WATER RESOURCES RESEARCH PROGRAM

NEARSHORE CURRENTS AT POINT BEACH, WISCONSIN

(1974-1975)

by

**K. D. Saunders, L. Van Loon,
C. Tome, and W. Harrison**

MASTER

GREAT LAKES PROJECT

**ENERGY AND ENVIRONMENTAL
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**ENVIRONMENTAL IMPACT
STUDIES DIVISION**

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March 1976

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WATER RESOURCES RESEARCH PROGRAM
NEARSHORE CURRENTS AT POINT BEACH, WISCONSIN (1974-1975)

by

K. D. Saunders, L. Van Loon, C. Tome, and W. Harrison

ABSTRACT

Coastal currents were monitored at stations 0.4, 1.1, and 3.8 km from shore along a coast-perpendicular transect located 1 km south of the Wisconsin Electric Power Company's nuclear generating station. Complete specifications are given for current meter calibrations, electronics used, winter and summer mooring configurations, and for the performance of each meter and mooring assembly. Local winds were monitored at the power plant intake using a mechanical, MRI wind system.

The following types of graphs are presented for current and wind observations: (1) U, V flow components versus time, (2) specific kinetic energy versus time, (3) flow speeds and directions versus time, (4) composite velocity histograms and associated U, V-component histograms, and (5) progressive vector diagrams.

A linear, optimal-filter design technique (Wiener filter) is used to estimate the efficiency of wind-driven, linear, nearshore current-prediction models. The poor predictions of the models probably relate to such factors as lack of input for superimposed lake currents, time-base errors, and wind-stress formulas.

I. INTRODUCTION

The present study was initiated: (1) to obtain an expanded data base for nearshore currents and winds in the vicinity of the Point Beach, Wisconsin nuclear power station (Fig. 1), (2) to determine the mechanisms governing the nearshore currents, (3) to develop a predictive capability for determining the nearshore currents, and (4) to improve understanding of the processes of dispersion in the nearshore regime.

This research effort is an outgrowth of the thermal-plume studies of the Great Lakes Research Project at Argonne. To verify and test empirical and numerical models of thermal plumes, local current structure at the time

plume measurements are taken must be known. Additionally, data on local local currents are required to formulate the correct boundary conditions for these models. As most of these models also parameterize, by the use of an eddy-diffusion or eddy-viscosity coefficient, the effects of turbulence, the characteristics of the nearshore dispersive processes must also be known.

The study of nearshore processes has wider applications. The Laurentian Great Lakes constitute the largest freshwater system on earth. To use the lakes effectively, both as sources for fresh water and as sinks for wastes, it is vital that the physical processes that transport materials between the nearshore and deep-water regions of the lakes be well understood. Documentation and development of a predictive capability for these fundamental processes is the ultimate goal of the nearshore studies at Argonne.

A three-year period had been planned to meet the stated project objectives. The first year was to have been devoted to the collection and reduction of field data. However, even though the entire period had to be shortened to one year, we have been able, at least partially, to satisfy the first three objectives.

Data acquisition for nearshore currents and winds began during the 1973 field year. The study area was located near the Point Beach nuclear generating station in Two Rivers, Wisconsin (see Fig. 1). The initial phase lasted from May 11 through October 9, 1973. Six current-meter records were obtained from this effort and the effort is described in Tokar, et al (1975). The expanded program was begun in the Spring of 1974, under the direction of Dan Frye. In August of 1974, Kim Saunders assumed responsibility for continuing the project.

This report is organized under three headings: Methods, Data, and Analysis. Under Methods, we discuss the techniques for obtaining current and wind data and data reliability. In the data section, we present all of the current and wind data obtained. These data are available to interested persons in computer-compatible form. The last section discusses the analysis of the data; in particular, the use of linear optimal filtering to estimate the possibility of constructing a linear numerical model to predict local currents, given the local wind at one point.

Fig. 1. Lake Michigan Bathymetry

II. INVESTIGATIVE METHODS

A. EQUIPMENT

1. Current Meters and Meteorological Station

As in the previous year, we used three Braincon Model 381, histogram, recording current meters. These meters record speed and direction on photographic film every 20 or every 40 minutes. They were modified by substituting a ducted impeller (ENDECO Corp.) for the standard Savonius rotor. This adjustment reduces the problems associated with rectification of wave orbital motion for current meters placed near the surface. The films were processed in the same manner as in the previous year (see Tokar, et al., 1975), being read by Argonne's ALICE computer, which produces computer-compatible output.

