 m.

Figure 2 shows the S4 meters that were used in this project. The S4 measures current by creating a magnetic field and sensing the voltage induced by the movement of water through the field. A CMOS microprocessor acquires instrument orientation from a flux-gate compass and computes earth-referenced current components in north and east coordinates. These current vectors are then recorded immediately (burst sample mode) or integrated over time and recorded (vector-averaged mode). All data are recorded in non-volatile solid-state memory.

Initialization and data retrieval were accomplished by using a field computer connected through an InterOcean Model S110 interface unit to the watertight input/output connector on the S4. The S4 has automatic data compensation for tilt angles of up to 45° from the vertical. These units can also measure conductivity, temperature, and depth. All sensors are mounted in the interior or on the surface to avoid any projection on the sphere.

In the field, the current meters were mounted on aluminum bases and installed 1 meter above the bases (Figure 2). Lead weights were added to the bases to maintain the stability of the units. The meters were programmed to collect velocity data in north and east components.

As shown in Figure 3, the meters were installed at depths of about 2.1 and 5.2 m and were 107 and 213 m from shore, respectively. The S4s were programmed to run continuously so that all the data collected would have a complete time history for the monitoring period, except for times when the data were downloaded.

Data on suspended sediment concentrations and bed materials also were collected. The location of the suspended sediment sampling tower relative to the S4 meters is shown in Figure 3. Figure 4 shows a photograph of a pair of sediment sampling towers of the same type, with standard suspended sediment nozzles attached to them. The nozzles on the towers are connected with tubing to pumps operated by marine cell batteries and located on a boat anchored near the towers. The pumps are manufactured by Instrument Specialties Corporation (ISCO) and have been used quite extensively in studies of open-channel flow. All the pumps are programmed to collect water-sediment samples at predetermined intervals. Researchers from the Water Survey have developed these types of sediment sampling techniques for a number of major projects on the Mississippi and Illinois River systems, and they have worked out exceptionally well.

Bed material samples were collected from four different locations at the Wilmette Harbor site: two sites close to the two S4 meters, one near the suspended sediment sampling tower, and one in between the S4 meters. The approximate locations of these sampling sites are shown in Figure 3.

A recording wind set also was installed at the site (see Figure 1), and data on wind velocity and directions were collected during the daylight hours only. A staff gage installed at the site was read frequently to determine the relative elevation of the lake level during the data collection period. The data collection at this site was conducted on September 19-21, 1989. All the data were analyzed in mid-1990 because of the nonavailability of funds in Calendar Year 1989.

TREE STUMP SITE

Early in 1990, the Water Survey was contacted by researchers from Northeastern Illinois University and the Illinois State Geological Survey to explore the possibility of collecting long-term velocity data near the site of 8,000-year-old tree stumps within the southern basin of Lake Michigan, about 15 miles east of Chicago. Because of keen interest by the Water Survey researchers and the extreme cooperation extended by Northeastern Illinois University and the State Geological Survey in providing the necessary diving facilities, the Water Survey researchers installed one S4 meter near the tree stump site for the period June 14 through July 9, 1990.

During this period, the meter was programmed to collect velocity data for about nine days at a time. At the end of this period, the meter was retrieved, the data were downloaded on a boat at the site, the data collection routine was reprogrammed, and the meter was redeployed at the same site. At the end of the data collection period, all the velocity data were processed and analyzed for inclusion in this report.

The tree stump site is located in about 23 m of water and is about 24 km from the shore within the southwestern basin of Lake Michigan. Figure 5 shows a sketch of the approximate setup for this data collection effort.

ANALYSES OF DATA

WILMETTE HARBOR SITE

Wind

Wind data collected at the Wilmette Harbor site show that on the average wind velocities ranged from 2.68 m/s (6 mph) to 4.02 m/s (9 mph). The wind blew from southeast to northwest.

Lake Levels

Figure 6 shows a plot of lake levels, as measured by staff gages during the data collection period. Some variations in lake levels were observed at this site, ranging in magnitude from about 0.03 to 0.06 m. Figure 7 shows the water depths measured above the S4 meters. These plots indicate that the lake level showed some decrease on the third day of data collection. Local wind conditions were not sufficient to initiate such a drop in water level. However, the overall wind conditions within the basin could have initiated this drop. On the other hand, the overall wind setup, wave setup, or lake-level fluctuations due to atmospheric pressure fluctuations or seiches could be the source of such lake-level drops. These fluctuations do not appear to have any significant impact on the circulation patterns observed at this site.

Bed Materials

Twelve bed material samples were collected from the site. The locations of the four sampling sites are shown in Figure 3. At each location, one sample was collected on each of the three days of the monitoring period, and the samples were analyzed to determine particle size distributions. Parameters such as the standard deviation (σ) and the uniformity coefficients (U) for the bed materials were computed on the basis of the particle size distribution curves.

$$\sigma = \frac{1}{2} \left[\frac{d_{84.1}}{d_{50}} + \frac{d_{50}}{d_{15.9}} \right] \tag{1}$$

$$U = \frac{d_{60}}{d_{10}} \tag{2}$$

where $d_{84.1}$, d_{60}, d_{50}, $d_{15.9}$, and d_{10} are the diameters of the bed materials for which 84.1, 60, 50, 15.9, and 10% of the particles, respectively, are finer.

Table 1 shows the d_{50} and d_{85} sizes of these samples with their corresponding values of σ and U. Figure 8 shows the particle size distributions for all twelve samples. An examination of these plots shows that almost all of these particles are within the fine to very fine sand ranges and also that they are uniform in size. Low values of σ and U also attest to the uniform nature of these particles. For all practical purposes the median diameter, d_{50}, of all the particles can be assumed to be about 0.12 millimeters (mm).

Table 1. Characteristics of the Bed Material Samples at the Wilmette Harbor Site.

Sample location	Date	d_{50}	d_{85}	σ	U
Near deep-water S4	9-19-89	0.11	0.16	1.37	1.73
	9-20-89	0.11	0.16	1.34	1.63
	9-21-89	0.12	0.15	1.29	1.65
Between two S4s	9-19-89	0.12	0.16	1.32	1.59
	9-20-89	0.12	0.15	1.28	1.59
	9-21-89	0.12	0.15	1.28	1.59
Near shallow-water S4	9-19-89	0.11	0.15	1.29	1.50
	9-20-89	0.11	0.15	1.29	1.46
	9-21-89	0.11	0.15	1.29	1.41
Near sediment intake tower	9-19-89	0.13	0.20	1.45	1.67
	9-20-89	0.13	0.20	1.45	1.67
	9-21-89	0.17	0.25	1.59	2.00

Note: d_{50} and d_{85} = diameters of bed materials (in mm) for which 50 and 85% of the particles are finer; σ = standard deviation; U = uniformity coefficient.

Suspended Sediments

A total of 144 suspended sediment samples were collected from two intakes on the sediment sampling tower, one located 0.15 m above the bed (Intake A) and the other located 0.15 m below the water surface (Intake B) as shown in Figure 3. All the samples were collected with ISCO pump samplers, and laboratory analyses were performed to determine the sediment concentrations of these samples.

Figure 9 shows plots of the sediment concentrations for various time intervals on all three days. An examination of this figure indicates that on September 19, suspended sediment concentrations varied from about 6 mg per liter (mg/l) to as much as 94 mg/l or more at Intake A, and from 6 to 38 mg/l at Intake B. The highest concentrations were observed to occur near the bed. Suspended sediment concentrations at both intakes on September 20 ranged from about 2 to 9 mg/l, with the majority of the concentration staying close to 3 to 4 mg/l. The suspended sediment concentrations at both intakes were more or less uniform on this day. On September 21, both intakes showed a slight increase in sediment concentrations, which varied from about 1 to about 15 mg/l. However, on this day, the sediment concentration at Intake B (located close to the water surface) generally showed the existence of a plume of higher sediment concentration than was observed 0.15 m above the bed.

These changes in sediment concentrations at the two intakes are contrary to the general observations normally made in cases of open-channel flow problems, where higher concentrations of sediments are normally observed near the bed. This flip-flop in sediment concentration gradients between September 19 and September 21 could have been caused by disturbances introduced at other places. It is quite possible that the overall circulation patterns within the southern basin of Lake Michigan did in fact resuspend large amounts of fine sediments, which remained in suspension near the water surface. This situation shows the difficulty that may arise when conclusions are made about sediment movement solely on the basis of areal distribution of sediment and/or turbidity plumes. In any case, turbidity is merely an optical property of the water, and a correlation between turbidity and sediment concentrations may or may not exist in actual field conditions. Determination of suspended sediment concentrations in the nearshore zone is an important goal for future study.

Water Temperature

Both S4 meters were programmed to measure water temperatures at two-minute intervals for the duration of the monitoring period. Figure 10 shows plots of water temperature at the Wilmette Harbor site for all three days. Obviously, both meters showed diurnal variations in temperatures. The shallow-water meter and deep-water meter showed increases in temperature in the daytime to about 19.3°C and decreases to about 18.6°C at night. However, the variations in temperature at the deep-water site were somewhat less than those at the shallow-water site. It is apparent that the meter located in the shallower water responded to variations in ambient air temperatures, which would not have been the case for the meter installed at the deeper site.

Velocity

Two-dimensional velocity data were collected at two sites by using the InterOcean S4 current meters. Characteristics of the velocities in both directions were analyzed to determine the general flow patterns at these locations. Parameters such as standard deviations, turbulence intensity, and direction and magnitude of the resultant velocity were computed. Other analyses included a preliminary determination of the alongshore, onshore, and offshore movement of flows. One velocity data sample was collected every second during daylight hours. During evenings and nights, one sample per two seconds was collected at Station A and one sample per five seconds was collected at Station B.

For the data analysis, a 15-minute time interval was selected and the mean velocities in both directions over this specified time period were computed by Equations 3 and 4. These types of equations have been discussed in books such as those by Daily and Harleman (1966) and Tennekes and Lumley (1972).

$$V_x = \frac{1}{T} \int_0^T v_x \, dt \tag{3}$$

$$V_y = \frac{1}{T} \int_0^T v_y \, dt \tag{4}$$

where v_x and v_y are two components of velocity in the Cartesian coordinate system, and T is the averaging time period. V_x and V_y are the average velocities in the x and y directions for the time period under consideration. The magnitude ($|V|$) and direction (θ) of the mean velocities were computed as follows:

$$|V| = \sqrt{V_x^2 + V_y^2} \tag{5}$$

$$\theta = \text{Arctan} \; \frac{V_x}{V_y} \tag{6}$$

The standard deviation for velocity is computed by Equation 7:

$$\sigma = \left(\frac{1}{T} \int_0^T (v - V)^2 \, dt\right)^{1/2} \tag{7}$$

where v is the magnitude of the instantaneous velocity. The turbulence intensity is computed by the relationship $\sigma/|V|$ where $|V|$ is as defined by Equation 5.

A computer analysis program (LAKMIC) was coded by using FORTRAN 77 programming language, and computation was implemented on the University of Illinois CONVEX computer to determine various parameters.

Characteristics of Measured Velocity

For the analysis of circulation patterns at the Wilmette Harbor site, velocity was measured at intervals of 1, 2, and 5 seconds, and the results were plotted. Typical plots are given in Figure 11. One can observe that the magnitude and direction of the resultant component of the instantaneous velocity vary quite significantly with time, especially at Station A, the nearshore station (see Figure 1).

At Station A, the velocity vectors change rather drastically, but in general, the flow directions are mainly toward the east to southeast. These large fluctuations in magnitude and direction may be associated with a combination of circulation patterns in the nearshore zone and wave action in this area. At Station B (farshore station), the velocity vectors indicate a dominant southeast movement without significant variations. The current pattern at this station has less fluctuation than that at Station A. A relatively uniform drift apparently exists at

Station B. One should remember that Station B is located farther from the shore and also in deeper water.

Characteristics of Mean Velocity

Mean velocities were computed by Equations 3 and 4, and the relative intensity of the turbulence was computed by using parameters derived from Equations 5 and 7. All these values were averaged over 15-minute periods. Two different types of plots were made to study mean velocity patterns: plots of resultant mean velocity in polar coordinates, and plots of resultant mean velocity with time. Typical plots in polar coordinates are given in Figure 12. Examples of time-history vector plots are given in Figure 13.

As shown in Figures 12 and 13, the directions of mean velocity at Station A vary significantly, even though the dominant direction is southeast. The 15-minute averaged data should have removed most of the instantaneous responses due to wave actions. However, residuals of wave and wind activity are still visible at this station. The vector plots indicate that, in general, deviations from the dominant direction increase during daylight hours and decrease at night. This can be explained by the fact that wind and wave actions, which are major causes of water movement in this nearshore zone, are generally greater during the daytime than at night. Variations in velocity are smaller at Station B (farshore station) than at Station A, and the dominant direction of the velocity vectors is southeast. As at Station A, fluctuations in mean velocity are greater during daylight hours than at night.

To obtain quantitative descriptions of velocity, some basic analyses were conducted on the mean velocity data. Median and mode were used in this study to represent the average values of velocities for this data set. Median is defined as the value that equally divides a set of observations displayed in ascending order. Mode is defined as the value that occurs most frequently in a distribution. Arithmetic mean was not computed because mean velocities are all vector quantities. Frequency histograms of the magnitude and direction of the resultant velocity are given in Figures 14 and 15, respectively, and median and mode values of the frequency distributions are given in Table 2.

Table 2. Median and Mode of the Frequency Distributions of Velocity Data at Stations A and B, Wilmette Harbor Site.

Average	Station A	Station B
	Magnitude of Resultant Velocity (cm/sec)	
Median	1.137	1.518
Mode	1.033	1.313
	Direction of Resultant Velocity (degrees)	
Median	133	142
Mode	110	137

As shown in Figures 14 and 15, distributions at both stations are positively skewed with longer tails to the right, i.e., both velocity magnitude and direction have a high probability of exceeding the mean values. Table 2 indicates that medians for both the magnitude and direction of the resultant velocity at both stations are greater than the respective modes, which is expected because of the skewed distributions at both stations.

Comparisons of the average values for the magnitude and direction of the resultant velocity at these two stations indicate that velocity is greater at Station B (farshore) than at Station A (nearshore), and that the directional deviation of velocity from magnetic north is also greater at Station B than at Station A. On the basis of these data, the circulation pattern in the southwestern basin of Lake Michigan near Wilmette Harbor during the measurement period can be characterized as follows: The water is flowing from the northwest to southeast, with magnitudes primarily varying around 1 centimeter per second (cm/sec) at Station A and around 1.3 cm/sec at Station B. This means that water is flowing faster at Station B than at Station A. Also, the direction of flow at Station A is in between southeast and east, whereas the direction of flow at Station B is close to southeast. This might be explained by the fact that at Station A (nearshore), the circulation pattern is complex, with high fluctuations due to complicated current action (alongshore, onshore, and offshore currents), and the magnitude of the velocity is reduced by these complex water movements. Moreover, the velocity at Station A may also be impacted by the presence of a jetty about 50 to 75 m south of it. But at Station B (farshore), the circulation pattern is uniform, following the pattern of the coastal currents, which normally flow only along the shore.

An analysis of the time-series characteristics of the velocity data collected at these two stations was also done. Time series are defined as sets of quantitative readings of some variable or composite variables which are observed or recorded in time (Yevjevich, 1972; Chao, 1974). Time series are composed of either deterministic or stochastic series. Deterministic series can be described by an explicit mathematical relationship, whereas stochastic series must be described in terms of probability statements and/or statistical properties rather than by explicit equations (Bendat and Piersol, 1986). Individual deterministic series are further categorized as being either periodic or non-periodic. Stochastic series are classified as stationary or non-stationary. Specific time-series analyses especially related to autocorrelations were used to examine the collected velocity data. Discussions of these analyses are given in the following paragraphs.