In addition to the Braincon meters, we used the Argonne-developed, current-measuring system, which achieved operational capability in Spring 1975. It uses a Bendix Q-15 current-meter head in conjunction with Argonne's data recording package. The new system was needed to eliminate the film-processing and reading step from the Braincon current-meter, data-reduction procedure and to increase the time-base reliability. Its electronic recording package stores current speed and direction, time, and temperature data on cassette magnetic tapes. These data can then be transcribed directly onto a seven track, IBM-compatible magnetic tape.

The data are obtained from a Bendix Q-15R current-meter head and from two thermistors. The time base is recorded internally.

The data flow for the system is presented in Fig. 2. Schematic diagrams for the electronics are presented in Figs. 3-6. For details of the Bendix Q-15R current-meter heads, see the Bendix Environmental Science Division Report: *Current Meter Model Q-15, Operating and Service Manual* 9-M11373A, January 1972.

Local winds were measured with an MRI Model 1071, mechanical recording meteorological station. This station was mounted on the intake crib for the power plant, about one kilometer north of the current meter site. In addition to hourly wind speed and direction, this station also gave a continuous record of air temperature, which was digitized hourly.

Fig. 2. Data Flow for the Bendix Q-15 Electronics Package

NOTE 1

SAMPLING FORMAT IS:
FOUR CONSECUTIVE DIRECTION READINGS AT THE SELECTED SAMPLING INTERVAL (2 MIN. IN THIS CASE)
THE FOURTH DIRECTION ENTRY IS IMMEDIATELY FOLLOWED BY - TWO TEMPERATURE READINGS - THEN
THE FLOW RATE READING - THEN THE CLOCK ENTRY. THIS PRODUCES ONE COMPLETE SAMPLING CYCLE
EVERY 8 MINUTES (IN THIS CASE). THE TWO TEMPERATURE READINGS ARE TAKEN INSTANTANEOUSLY
AT THE END OF THE CYCLE. THE FLOW RATE IS AVERAGED OVER THE TOTAL CYCLE PERIOD.

5 PC 064

Fig. 3. Electronic Recording Package - Schematic Diagram, Timing Circuitry

Fig. 4. Electronic Recording Package - Schematic Diagram, Analog Inputs and A - D Conversion

Fig. 6. Electronic Recording Package - Schematic Diagram, Interface to Cassette Recorder

2. Current-meter Calibration

Three Braincon and one ANL-Electronic current meters were removed from their moorings at Point Beach in November of 1974. We decided to calibrate the meters before redeploying them in December. This action was absolutely necessary because if a meter were lost during the ensuing winter storms, it would be impossible to properly interpret the uncalibrated record from the previous summer.

Dr. Wallis Hamilton, of the Civil Engineering Department, Northwestern University, allowed us to use his tow-tank for the calibration runs. The tow-tank setup was less than ideal because the speed control for the carriage had a lower limit of about 0.03 m/s and this speed was extremely difficult to obtain.

The tow tank is about 1-m deep and about 20-m long. For calibration purposes, the tank was marked off into three 5-m zones. A stopwatch was used to determine the time needed to traverse the 15 meters.

Three Braincon current meters, B96, B97, and B98 were calibrated. Four Bendix, Q-15R current-meter heads (Serial nos.: 173-2361, -2362, -2363, and 369-2036) were calibrated. For the Braincon current meters, with ENDECO ducted-impeller modifications, the revolutions of the impeller were counted visually. The number of revolutions for the Q-15 current-meter heads were counted by an electronic counter. The raw data for the calibrations are presented in Tables 1 and 2. Table 3 presents a summary of the calibrations for the linear regions of the calibration curves.

The calibration data for the Braincon current meters are plotted in Figs. 7 and 8; data for the Bendix Q-15 heads are plotted in Figs. 9 and 10. These figures clearly indicate that the nonlinear range of all the current meters is below 0.10 m/s. The threshold speed required to activate the Braincon current meters is about 0.05 m/s and is below that for the Q-15 heads. Previous calibrations have indicated a cutoff for these current meters at about 0.03 m/s (Frye, 1974).