Time-history plots of the magnitude of the resultant velocity at both stations for September 19-21 are given in Figure 16. Data gaps caused by the downloading of data were filled by using a quadratic seven-point moving-average method so trends could be preserved. As shown in the figure, velocities at both stations show some short-term fluctuations. Roughly speaking, some daily cyclic variations are found for both data sets, i.e., higher velocities occur during daytime and lower velocities are recorded during night hours. This might be explained by the previously noted fact that wind and wave actions, which are the main causes of water movement, are generally stronger during daytime than at night. Autocorrelation analysis is frequently used to investigate the sequential properties of time series (Yevjevich, 1972). It is used to determine the linear dependence among the successive values of a series that are separated by fixed time lags. The autocorrelation coefficient, ρ_T, is given (Yevjevich, 1972) as:

$$\rho_\tau = \frac{\text{cov}\,(X_t, X_{t+\tau})}{\text{var}\,X_t} \tag{8}$$

in which $\text{cov}(X_t, X_{t+\tau})$ = covariance of X_t and $X_{t+\tau}$, and is given as

$$\text{cov}(X_t, X_{t+\tau}) = \frac{1}{T-\tau} \int_0^{T-\tau} (X_t-\mu_t)\,(X_{t+\tau}-\mu_t)\,dt \tag{9}$$

in which T = length of a time series; τ = time lag; and μ_t = the expected value (average) defined as

$$\mu_t = \frac{1}{T} \int_0^{T} X_t\,dt \tag{10}$$

The variance, var X_t, is given as

$$\text{var}\,X_t = \frac{1}{T} \int_0^{T} (X_t-\mu_t)^2\,dt \tag{11}$$

Autocorrelation coefficients were computed for both stations by using Equation 8. The correlograms (plots of autocorrelation coefficients versus time lag) are given in Figures 17 and 18. In these correlograms, the heights of the bars represent the estimated correlation coefficient; the dashed lines are plotted at zero plus and minus twice the standard errors for each coefficient. These boundaries are useful for determining the time lag beyond which all correlations are not significantly different from zero.

The autocorrelation function plots in Figure 17 indicate that neither the magnitude nor the direction of the velocity is stationary. At Station A, resultant velocity remains correlated for three to four lags (45 minutes to one hour), but after that time period very little correlation remains. The direction of velocity, however, is correlated over longer time periods, which indicates that the changes in direction are gradual. The correlogram shows a dampening similar to that in a sine wave. The correlogram for direction of velocity at Station B (Figure 18b) is very similar to that for Station A, except that the magnitudes are smaller. The resultant velocity at Station B (Figure 18a) demonstrates stronger sequential dependence and has an exponential decay pattern. Comparison of the two correlograms for resultant velocity shows that the autocorrelation coefficients of the resultant velocity at Station A decay much faster than those for Station B. This means that the velocity magnitudes at Station A fluctuate much faster than those at Station B. None of these time series are stationary in nature.

Turbulence Intensity

Time-history plots of the relative turbulence intensities at both stations are given in Figure 19. As shown in this figure, very high spike-like fluctuations of the turbulence intensity are observed in both data sets over short-term periods during daylight hours. Similar to the velocity data, some daily cyclic variations are found for both data sets, i.e., higher turbulence intensities occur during daytime, and lower and almost constant turbulence intensities are recorded during nighttime. This can be explained by the fact that turbulence intensities are closely related to the velocity fluctuations, which are much stronger during daytime than at night. Comparison of the two plots in Figure 19 indicates that the turbulence intensities measured at Station A are much higher than those at Station B.

Alongshore, Offshore, and Onshore Currents

The velocity data collected at these two stations were also analyzed to determine the magnitudes of the alongshore and offshore currents. These two components of velocity normally determine how and where sediment and other suspended and dissolved materials will disperse. This type of analysis is also important for determining the frequency of beach nourishment, since some of the beach materials will be transported either along or away from the shoreline. At the same time it should be pointed out that if a dominant component of flow toward the shore exists, the nourished beach may maintain a stable beach form for a longer period of time. Efficient spur dikes can be designed once a clear knowledge of the longshore currents is available.

As defined here, an alongshore component has a positive axis deviating 60° from north to west, and an offshore component is assumed to be normal to this axis (Figure 20). Thus the alongshore current is approximately parallel to the shoreline, and the offshore component is perpendicular to the shoreline. Along the offshore axis, positive direction represents offshore velocity and negative direction represents onshore velocity. The alongshore currents at both stations are plotted in Figure 21. These plots are for 15-minute averaged data. Missing data are filled in by using a quadratic seven-point moving-average method, as discussed previously.

One can observe from Figure 21 that the current had a tendency to flow toward the southeast (negative) direction except during a few short periods where water moved in a northwest direction. These deviations were primarily found during the daytime; therefore a comparison with wind strength was made. A peak northwest (positive) current occurred around noon on September 20 at Station A, while a similar peak current occurred at Station B around 2:00 p.m. An examination of the wind data (Table 3) reveals that between 10:00 a.m. and 3:00 p.m. on September 20, winds were relatively strong - around 4.02 meters per second (m/s), or 9 miles per hour (mph) - and blew in the positive alongshore direction (northwest). During this time period, alongshore components at both stations showed a movement from the negative (southeast) direction to the positive (northwest) direction. With a decrease in wind speed and direction after 3:00 p.m., the alongshore current at Station A reversed its direction, showing a movement toward the southeast. A comparison of the flows between Stations A and B shows that the flow was rotating in a counter-clockwise direction between these two stations.

When the wind strength was less than 3.12 m/s (7 mph), the alongshore current did not show a reversal of direction. Assuming that the wind characteristics measured by the wind station were fairly uniform for the local area, one can postulate that the current movement at Station A responded to wind stress more quickly than that at Station B.

Table 3. Characteristics of Wind at the Wilmette Harbor Site.

Time (hour)	Wind Speed (mph)	Wind Direction (degrees)	Alongshore (mph)	Offshore (mph)	Angle/ shore (degrees)
September 19					
1530	9.0	129	-8.89	1.41	189
1538	10.3	123	-10.29	0.54	183
1555	8.8	116	-8.78	-0.61	176
1612	10.6	116	-10.57	-0.74	176
1619	10.2	115	-10.16	-0.89	175
1632	10.2	110	-10.05	-1.77	170
1640	8.9	111	-8.79	-1.39	171
1650	7.1	110	-6.99	-1.23	170
1700	7.8	108	-7.63	-1.62	168
1710	9.5	104	-9.13	-2.62	164
1719	7.8	107	-7.60	-1.75	167
1730	8.2	111	-8.10	-1.28	171
1740	8.9	112	-8.81	-1.24	172
1750	9.1	111	-8.99	-1.42	171
1819	9.3	119	-9.30	-0.16	179
1830	9.7	133	-9.45	2.18	193
September 20					
940	4.6	130	-4.53	0.80	190
1140	9.8	134	-9.51	2.37	194
1215	8.9	134	-8.64	2.15	194
1350	9.1	138	-8.65	2.81	198
1410	8.6	134	-8.34	2.08	194
1435	9.0	146	-8.09	3.95	206
1455	3.2	91	-2.80	-1.55	151
1543	4.5	79	-3.40	-2.95	139
1608	5.6	80	-4.29	-3.60	140
1700	5.4	78	-4.01	-3.61	138
1710	5.1	80	-3.91	-3.28	140
September 21					
940	2.5	85	-2.05	-1.43	145
1014	3.8	98	-3.52	-1.42	158
1040	4.0	86	-3.32	-2.24	146
1130	6.6	102	-6.28	-2.04	162
1200	7.2	105	-6.95	-1.86	165
1230	5.0	95	-4.53	-2.11	155
1305	7.0	118	-7.00	-0.24	178
1335	7.6	116	-7.58	-0.53	176
1500	4.8	108	-4.70	-1.00	168
1555	8.6	96	-7.86	-3.50	156
1635	6.8	102	-6.47	-2.10	162
1700	6.9	95	-6.25	-2.92	155
1705	6.5	99	-6.07	-2.33	159
1710	8.2	93	-7.31	-3.72	153

Note: 1 mph = 0.447 m/s

Correlograms for alongshore components at both stations are given in Figure 22. The relatively high, positive correlation coefficients indicate that the alongshore components are highly correlated from one time period to the next. Both of the time series are nonstationary and show a gradual dampening similar to that in a sine wave. The plot for Station B suggests that velocity patterns may reoccur after about 10 to 12 hours.

Figure 23 shows the offshore velocity components measured at Stations A and B. At both stations, currents fluctuated between onshore and offshore directions, with the major tendency averaging out around the zero velocity line. The near-zero average of the offshore component indicates that up/downwelling did not occur at this site during the time of measurement. On the other hand, the winds played a governing role in generating on/offshore current patterns. The directions and magnitudes of the offshore velocity component can be directly correlated with the wind strength presented in Table 3. Correlograms for the offshore components at both stations are presented in Figure 24. Again the correlations for three or four lags (45 minutes to one hour) are high at both stations. Both offshore velocity correlograms demonstrate the combination of exponential decay (up to 15 lags) and sinusoidal wave decay (after 15 lags). This characteristic is not shown to be present for the alongshore component.

Other analyses that were performed included determination of the variance and energy content of the velocities measured at these two stations. In general, the shallow-water meter at Station A showed more variance in velocities than was observed at Station B. Again, this is similar to the variability observed at this station for turbulence intensity. This comparison also shows that the circulation patterns close to the shore are more subject to local topographic variations, wind stresses, and local conditions than are zones located farther from the shore. At deeper portions of the lake, the circulation patterns are probably well established and remain fairly steady for longer periods of time.

TREE STUMP SITE

At the tree stump site, velocity data were collected for approximately four weeks, from June 14 through July 9, 1990. Only one S4 current meter was available for measurements at that time. This S4 was fix-mounted on an aluminum base 1 m above the bottom at a depth of 23 m. The sampling interval of the S4 at this site was set at 30 seconds. Water depths, temperature, and conductivity were noted every hour (instantaneous values). Because of the deep water deployment, information on suspended sediment concentrations and bed materials was not collected. Velocity data collected at the tree stump site were analyzed according to the procedures outlined previously for the Wilmette Harbor site.

Water Temperature

Figure 25 shows the variations in water temperature observed during this period. For the first eight to nine days of data collection, the temperature at the meter site remained more or less constant at a value close to 7°C. Then starting on about June 23, the temperature at the 23 m depth increased gradually to about 11°C by June 24 or 25, after which it decreased gradually to about 8°C on June

27. The temperature showed increases twice during the next two-week period. It appears that a cyclic variation of water temperatures existed at this location, with cycles of about four to five days. These changes in temperatures could be caused by density currents within this basin. Long-term data on temperatures and current patterns would show whether temperature changes do initiate density currents at this site and, if so, the relative magnitudes of these induced density currents. The water surface elevations did not show much change during the time of measurement.

Velocity

Raw velocity data for two four-hour periods (time-averaged over 30-second intervals) are shown in Figure 26. Mean velocities for the entire data set, time-averaged over 15-minute intervals by using Equations 3 and 4, were computed. The magnitude and direction of the resultant components of the mean velocities and the relative intensity of the turbulence were also computed by using Equations 5 through 7. All the velocity data are shown in Figure 27 in vector plots. Velocities shown in this figure are the progressive 15-minute average resultant velocity and direction for the period June 14 - July 9, 1990. The directions of the velocity vectors vary significantly, ranging from southwest to northwest. Over a four- to five-day period, flow rotates completely by 360° in a clockwise direction. This flow reversal has been observed in other parts of Lake Michigan by several other researchers (Gottlieb et al., 1989a,b). An explanation of this flow reversal (e.g., Mortimer, 1978) is that local flow consists of three types of water movement: inertial rotating flow, seiche, and local unidirectional flow. The superposition of these types of water movement (Figure 28) can produce a flow reversal.

As found for the velocity vectors measured at the Wilmette Harbor site, velocity vectors at the tree stump site vary quite significantly with time. Frequency analyses and other descriptive statistical analyses were conducted to determine frequency distributions for these data. Median and mode were used to represent averages for these velocity vectors. Frequency histograms of the direction and magnitude of the resultant velocity are given in Figures 29 and 30, respectively, and median and mode values are given in Table 4. Both distributions are skewed, and the dominant direction of the velocities is about 240 - 300° north. This indicates that water was primarily flowing toward the lakeshore in a southwesterly direction. The dominant magnitude of the resultant velocity ranged from 1 to 4 centimeters per second.

Table 4. Median and Mode of the Frequency Distributions of Velocity Data at the Tree Stump Site.

	Magnitude (cm/sec)	Direction (degrees)
Median	2.60	242
Mode	2.39	278

Figure 31 shows a time-history plot of the resultant velocity (time-averaged over 15-minute intervals) collected from June 14 to July 9, 1990. As shown in this figure, velocity varied significantly during this particular period. Some daily cyclic variation can be identified during the early stage of the data collection period. The mean velocity increased during daylight hours and decreased during the nights. Such fluctuations suggest that at this depth, the water movements are affected by wind and other factors. The water temperature did not fluctuate during this specific time (Figure 25). As stated previously, the temperature stayed relatively low between June 14 and June 22, when the magnitudes of flow were relatively high. A flow rotation occurred on the afternoon of June 18 (Figure 27), which did not appear to be related to the changes in temperature. On the afternoon of June 22, the velocity started to increase (Figure 31b) and flow directions started to change (Figure 27). At this time the water temperature also showed an increase (Figure 25), which may have been responsible for the initiation of a density current at this location. However, after June 23, water temperature at the site remained higher than in the earlier period, with somewhat lowered velocities. Thus the flow pattern measured at this site may be influenced by a variety of external forces which cannot be evaluated at this time on the basis of this limited set of data.

To evaluate the sequential properties of the velocities, autocorrelation analysis was performed on the resultant velocities and their angular deviations from north. The correlograms for the resultant velocity are shown in Figure 32 (note that lags have been converted to days). As shown in this figure, both the magnitude and direction of the resultant velocity are non-stationary. The correlogram for resultant velocity has an exponential decay and indicates positive correlations for periods of about one hour. On the other hand, for the direction of velocity, the correlogram demonstrates a sinusoidal wave pattern and the magnitude does not dampen quickly. A recurrence pattern exists in resultant velocity which suggests that there may be a large rotating flow field which traverses this area at intervals of about six to seven days. However, the correlation coefficient is small, and a definitive statement on this situtation cannot be made. Figure 32 shows that the directions of the flows exhibit a cyclic pattern, with cycles of about 36 hours. Also, it is quite possible that the direction of the flow may be repeated after about 4-1/2 days.

Turbulence Intensity

A time-history plot of the turbulence intensity is given in Figure 33. As shown in this figure, very high, spike-like fluctuations occurred. As with the velocity data for the Wilmette Harbor site, some daily cyclic variations were found at this location, but these are not as dominant as those observed at the Wilmette Harbor site.

SUMMARY

This report summarizes the data collected in Lake Michigan near Wilmette Harbor in 1989 and near the site of 8,000-year-old tree stumps in 1990. Data on velocities were collected from both sites by two-dimensional electromagnetic current meters. At the Wilmette Harbor site, data on suspended sediment and bed materials were also collected.

The suspended sediment concentrations at the Wilmette Harbor site did not show much variation over the data collection period. However, on the last day of data collection, suspended sediment concentrations near the water surface were slightly above the sediment concentrations near the bed, indicating the presence of fine sediments that may have been suspended at a location close to the site. The bed materials at this site are mostly in the fine to very fine sand ranges.

Analyses of the two-dimensional velocity data collected at the Wilmette Harbor site indicated that the current pattern at the nearshore station is very complex. This pattern is closely related to the existence of onshore and offshore currents due to wave action, as well as to the longshore current in the nearshore zone. At the farshore station, the current pattern is very similar to that of the coastal currents that flow roughly parallel to the shore and constitute a relatively uniform drift in the deeper water. At both stations, water flows from northwest to southeast, with magnitudes primarily varying around 1 cm/sec at the nearshore station and around 1.3 cm/sec at the farshore station. The resultant velocities show both short-term fluctuations and daily cyclic variations, i.e., higher velocities occurring during daytime hours and lower velocities occurring during nighttime hours. Comparison of the autocorrelation coefficients at the two stations indicates that fluctuations (variations) in velocity at the nearshore station have shorter durations than those at the farshore station.

Analyses of the two-dimensional velocity data collected at the tree stump site indicated that the average velocity at this site for the four-week period was 2.6 cm/sec and the average direction of flow was westward. Over a four- to five-day period, the direction of flow rotated completely by 360° in a clockwise direction. On the basis of the average velocity and the frequency of velocity rotations, it is estimated that these eddies have longitudinal diameters of several kilometers. At this site, the resultant velocities show weekly cyclic variations, with cycles of about six to seven days. Velocities also showed daily cyclic variations similar to those observed at the Wilmette Harbor site.

Data from the tree stump site showed at least three peaks in water temperature during the data collection period. However, no correlation was found between the temperature peaks and the altered velocity structures. These daily changes are thought to be related to the daily fluctuations of wind and other induced stresses. However, because of the short duration of data collection, no detailed evaluation of the interrelationships between various parameters could be developed. Research such as this needs to be conducted for a longer period of time, with detailed velocity data collected from an array of current meters installed in at least three different sites in a triangular pattern. This would enable the researchers to systematically evaluate two- and three-dimensional circulation patterns and their implications for lake circulation and the transport of solid and dissolved materials.

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APPENDIX. FIGURES 1 THROUGH 33

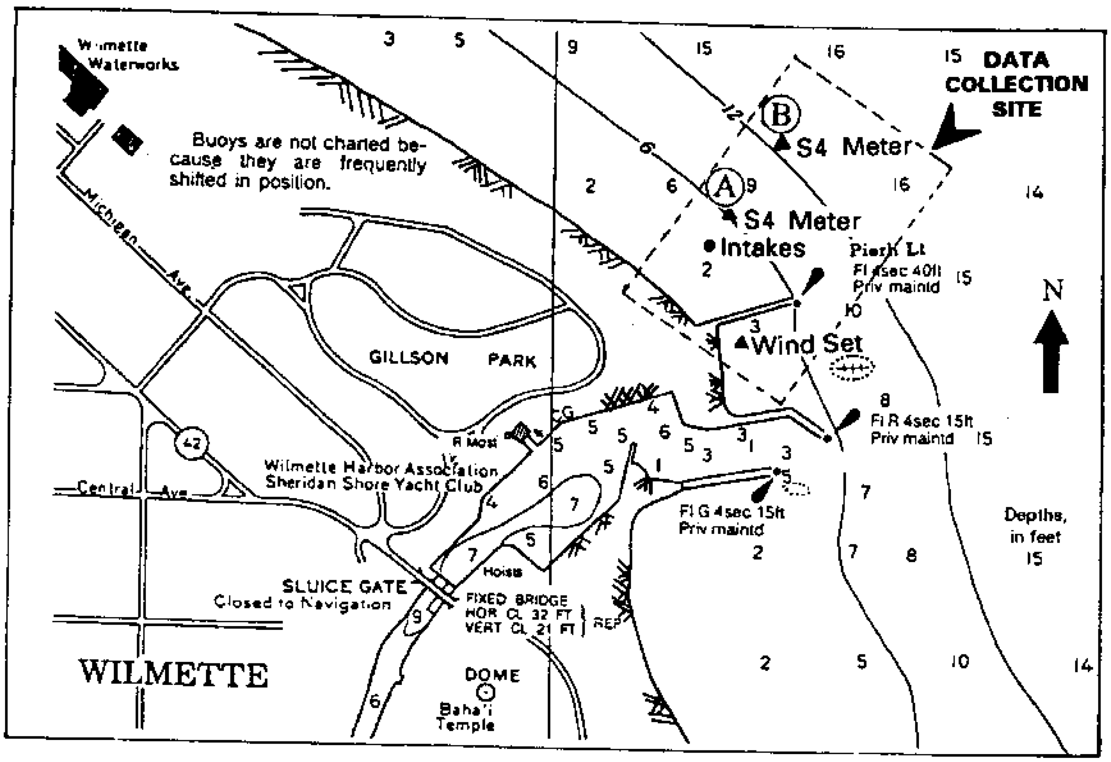

Figure 1. Data Collection Site near Wilmette Harbor

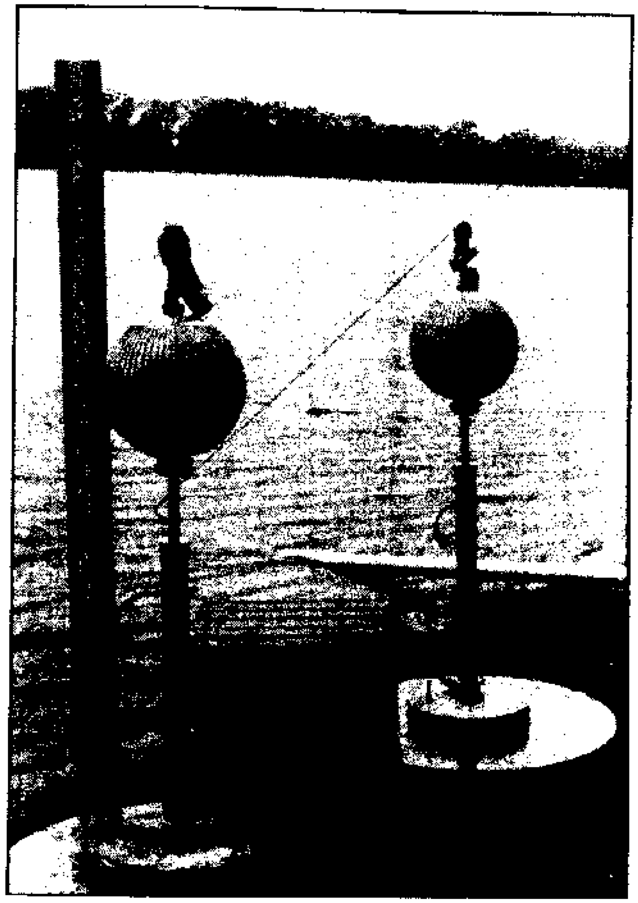

Figure 2. S4 Meters with Mounting Bases

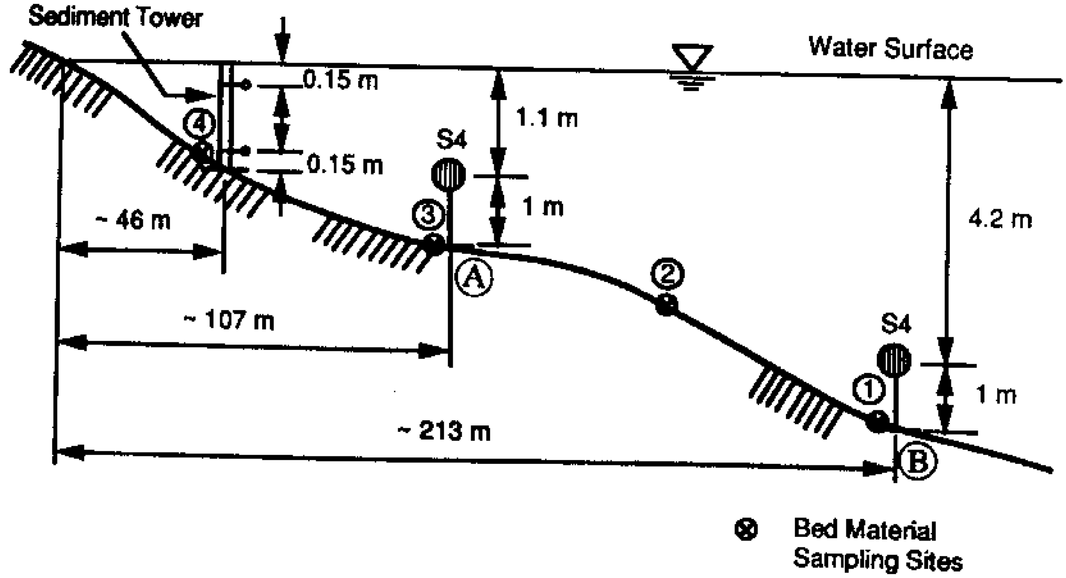

Figure 3. Locations of S4 Current Meters, Sediment Sampling Tower, and Bed Material Sampling Sites, Wilmette Harbor Site

Figure 4. Suspended Sediment Sampling Towers

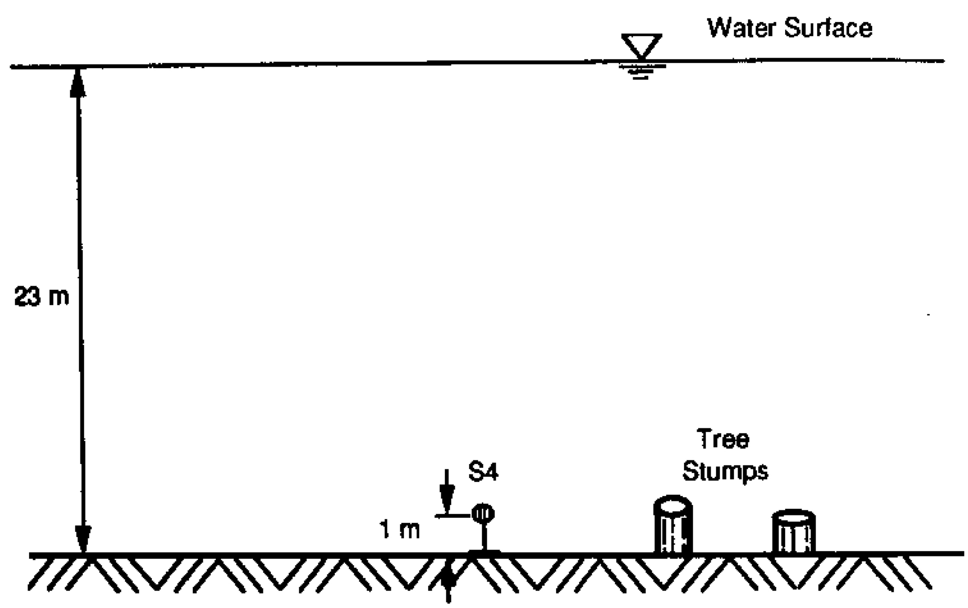

Figure 5. Schematic Diagram Showing the Installation of an S4 Current Meter at the Tree Stump Site