The errors in the calibrations were determined to be:

$$\text{Braincon: } \frac{\epsilon_{\phi}}{\phi} \approx 0.043$$

TABLE 1. Current Meter Calibrations

Meter No.	Distance	Time	Speed	Counts	Scaling (CNTS/REV)	Revs	Rev/cm	Comments
B98	15 m	144.5	0.103			35	0.0233	Visual
	15 m	68.0	0.221			40	0.0266	"
	15 m	64.0	0.234			38	0.0253	"
	15 m	66.0	0.227			38	0.0253	"
	15 m	143.0	0.104			34	0.0227	"
	15 m	46.0	0.326			39.5	0.0263	"
B96	15 m	46.5	0.323			35	0.0233	Visual
	15 m	31.0	0.484			37	0.0247	"
	15 m	49.5	0.303			36.5	0.0243	"
	15 m	67.5	0.222			36	0.0240	"
	15 m	152.0	0.0986			32	0.0213	"
	15 m	263.0	0.0570			22.5	0.0150	Visual threshold
B97	15 m	23.0	0.652			33	0.0220	Visual
	15 m	31.5	0.476			33	0.0220	"
	15 m	41.0	0.3658			32	0.0213	"
	15 m	56.0	0.2679			33	0.220	"
	15 m	48.5	0.3093			32	0.0213	"
	15 m	122.0	0.1229			29.5	0.0197	"
	15 m	238.5	0.0629			22	0.015	Threshold
	5 m	104.0	0.0480			2	0.004	Threshold or just below
Q-15R (Old one 173-2362)	15 m	27.0	0.555	527	5	105.4	0.070	Last digit uncertain
	15 m	34.0	0.441	522	5	104.4	0.070	" " "
	15 m	43.0	0.349	529	5	105.4	0.070	" " "
	15 m	60.0	0.250	529	5	105.8	0.067	" " "
	15 m	102.5	0.146	506	5	101.0	0.067	" " "
	15 m	286.5	0.052	396	5	79.2	0.053	" " "
Q-15R	15 m	347.5	0.0432	337	5	67.4	0.0449	
	15 m	271.7	0.0552	423	5	84.6	0.0564	

TABLE 1. Current Meter Calibrations (Cont'd)

Meter No.	Distance	Time	Speed	Counts	Scaling (CNTS/REV)	Revs.	Rev/cm	Comments
Q-15R	15 m	21.7	0.0691	461	5	92.2	0.0615	Meter running backwards
173-2363	15 m	23.7	0.633	451	5	90.2	0.601	" " "
	15 m	25.7	0.584	470	5	94.0	0.0627	" " "
	15 m	29.8	0.503	470	5	94.0	0.627	" " "
	15 m	37.2	0.403	460	5	92.0	0.613	" " "
	15 m	45.7	0.328	465	5	93.0	0.620	" " "
	15 m	66.9	0.224	463	5	92.6	0.0617	" " "
	15 m	61.8	0.243	470	5	94.0	0.0627	Forward run
	15 m	75.2	0.199	460	5	92.0	0.0613	Backward
	15 m	72.8	0.206	468	5	93.6	0.624	Forward
	15 m	90.0	0.0165	463	5	92.6	0.0617	Backward
	15 m	92.8	0.0162	466	5	93.2	0.0621	Forward
	15 m	209.4	0.0716	420	5	84.0	0.0560	Backward - sporadic count rate
	15 m	170.0	0.0882	434	5	86.8	0.1578	Forward
	15 m	455.8	0.0329	346	5	69.2	0.0461	Backward
173-2321	15 m	19.7	0.761	530	5	106.0	0.0707	
	15 m	23.2	0.647	630	5	126.0	0.0840	Forward runs
	15 m	29.3	0.512	729	5	145.8	0.0972	Count rate
	15 m	32.0	0.469	865	5	173.0	0.1153	seems sporadic
	15 m	33.0	0.455	940	5	188.0	0.1253	
	15 m	33.4	0.449	730	5	146.0	0.0973	
	15 m	33.4	0.449	789	5	157.8	0.1052	
	15 m	43.1	0.348	590	5	118.0	0.0787	
	15 m	42.5	0.353	613	5	122.6	0.0817	
	15 m	77.4	0.194	500	5	100.0	0.0677	
	15 m	78.4	0.191	501	5	100.2	0.0668	
	15 m	338.7	0.0443	390	5	78.0	0.052	
	15 m	26.5	0.566	670	5	134.0	0.0893	Backward run
	15 m	25.5	0.588	660	5	132.0	0.088	