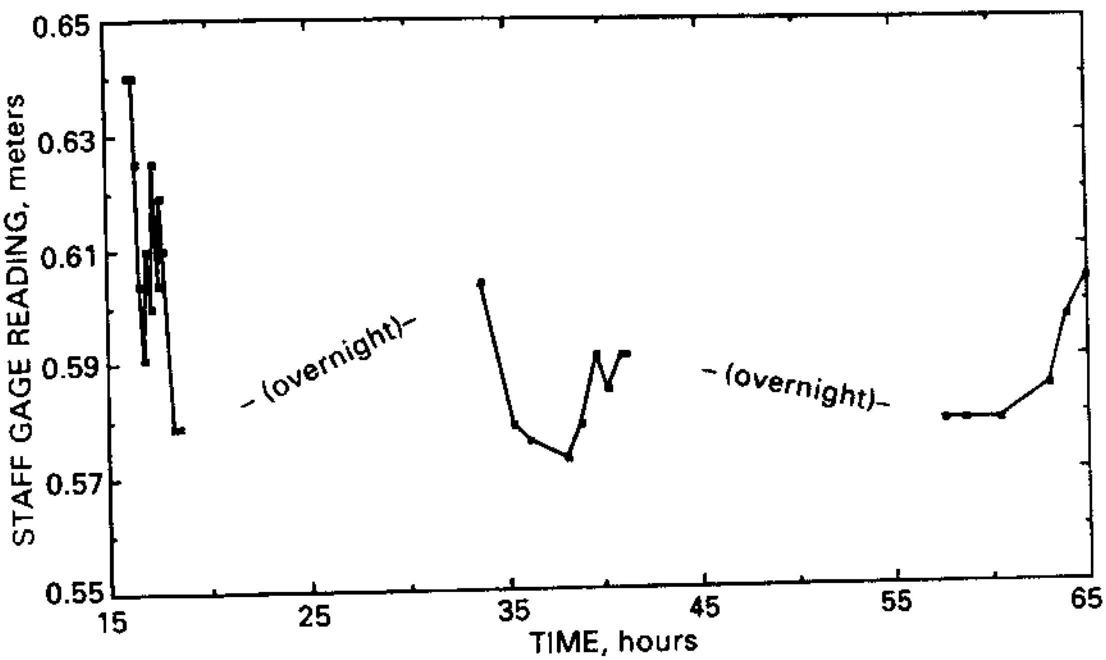

Figure 6. Lake-Level Changes at the Wilmette Harbor Site, September 19-21, 1989

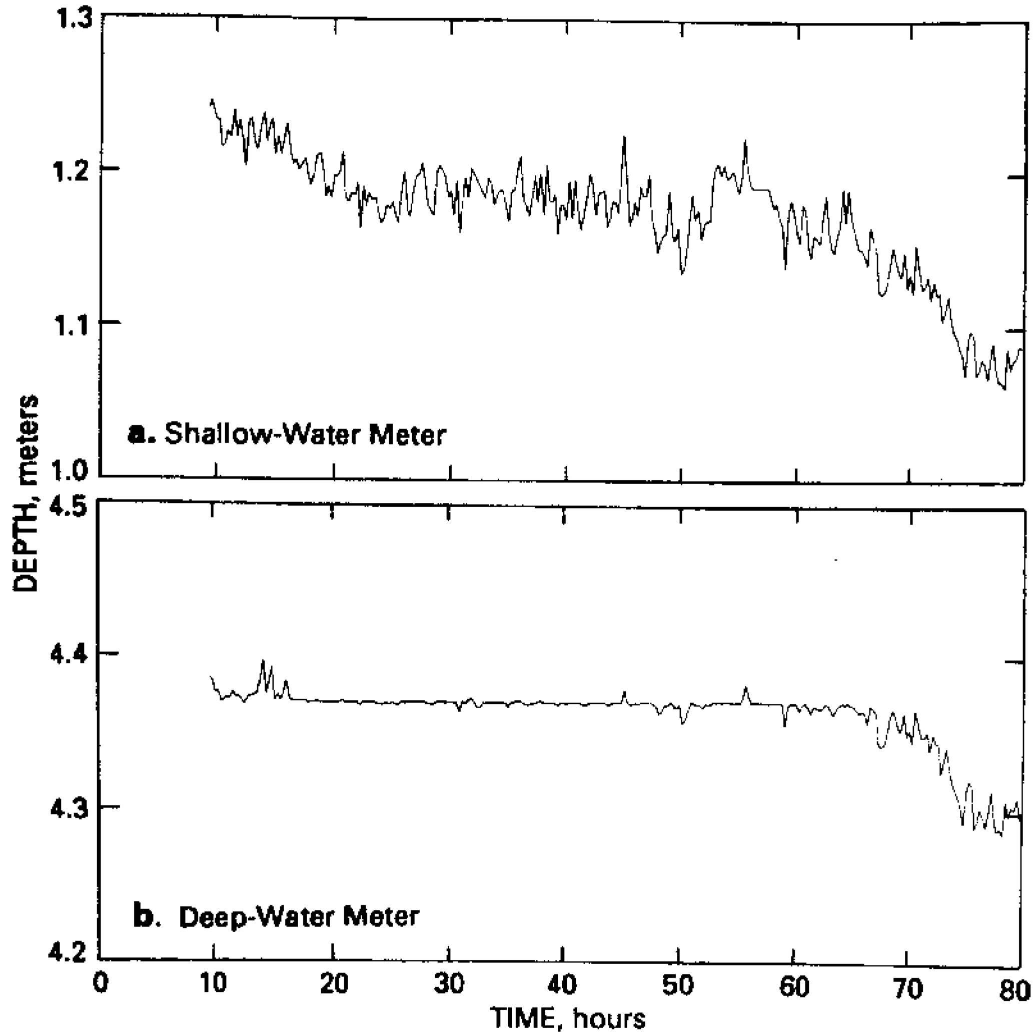

Figure 7. Changes in Water Depths near the S4 Meters, Wilmette Harbor Site

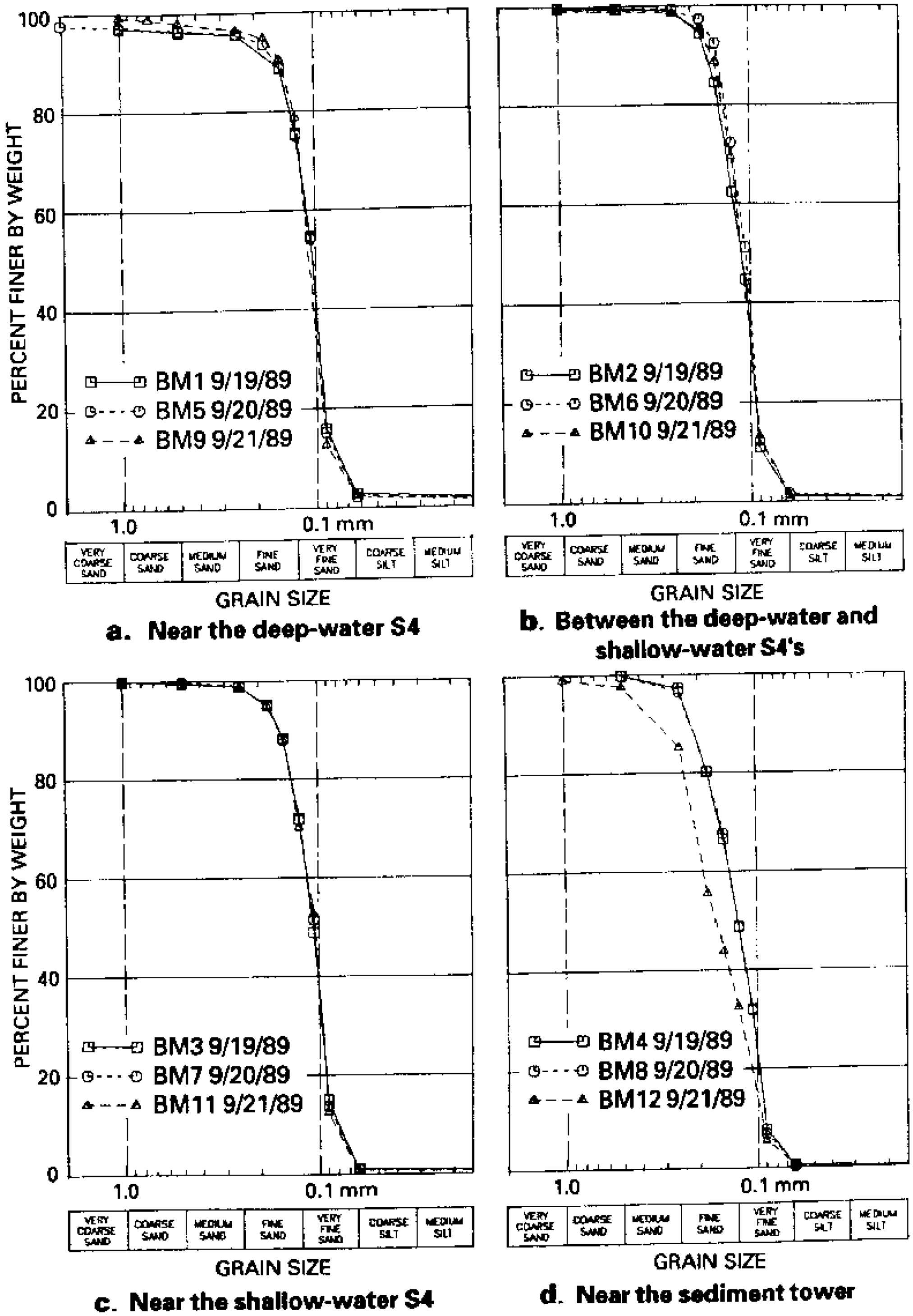

Figure 8. Particle Size Distributions of the Bed Materials, Wilmette Harbor Site

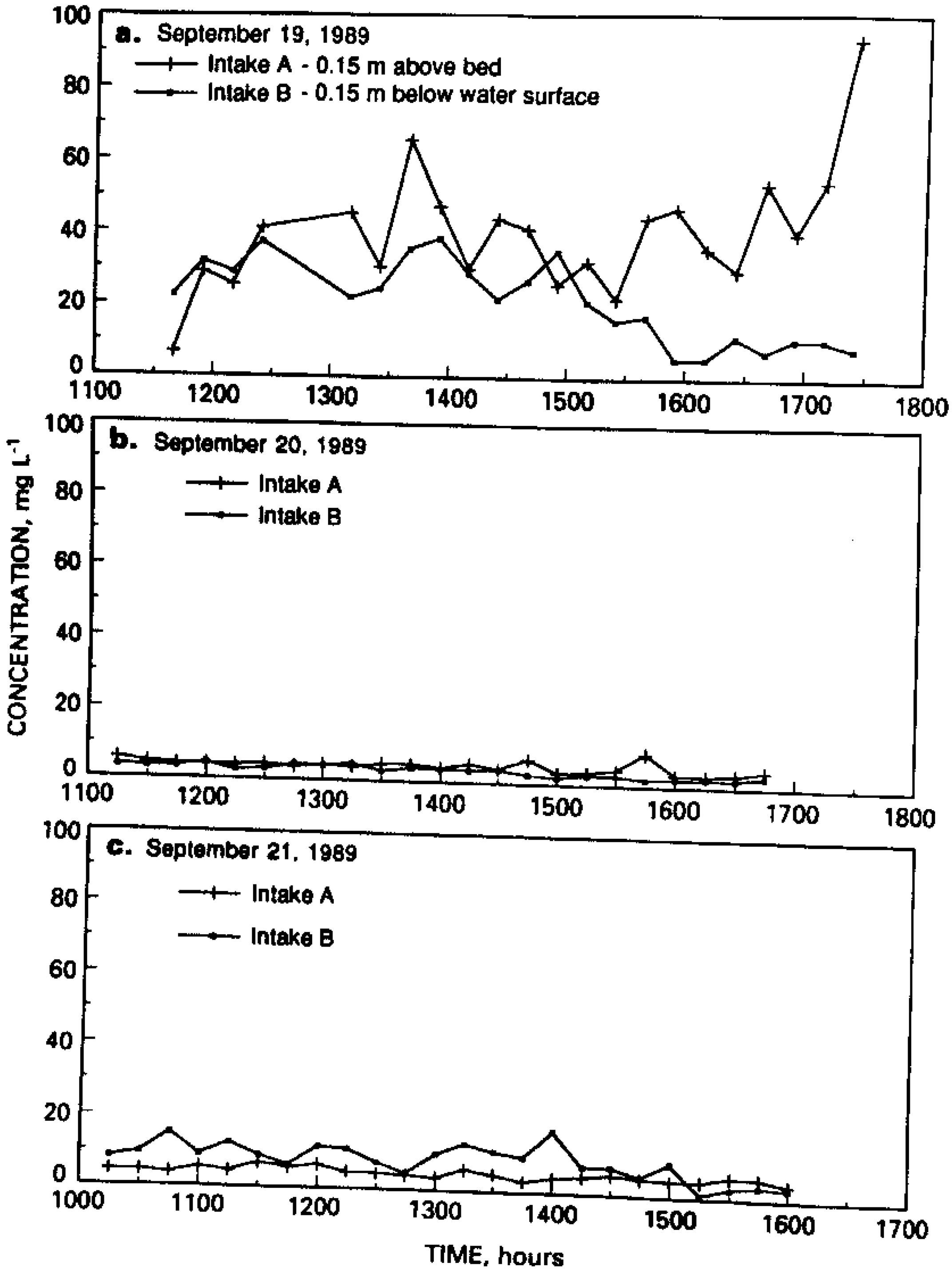

Figure 9. Distributions of Suspended Sediment Concentrations at the Wilmette Harbor Site, September 19-21, 1989

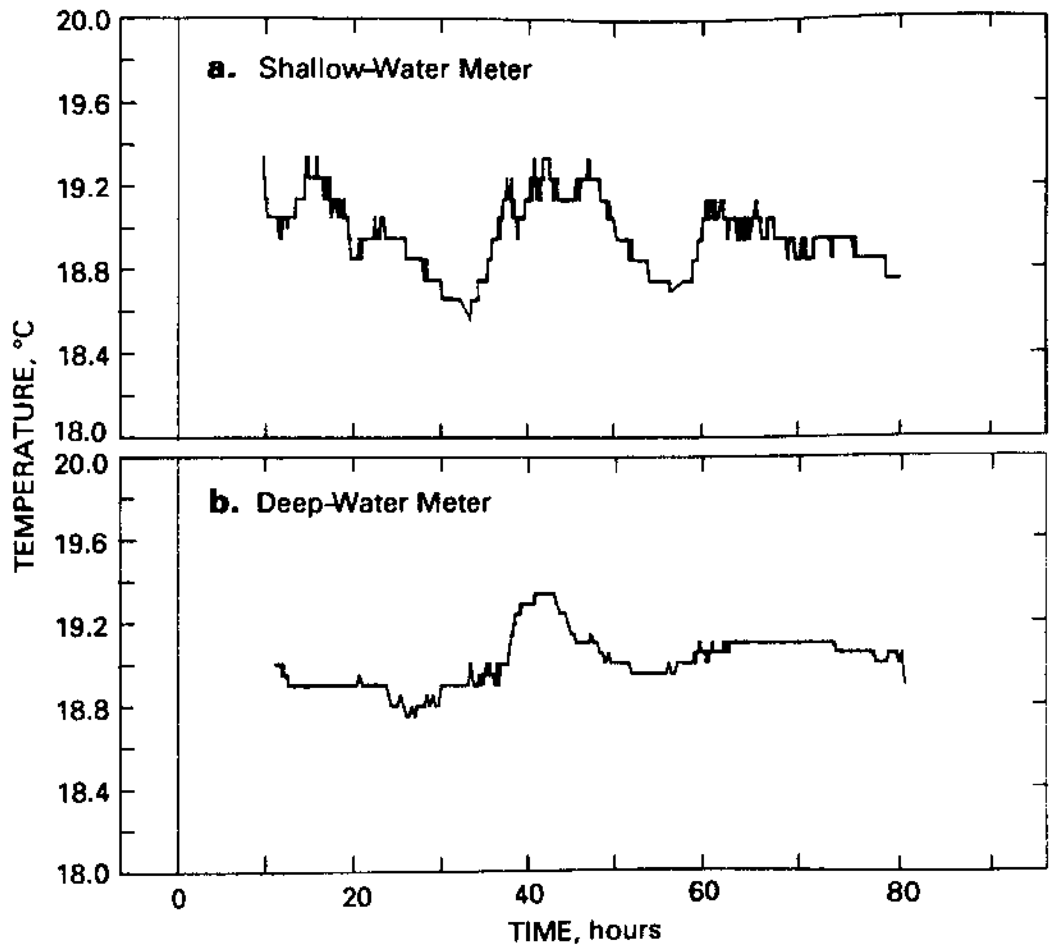

Figure 10. Variations in Water Temperature near the S4 Meters, Wilmette Harbor Site

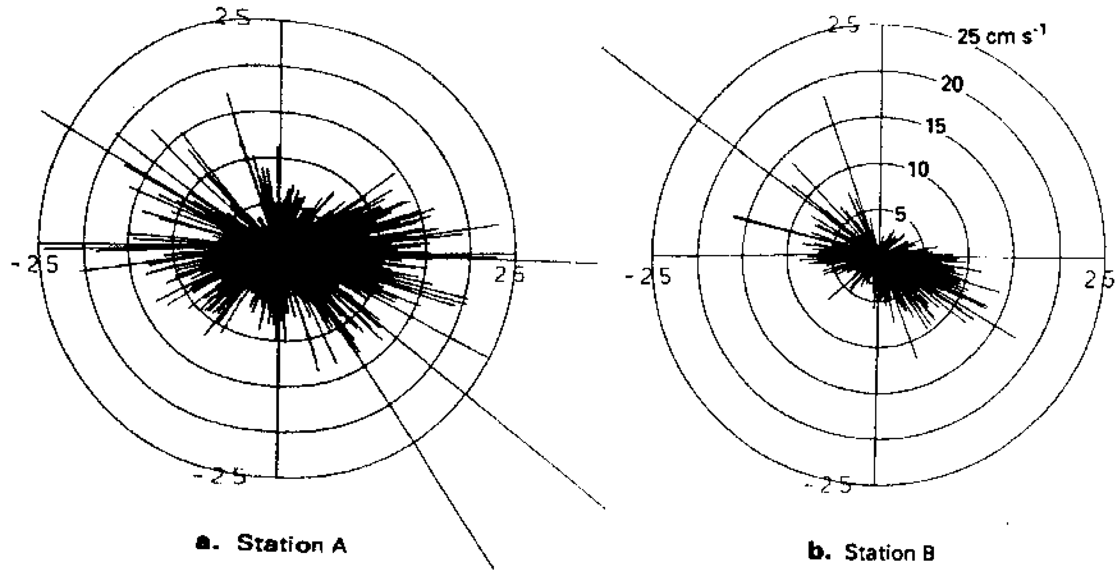

Figure 11. Instantaneous Velocity Distributions at the Wilmette Harbor Site, September 19, 1989, 10:00 a.m. – 10:15 a.m.

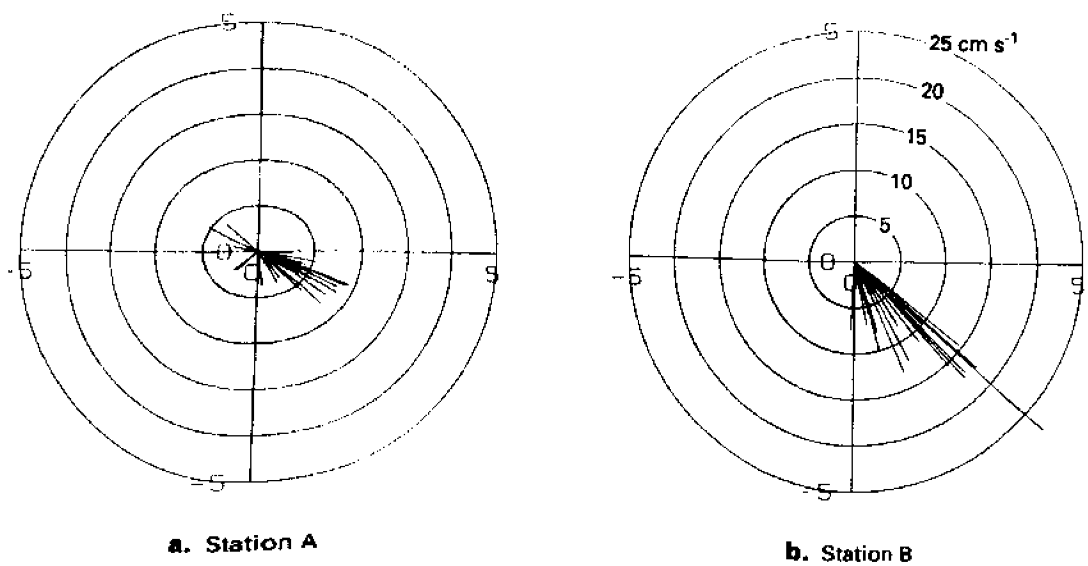

Figure 12. Mean Velocity Patterns in Polar Coordinates, September 19, 1989, 9:00 a.m. – 3:00 p.m.

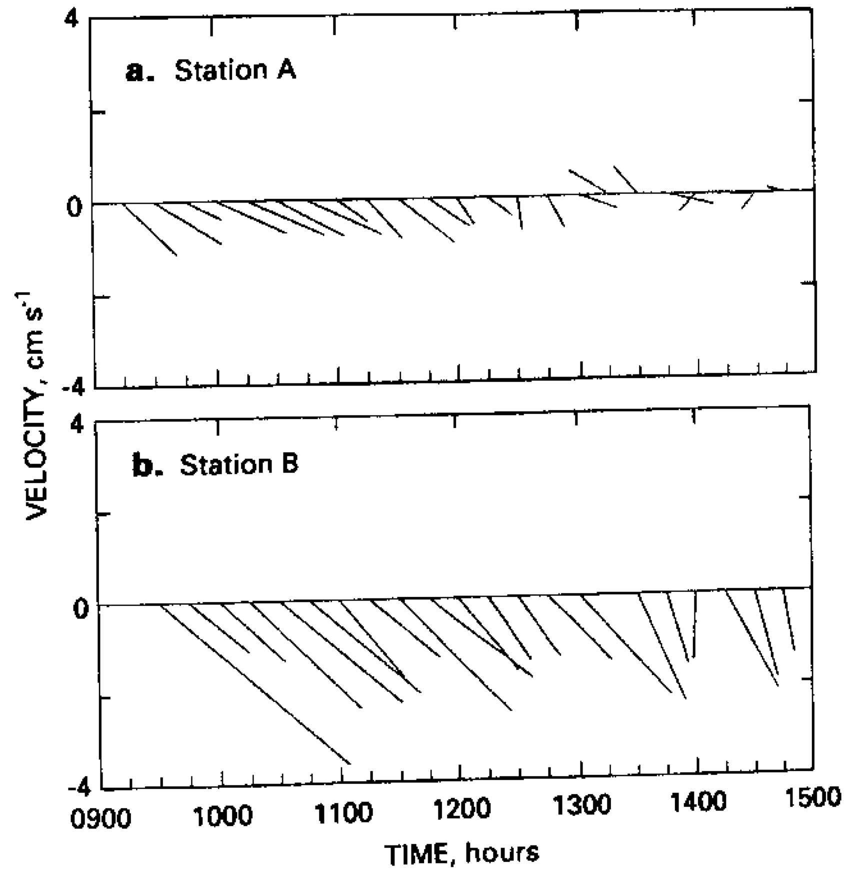

Figure 13. Mean Velocity Patterns in Vector Form, September 19, 1989, 9:00 a.m. – 3:00 p.m.

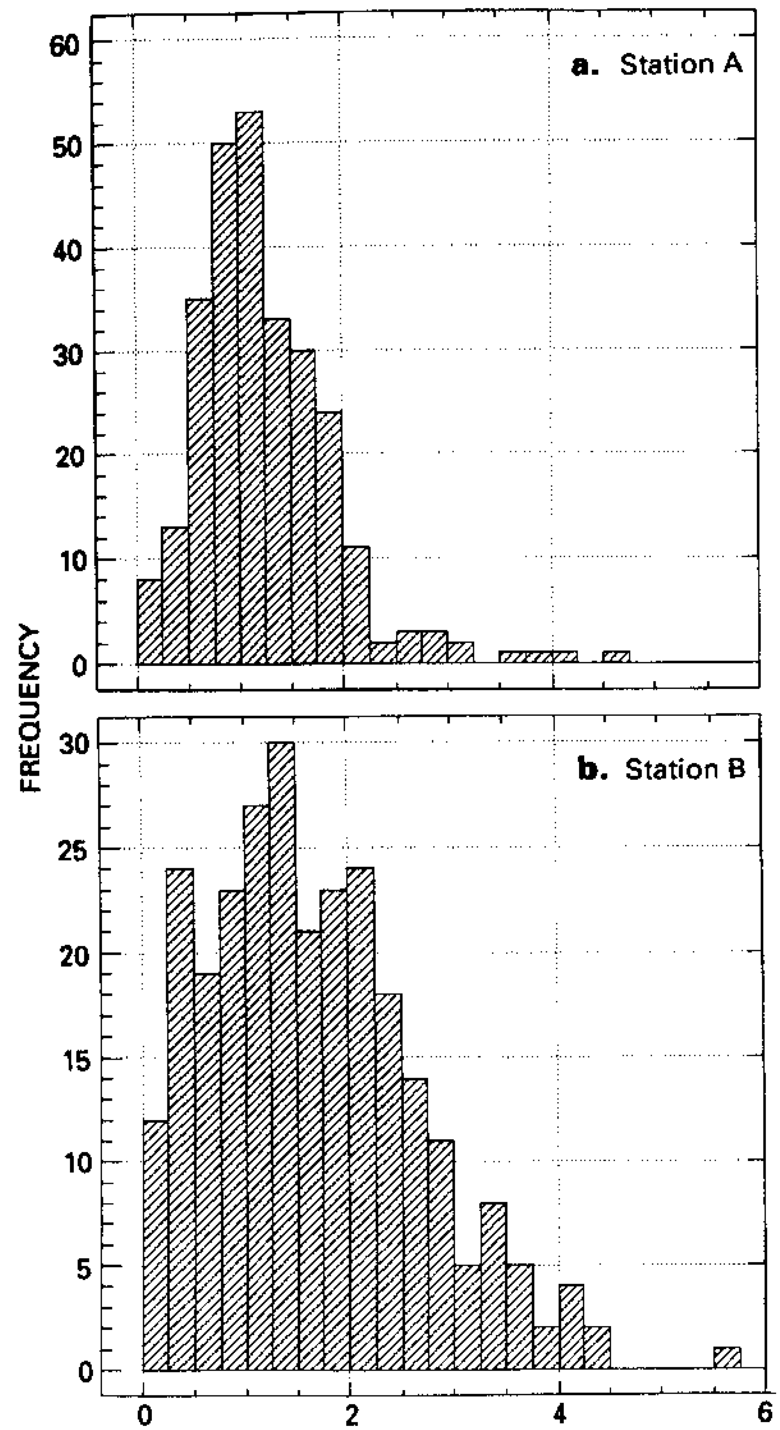

Figure 14. Frequency Histograms of Magnitude of Resultant Velocity, Wilmette Harbor Site

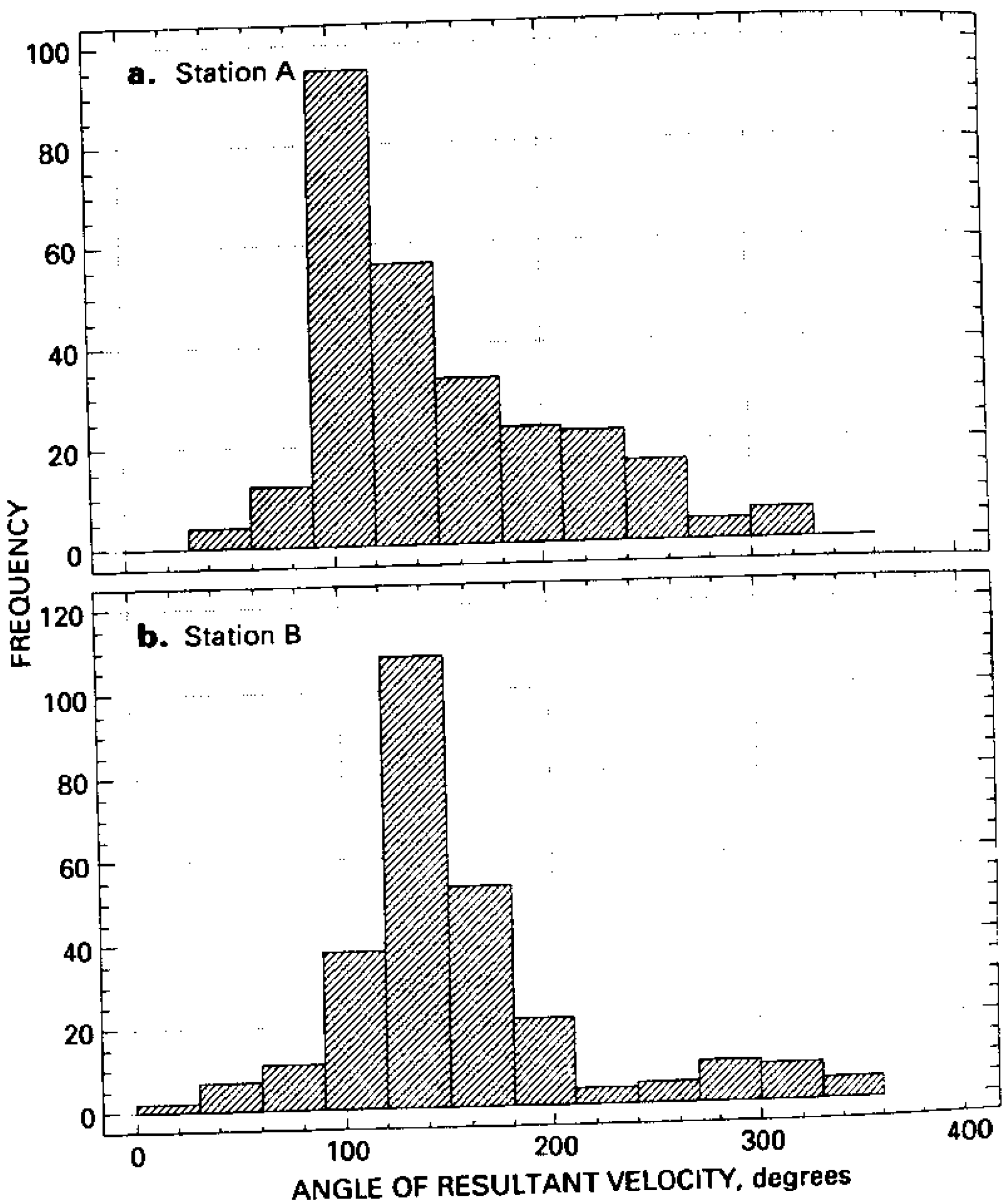

Figure 15. Frequency Histograms of Direction of Resultant Velocity, Wilmette Harbor Site

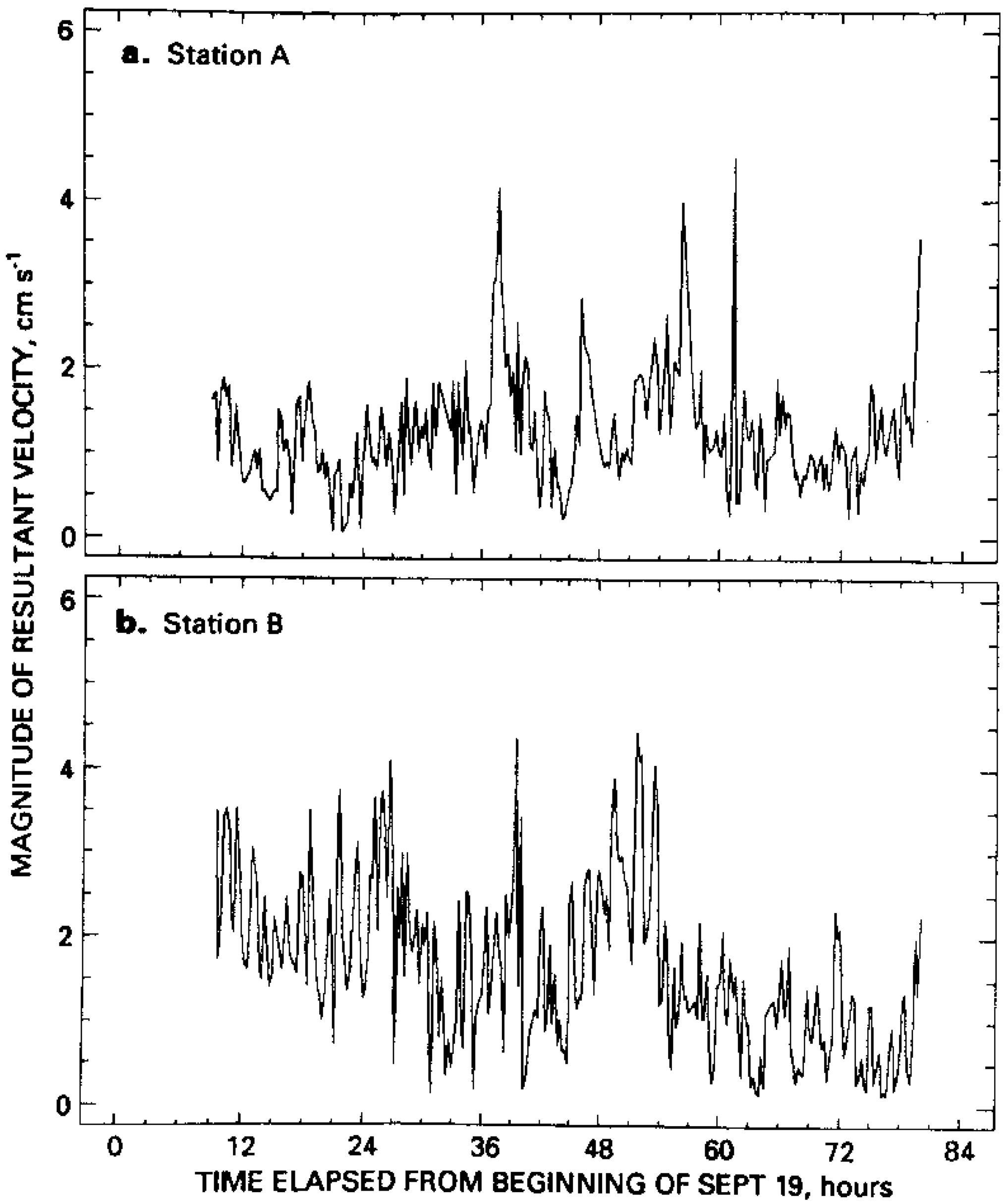

Figure 16. Time-History Plots of Magnitude of Resultant Velocity, Wilmette Harbor Site

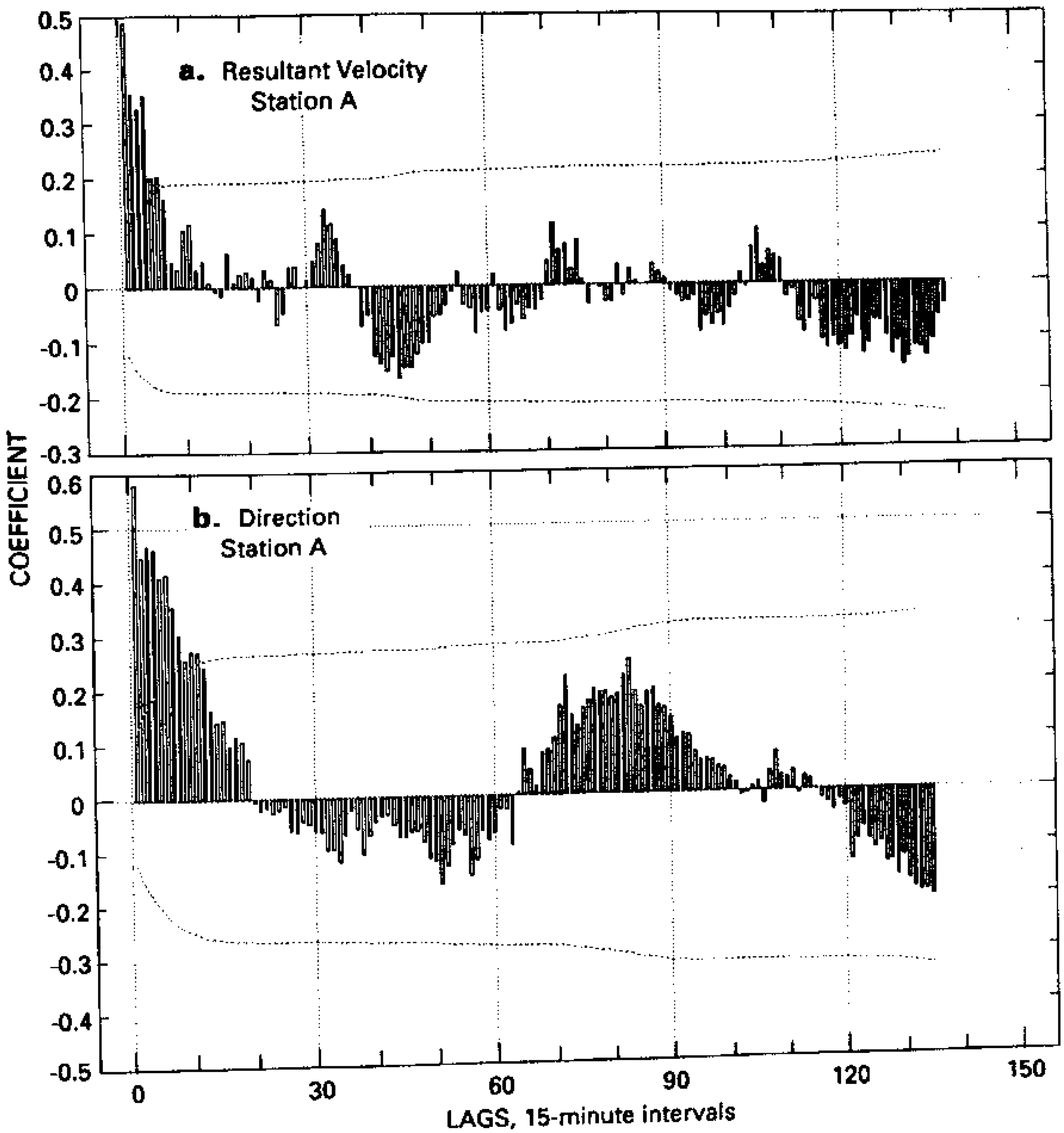

Figure 17. Correlograms for Resultant Velocity and Direction at Station A, Wilmette Harbor Site