TABLE 1. Current Meter Calibrations (Cont'd)

Meter No.	Distance	Time	Speed	Counts	Scaling (CNTS/REV)	Revs.	Rev/cm	Comments
369-2036	15 m	32.0	0.456	498	5	99.6	0.0664	
	15 m	46.3	0.324	515	5	103.0	0.0687	
	15 m	47.0	0.319	540	5	108.0	0.072	
	15 m	139.5	0.108	460	5	92.0	0.0613	
	15 m	325.6	0.046	338	5	67.6	0.0451	

TABLE 2. Current-meter Calibrations

Meter no.	Speed cm/s	Counts rps	Braincon - rev/m Q-15 - pps/kt
B96	5.70	0.085	1.50
	9.86	0.211	2.14
	22.2	0.533	2.40
	30.3	0.737	2.43
	32.3	0.758	2.47
	48.4	0.175	2.33
B97	4.80	0.019	0.40
	6.29	0.092	1.50
	12.29	0.242	1.97
	26.73	0.589	2.20
	30.93	0.660	2.13
	36.58	0.780	2.13
	65.2	1.435	2.20
B98	2.74	0	0
	5.62	0.084	1.50
	6.21	—	—
	10.3	0.242	2.33
	10.4	0.238	2.27
	22.1	0.588	2.66
	22.7	0.576	2.53
	23.4	0.594	2.53
	32.6	0.859	2.63
	56.6	1.585	2.80
173-2362	0.052	1.38	13.7
	14.6	4.94	17.4
	25.0	8.82	18.2
	34.9	12.30	18.1
	44.1	15.35	17.9
	55.5	19.52	18.1
	4.32	0.97	11.6
	5.52	1.56	14.5
173-2363	3.29	0.76	11.9
	8.82	2.55	14.9
	7.16	2.01	14.4
	16.2	5.02	16.0
	16.5	5.09	15.9
	19.9	6.12	15.8
	20.6	6.43	16.1
	22.4	6.92	15.9
	24.3	7.61	16.1
	32.8	10.18	16.0
	40.3	12.37	15.8

TABLE 2. Current Meter Calibrations (Cont'd)

Meter no.	Speed cm/s	Counts rps	Braincon - rev/m Q-15 - pps/kt
173-2363	50.3	15.77	16.1
Cont'd.	58.4	18.29	16.1
	63.3	19.63	15.5
	69.1	21.24	15.8
173-2361	4.43	1.15	13.4
	19.1	6.39	17.2
	19.4	6.46	17.1
	34.8	13.69	20.3
	35.3	14.42	21.0
	44.9	23.62	27.1
	44.9	21.86	27.1
	45.5	28.58	32.2
	46.9	27.03	29.7
	51.2	24.88	25.0
	56.6	25.28	23.0
	58.8	25.88	22.7
	64.7	27.16	21.6
	76.1	26.90	18.2
369-2036	4.6	1.04	11.64
	10.8	3.70	15.7
	31.9	11.49	18.5
	32.4	11.12	17.7
	45.6	15.14	17.1

TABLE 3. Current Meter Calibration Summary

Current Meter	ϕ (rev/m)	σ_{ϕ}	σ_{ϕ}/ϕ
B96	2.408	0.051	0.021
B97	2.172	0.034	0.016
B98	2.63	0.0998	0.038
173-2361	UNCERTAIN DATA		
173-2362	6.96	0.136	0.020
173-2363	6.19	0.073	0.012
369-2036	6.17	0.390	0.058

Fig. 7. Braincon Current-meter Calibrations, I

Fig. 8. Braincon Current-meter Calibrations, II

Fig. 9. Bendix Q-15R Calibrations, I

Fig. 10. Bendix Q-15R Calibrations, II

$$Q-15: \frac{\epsilon_{\phi}}{\phi} \approx 0.017,$$

where ϵ_{ϕ} is error in measuring ϕ and ϕ is the number of revolutions per meter. These errors are comparable to the standard deviations from the linear range, except for heads 173-2361 and 369-2036.