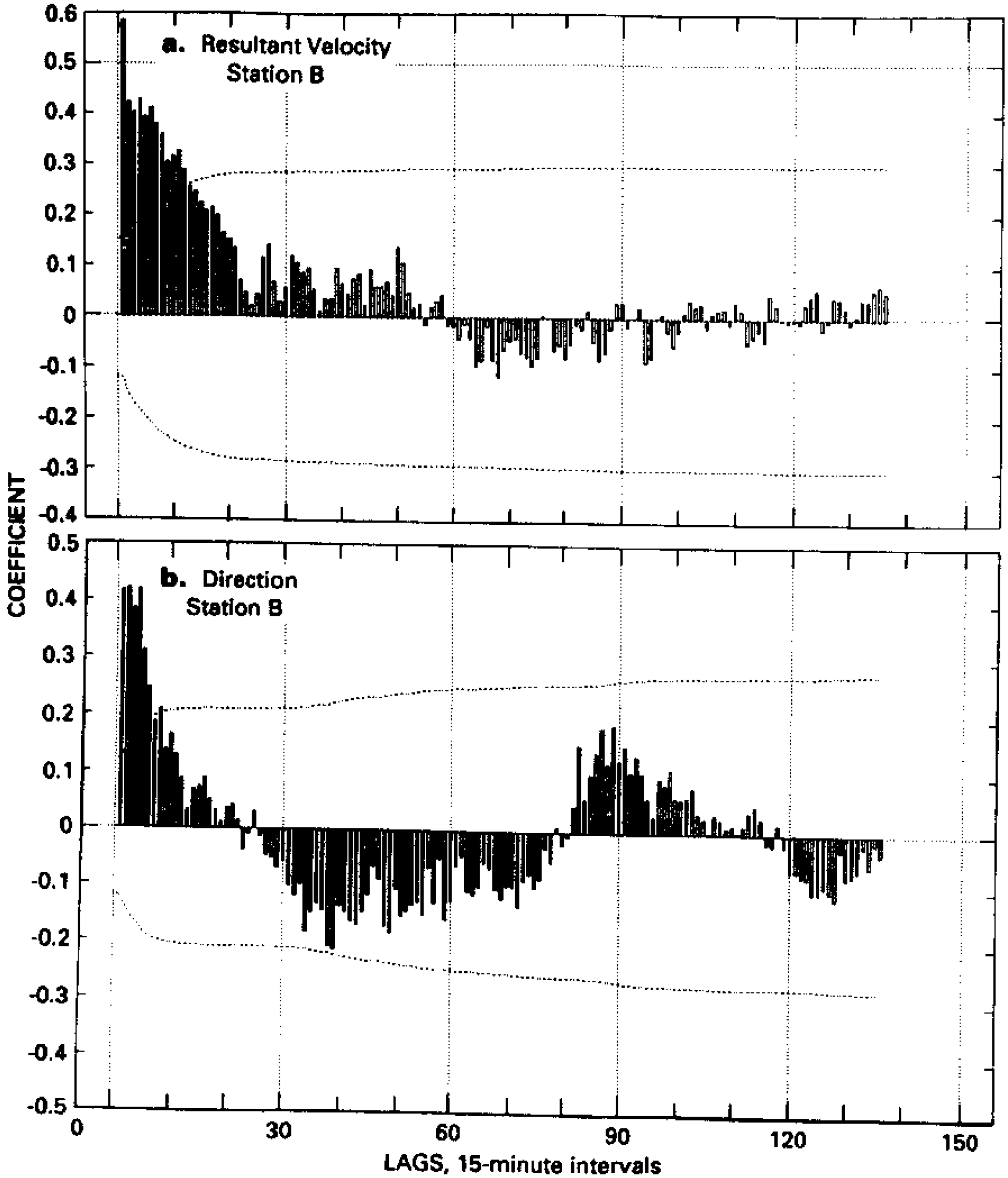

Figure 18. Correlograms for Resultant Velocity and Direction at Station B, Wilmette Harbor Site

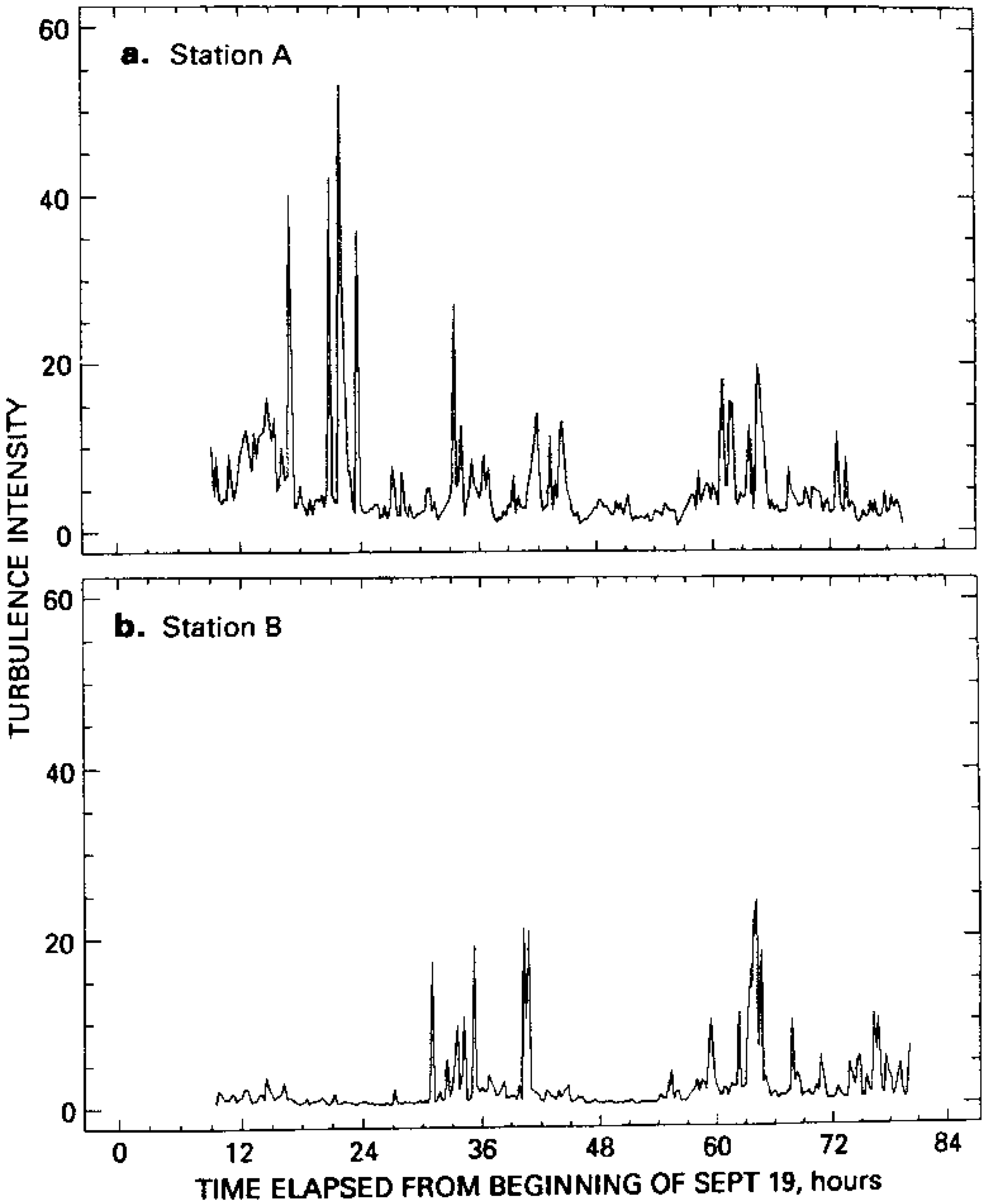

Figure 19. Time-History Plots of Turbulence Intensity, Wilmette Harbor Site

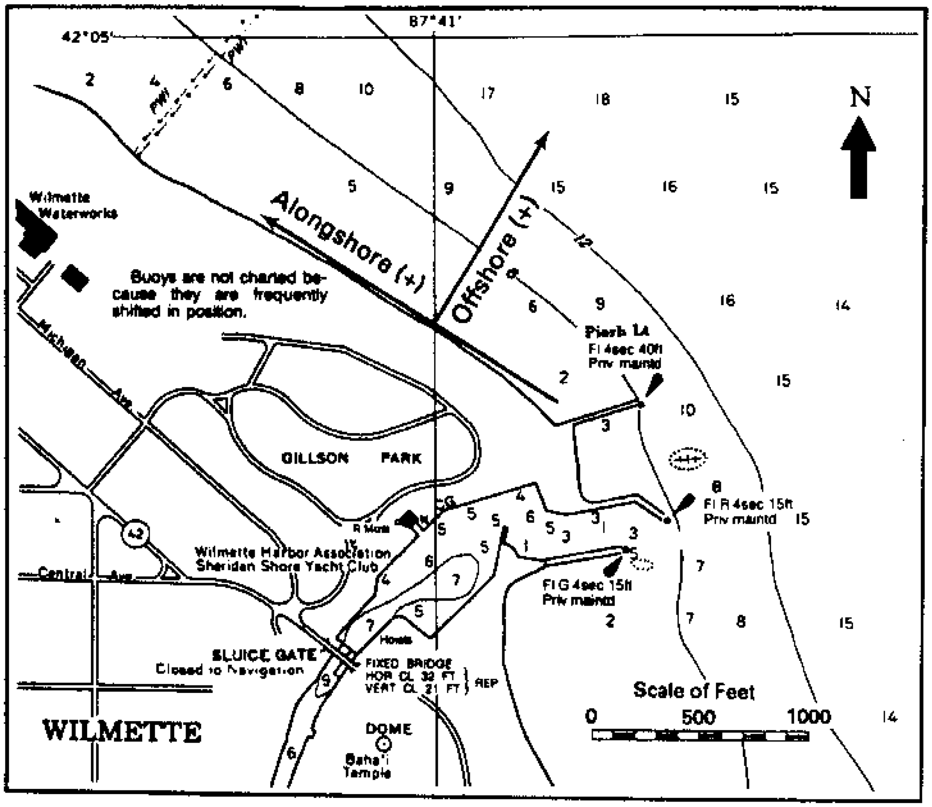

Figure 20. Definition Sketch of Coordinate System for Alongshore and Offshore Velocity Components

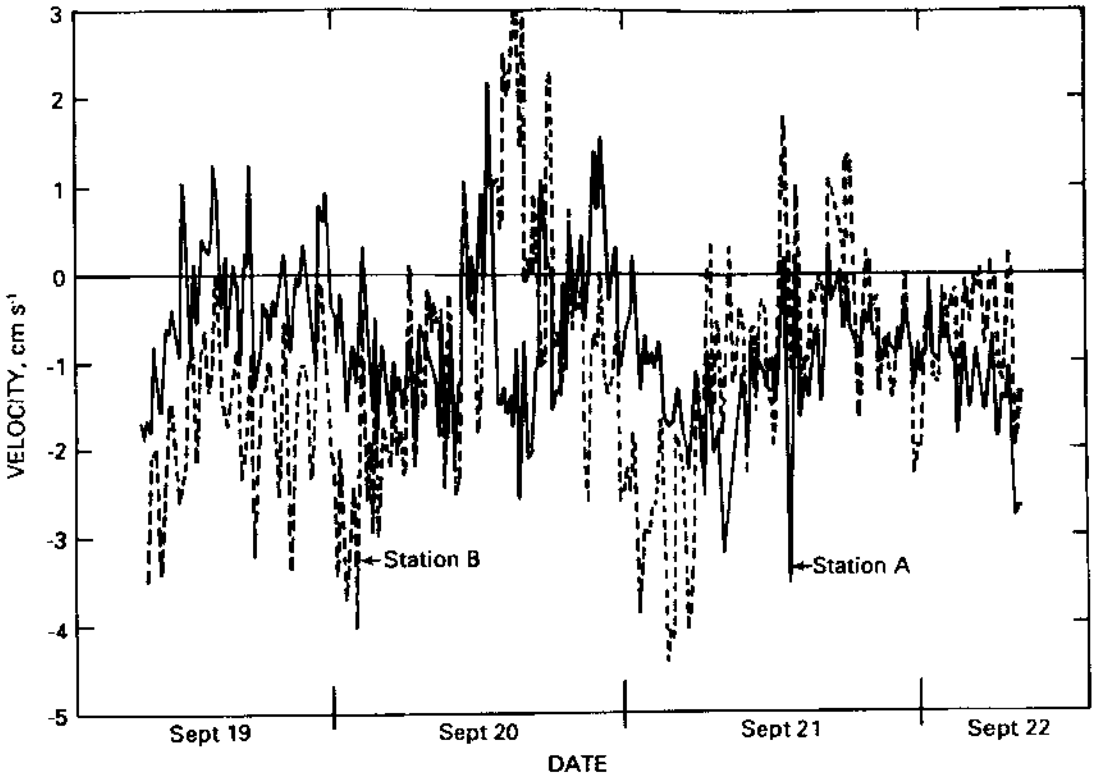

Figure 21. Alongshore Velocity Components Measured at Stations A and B, Wilmette Harbor Site

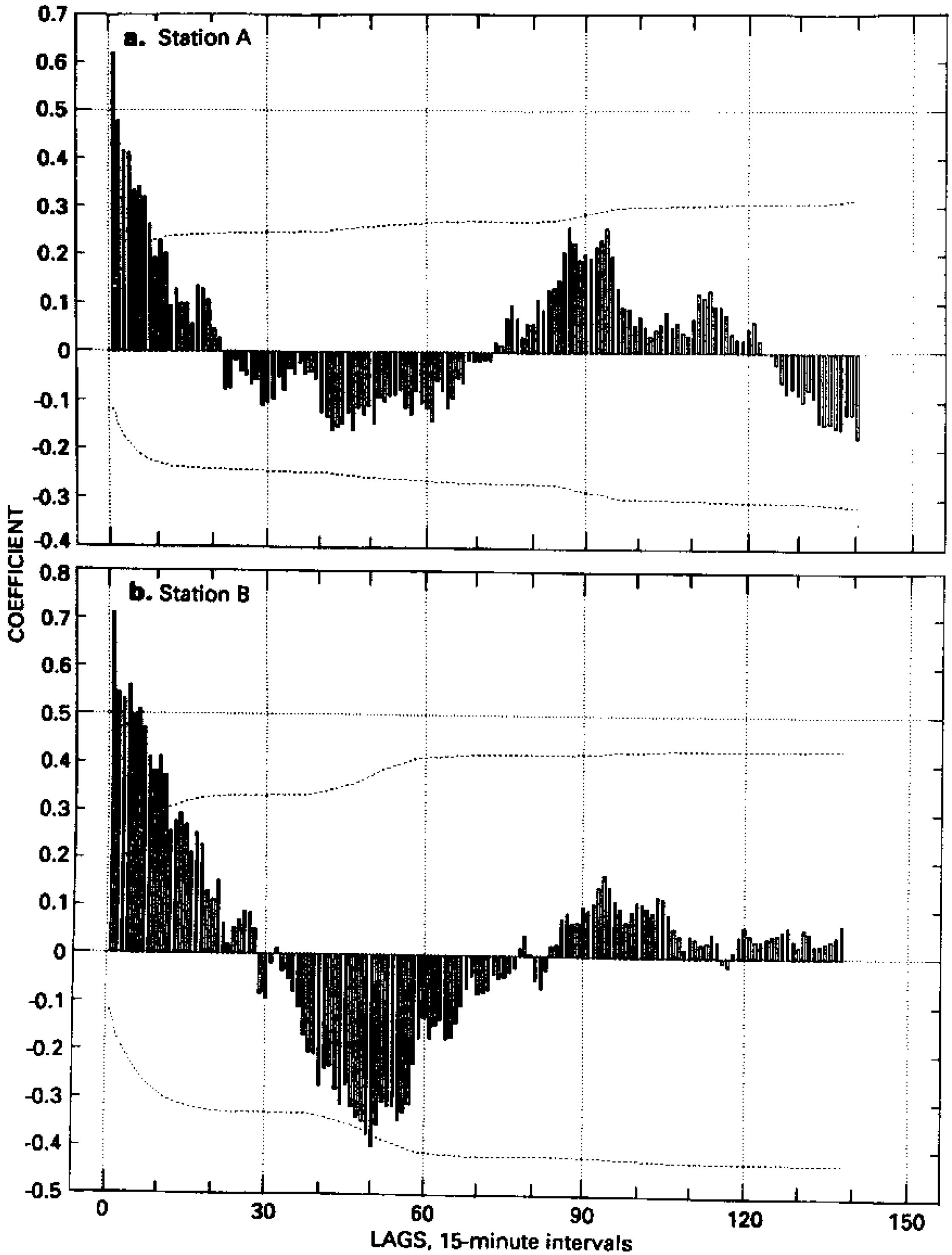

Figure 22. Correlograms for Alongshore Components of Velocity at Stations A and B, Wilmette Harbor Site