3. Numerical Simulation of Current-meter Response

Both types of current meters used in this study are histogram, recording current meters. This means that current speed and direction are averaged over a certain time period (20 min for the Braincon current meters and 8 min for the Bendix Q-15 current meters). Thus, even if the response were perfect, the components of the average speed and direction would be, in general, not the same as the vector-averaged components. As will be shown in a later section, the relation between them is given by

$$\langle s \rangle e^{i \langle \theta \rangle} = \frac{\langle s e^{i\theta} \rangle - \langle s' e^{i\theta'} \rangle}{\langle e^{i\theta'} \rangle},$$

where s is the speed, θ is the angle (the velocity being expressed as a complex number), and

$$s = \langle s \rangle + s', \quad \theta = \langle \theta \rangle + \theta'.$$

This, however, is only half the story. If we let s be the true speed and s_o , the observed speed, then

$$s_o = f(s),$$

where f is the functional response of the current meter. This response can be approximated by,

$$s_o = \begin{cases} s (1 - e^{-\alpha(s-5.0)}), & s > 5.0 \text{ cm/s} \\ 0 & , s < 5.0 \text{ cm/s} \end{cases}$$

where α has been chosen = 0.6 s/cm.

Thus, what we are actually measuring is

$$\langle s_o \rangle e^{i\langle \theta \rangle}$$

Without a knowledge of the probability density function of s , it is not possible to relate s to s_o . It was decided, therefore, to try a simple numerical experiment to simulate the response of a current meter, using the power spectrum coherence and phase between two components as the compared variables.

A random, two-component time series was generated according to a method proposed by Thompson (1969), which possessed a known spectrum. The form of the spectrum chosen was

$$S(f) = \frac{S_o}{1 + bf^2}$$

This spectrum is flat at very low frequencies and falls off as f^{-2} at higher frequencies, which, as shown in Appendix III, might be expected. S_o and b were chosen to be representative of actual (observed) spectra. The two components of the current thus had similar spectra and a true coherence of 1.0 and a phase of 90.0° at all frequencies.

These currents were then used as input to a program that computed:

1. histogram-averaged currents with the approximate nonlinear-response function given above,
2. vector-averaged currents with the nonlinear response,
3. histogram-averaged currents without the nonlinear response, and
4. vector-averaged currents without the nonlinear response.

The computed "observed" currents were then spectrally analyzed in the usual manner; that is, autospectra were computed for both components as well as the cross-spectra, phase, and coherence. The results are presented in Figs. 11-22.

From the figures, one can see that below frequencies of 0.1 hr^{-1} all methods produce essentially the same results. Clearly, the best method is the vector-averaging method, even when the response of the meter is not

Fig. 11. Case, Phase vs. Frequency. Nonlinear Response, Histogram Averaging

Fig. 12. Case 2, Phase vs. Frequency. Nonlinear Response, Vector Averaging.

Fig. 13. Case 3, Phase vs. Frequency. Linear Response, Histogram Averaging.

Fig. 14. Case 4, Phase vs. Frequency. Linear Response, Vector Averaging.

Fig. 15. Case 1, Coherence vs. Frequency. Nonlinear Response, Histogram Averaging.

Fig. 16. Case 2, Coherence vs. Frequency. Nonlinear Response, Vector Averaging.

Fig. 17. Case 3, Coherence vs. Frequency. Linear Response, Histogram Averaging.

Fig. 18. Case 4. Coherence vs. Frequency. Linear Response, Vector Averaging.

Fig. 19. Case 1, Power Spectrum vs. Frequency. Nonlinear Response, Histogram Averaging.

Fig. 20. Case 2, Power Spectrum vs. Frequency. Nonlinear Response, Vector Averaging.

Fig. 21. Case 3, Power Spectrum vs. Frequency. Nonlinear Response, Vector Averaging.