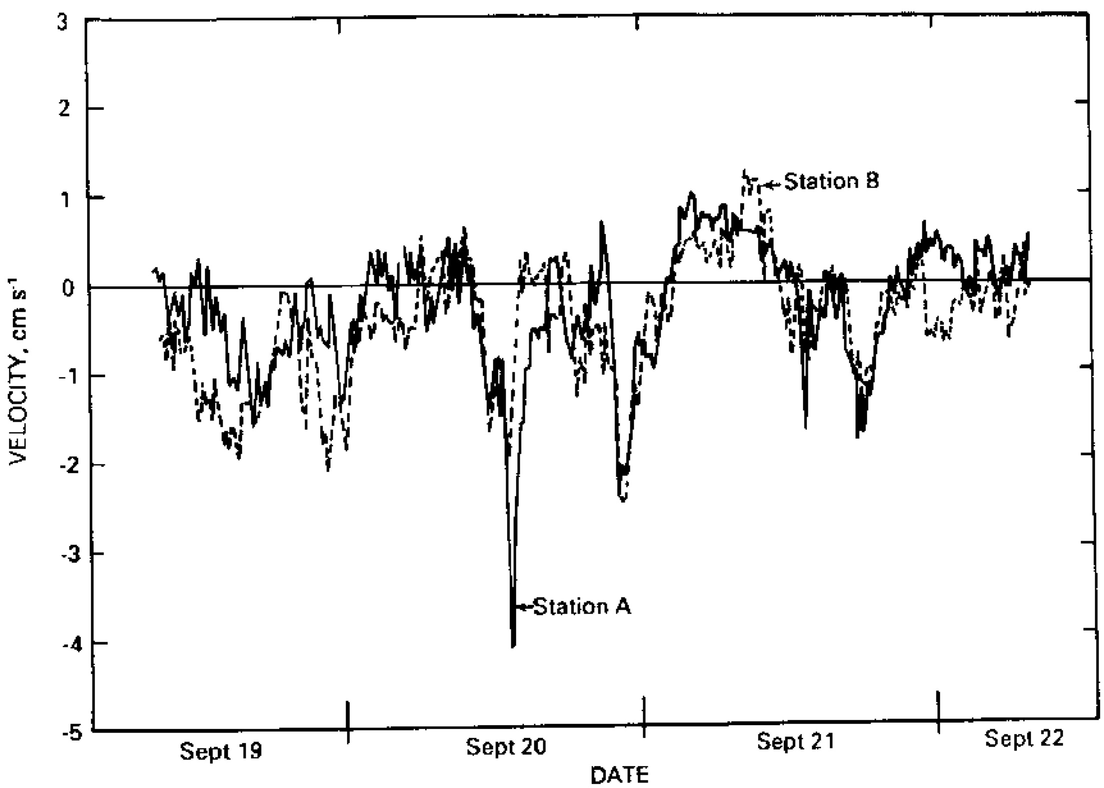

Figure 23. Offshore Velocity Components Measured at Stations A and B, Wilmette Harbor Site

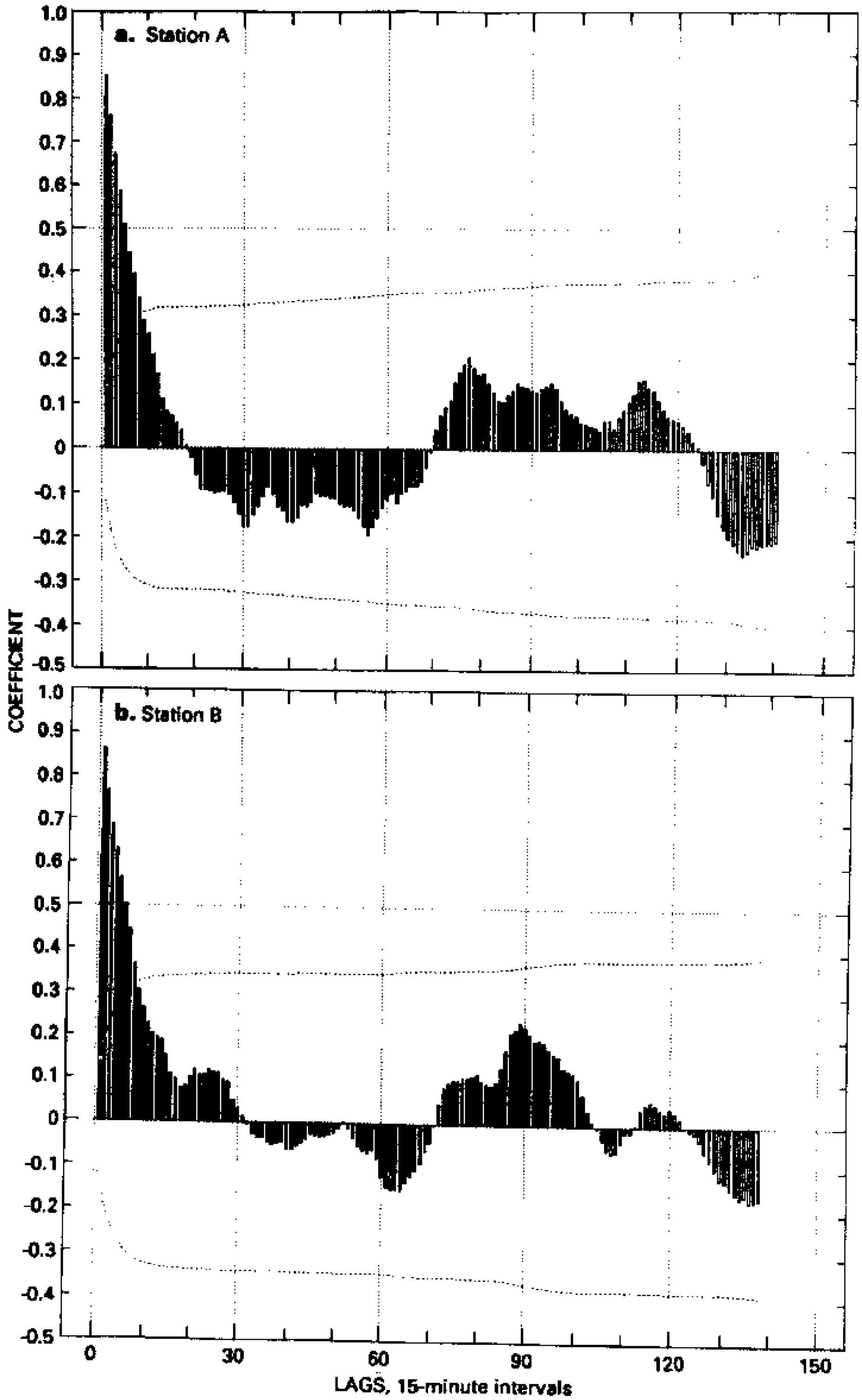

Figure 24. Correlograms for Offshore Components of Velocity at Stations A and B, Wilmette Harbor Site

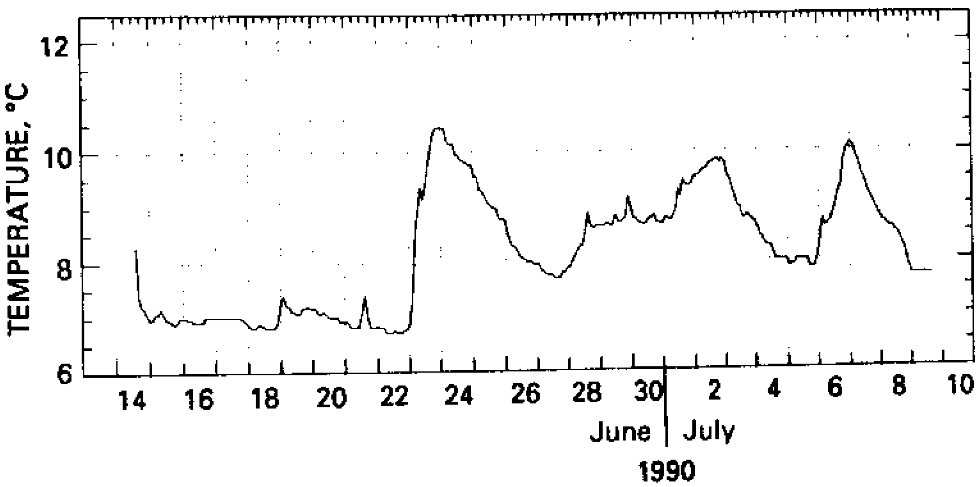

Figure 25. Variations in Water Temperature at the Tree Stump Site

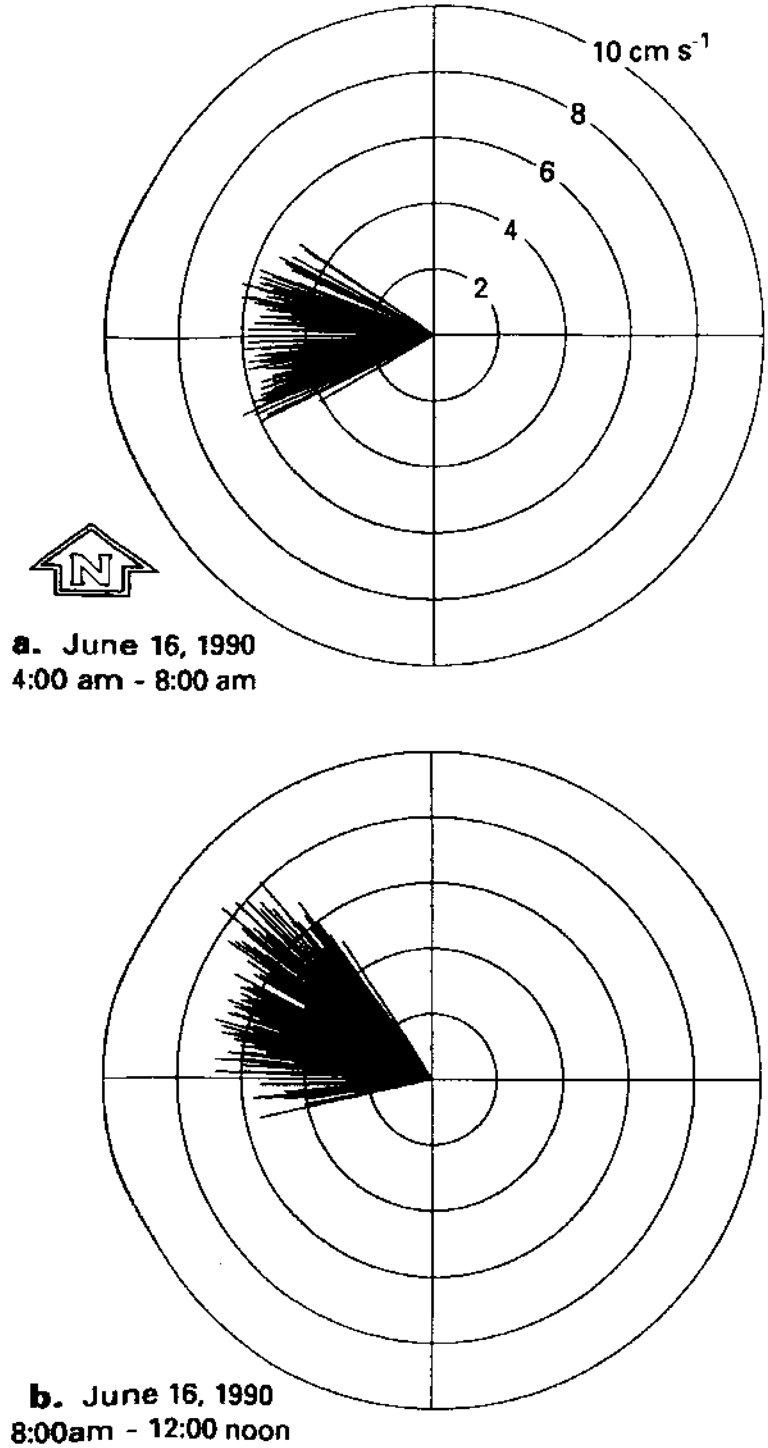

Figure 26. Patterns of Velocity (Time-Averaged over 30-Second Intervals) at the Tree Stump Site

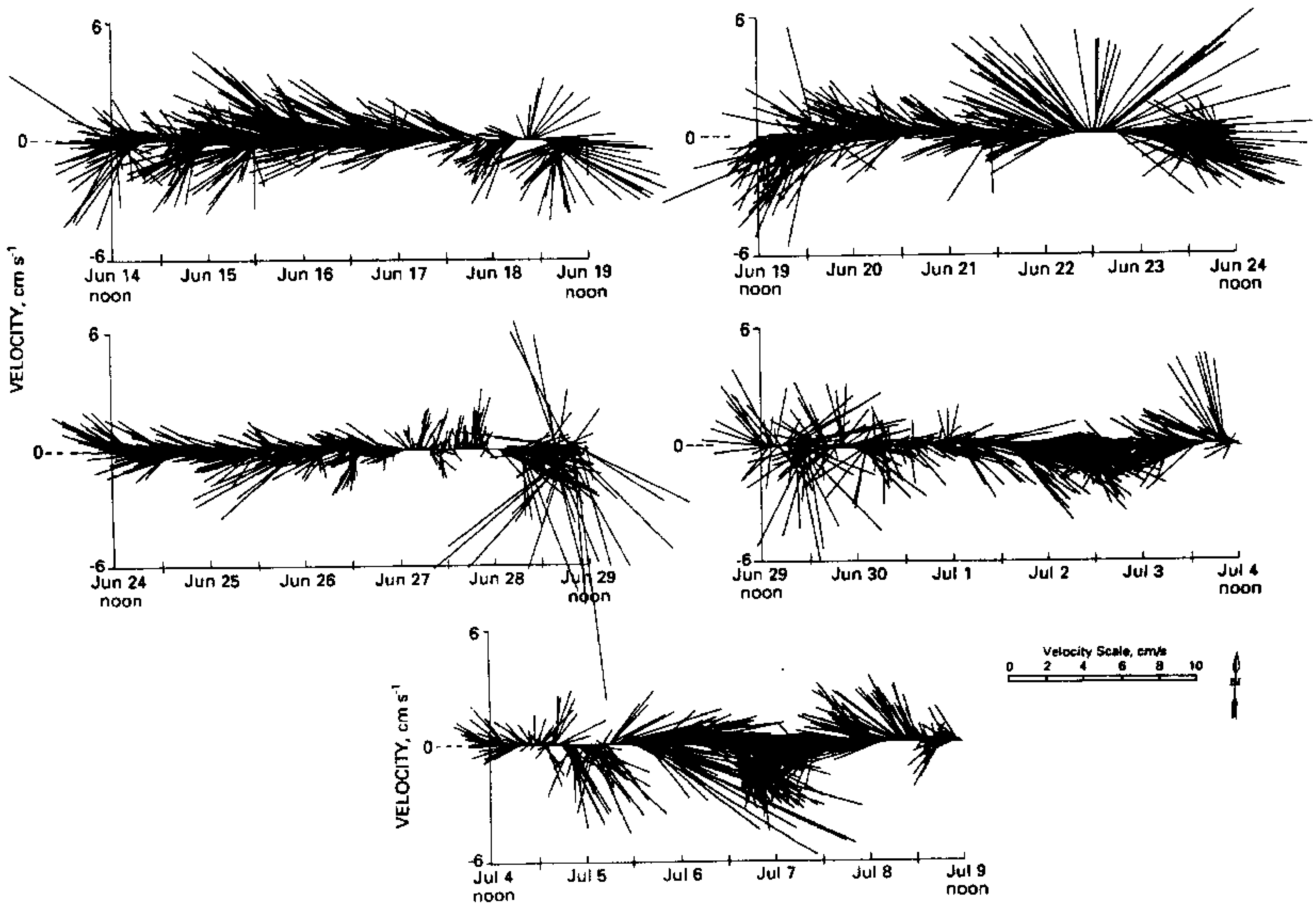

Figure 27. Resultant Velocity (Time-Averaged over 15-Minute Intervals) and Direction at the Tree Stump Site, June 14 – July 9, 1990

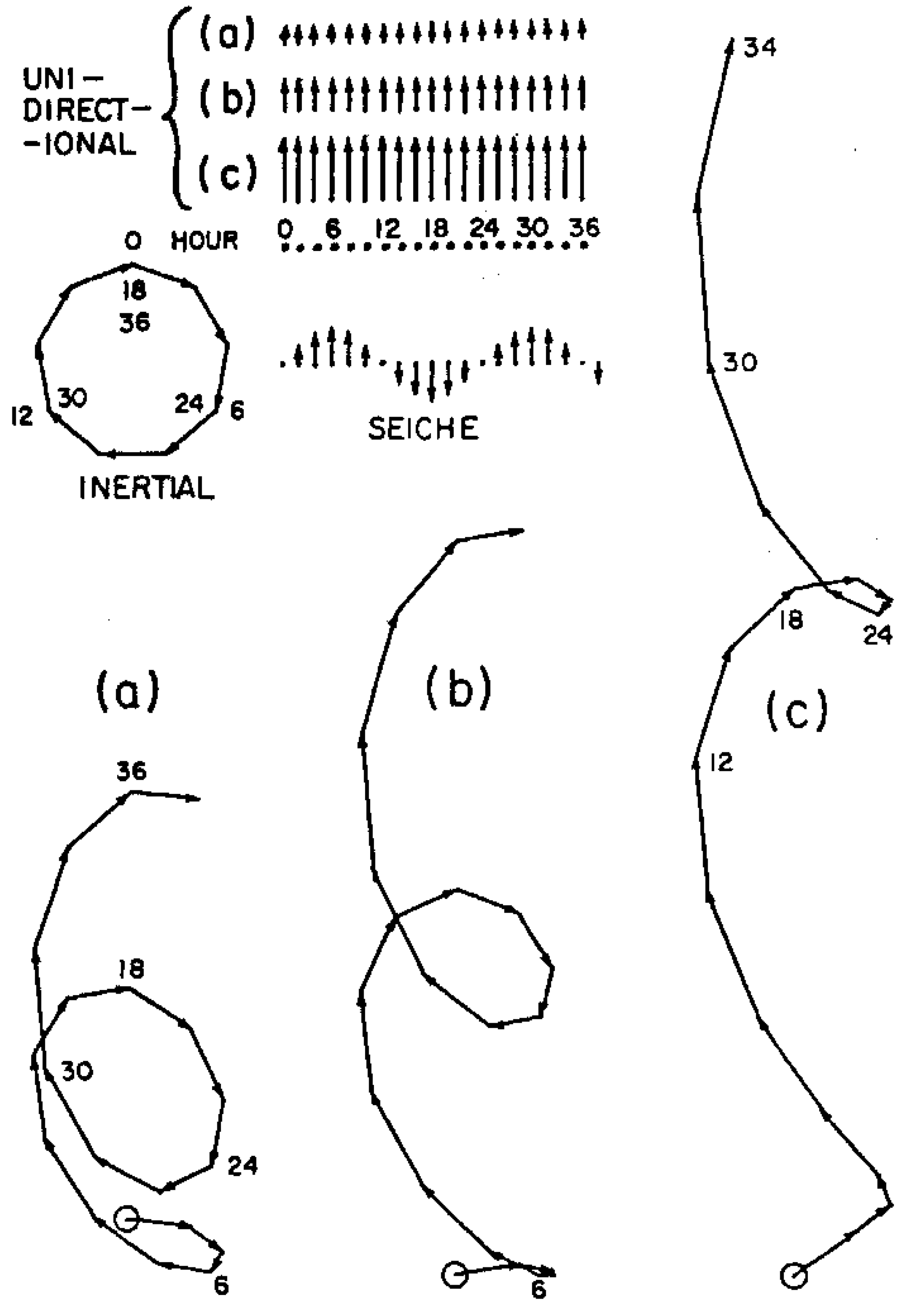

Figure 28. Vector Combination of a Rotating Inertial Current, a Seiche Current, and Unidirectional Current Components of Three Speeds (From Mortimer, 1978)

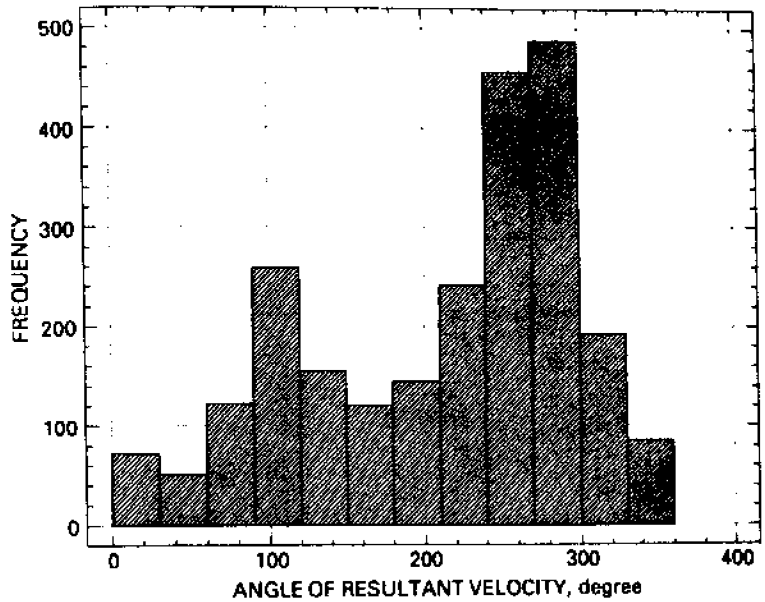

Figure 29. Frequency Histogram of Direction of Resultant Velocity at the Tree Stump Site

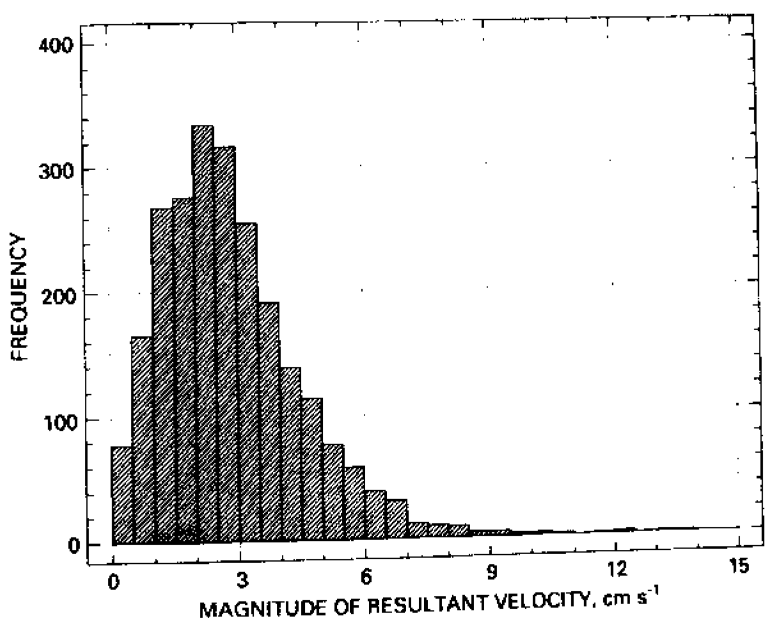

Figure 30. Frequency Histogram of Magnitude of Resultant Velocity at the Tree Stump Site

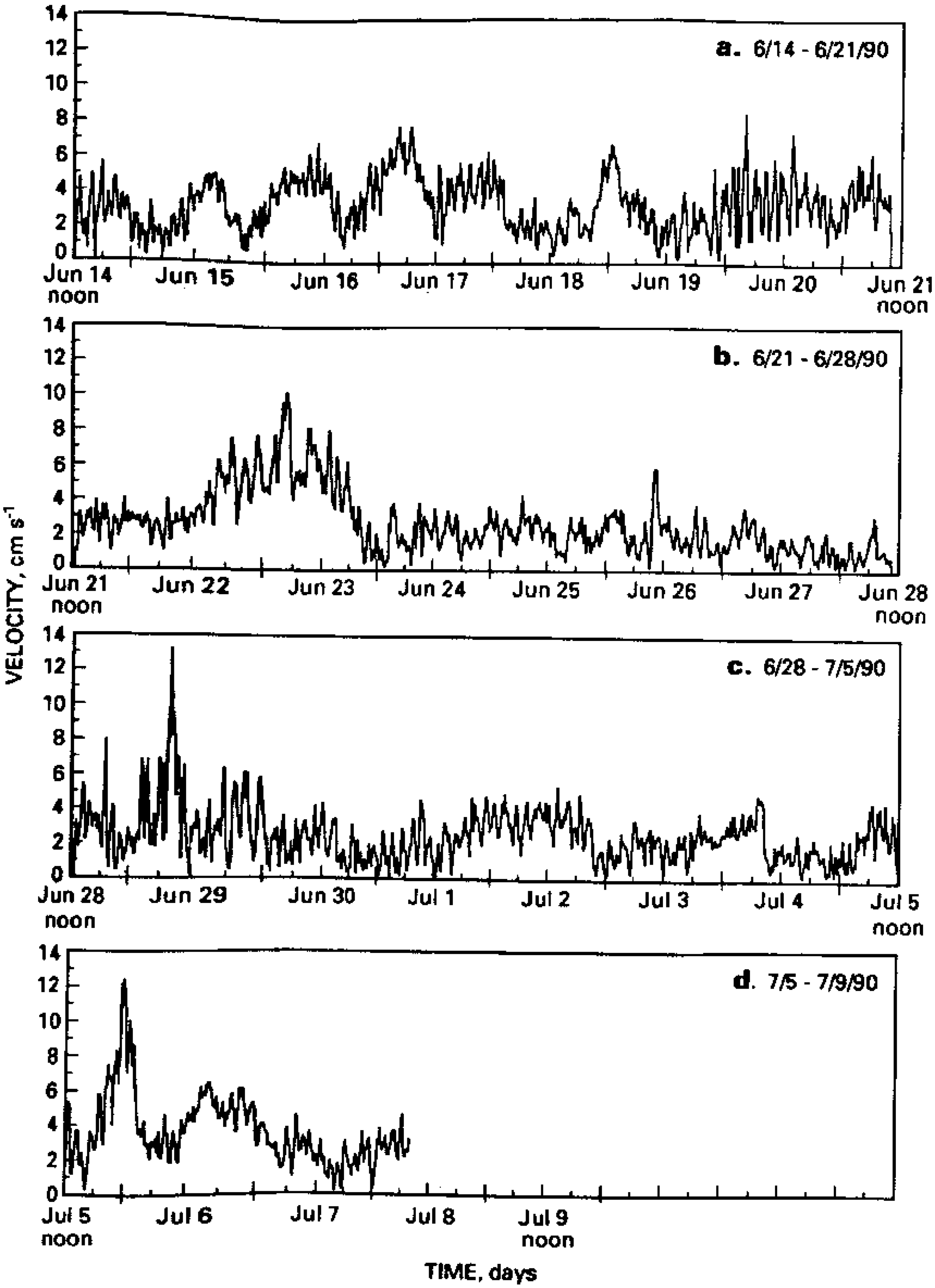

Figure 31. Variation of Resultant Velocity with Time at the Tree Stump Site

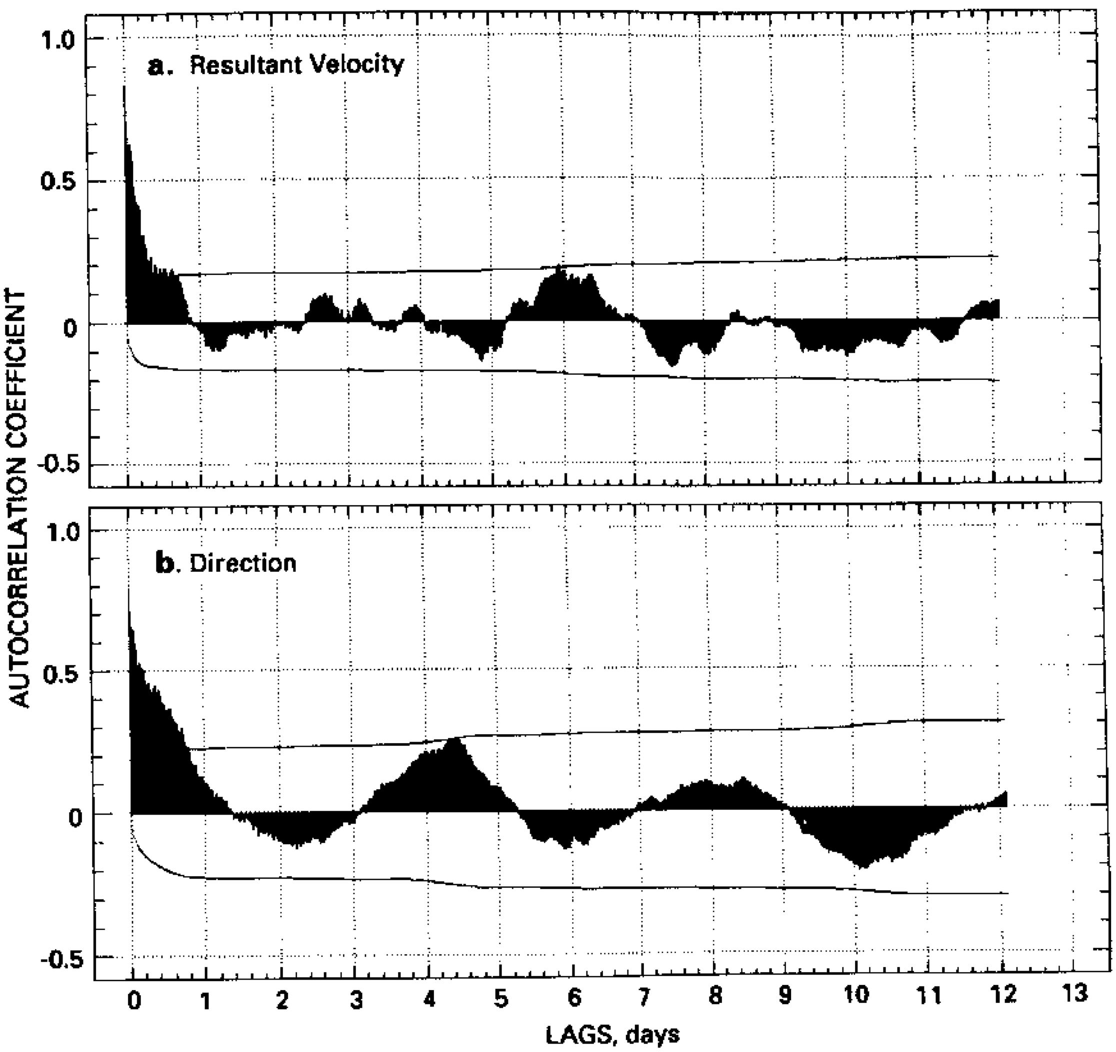

Figure 32. Correlograms for Resultant Velocity and Direction at the Tree Stump Site

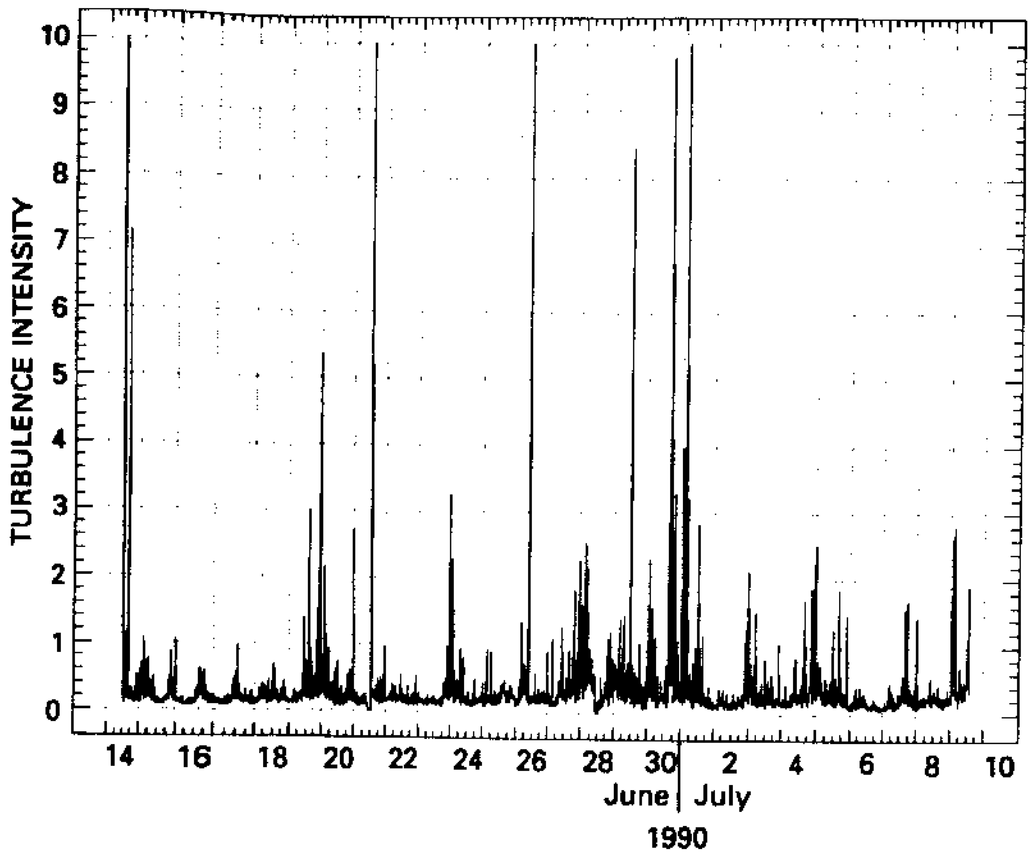

Figure 33. Time-History Plot of Turbulence Intensity at the Tree Stump Site

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