Fig. 22. Case 4, Power Spectrum vs. Frequency. Linear Response, Vector Averaging.

linear; but even the worst method (nonlinear-response, histogram-averaging) gives reasonable results at periods greater than about three hours. At higher frequencies, the spectrum becomes flatter than the true spectrum and the coherence and phase between the two components become lower and more random, respectively. From these experiments, it is possible to conclude that the histogram-recording current meters give a reasonably accurate estimate of current components with periods longer than about three hours, but appear to enhance components with shorter periods.

4. Cassette-to-IBM-Tape Transcription Problem

During April and May of 1974, the cassette-to-IBM-tape transcriber, which had been used to process cassettes from the ANL data-acquisition system (16 bit BCD), was modified to read current-meter and thermograph cassettes (8 bit binary).

After this modification, current-meter test tapes were read incorrectly by the transcriber, but the acquisition-system tapes apparently were read correctly. Later, however, it became increasingly obvious that on acquisition-system tapes more errors were occurring than normally, which, because the data produced were entirely usable, previously had gone unnoticed.

Since troubleshooting the transcriber during the summer months would have produced an intolerable delay in data reduction of the acquisition-system tapes, its repair was deferred until fall. Also during this time, test current-meter records were saved for later reduction. These tests were run with special tapes to try to isolate the problem in the transcriber so that repair could be more easily accomplished.

During the troubleshooting procedure, a problem was discovered in the pulse-shaping circuitry within the cassette reader that caused marginal reading (marginal timing problems) of tapes produced by the current-meter cassette writer. This problem occurred when producing interrecord and interword gaps and did not affect the acquisition-system tapes as it did the current-meter tapes. The faulty component (a disc-ceramic capacitor) was due to a design change made at the factory on subsequent models of the reader. Factory information covering this change had not been forwarded to the Electronics Division engineer who designed the transcriber, which resulted

in the lengthy repair time. The change, when made, allowed correct transcription of current-meter records and cleaned up the bad data of earlier acquisition-system tapes.

5. Current-meter Design Problems

After repair of the tape transcriber, the current-meter records were reduced (in October 1974). Unfortunately, the data proved to be erroneous. The current-meter electronics package was recording what appeared to be random current speeds. This effect also made the current direction appear to be random although the directional data were correct. The speed error was caused by a basic design problem in the electronics package.

Speed is detected in the Bendix Model Q-15R by closing two reed switches in the duct that houses the impeller. Magnets, embedded in each impeller blade, pass near the two reed switches producing pulses that are convenient to count in typical digital electronics circuitry. Two switches are used in order to sense which closes first, thus indicating direction of impeller motion. This operation is necessary to obtain a true, steady-state current indication when orbital motion of the water is present, as in a wave zone. The electronic circuitry used involves decade counters that have inputs allowing for an add-subtract operation (up-down counters). One reed switch sets the counter in either mode (up or down). The mode is determined by the flow direction in the ducted impeller. The other reed-switch signal is used to advance the counter either up or down, depending on the condition of the direction reed switch at the time of count-switch closure. The design error involved switching the up-down input line during random states of the counter input line; doing so produced the random count situation. The foregoing problem was not discovered in initial bench tests, due to the difficulty of trying to produce random, up-down counting sequences. Initial tests accumulated known total counts in the up direction, followed by known total counts in the down direction. When used in this way, the electronic circuitry performed correctly.

Following discovery of the above problem, a new bench simulator was produced for initial tests of new units. The existing model of the current meter was quickly tested for two weeks in Lake Michigan during late November and early December, 1974, in preparation for winter deployment at Point

Beach. The lake test indicated proper operation, and the package was deployed on December 18, 1974.

6. Cable "Crosstalk" Problem

After recovery of the Q-15R electronics package, in March of 1975, data reduction indicated a malfunction of the speed-recording circuit, which usually produced a net count of zero. Investigation of this problem indicated capacitive coupling of the leading edge of the signal from the up-down switch into the counter input line. This coupling produced one extra count pulse on the counter input line, per magnet passage. The extra count occurred coincident with a change of voltage level on the up-down input line. The result of this "crosstalk" was to produce a count-up-one pulse followed by a "phantom" count-down-one pulse for every magnet passage. The final recorded result was usually a net current speed of zero.

Why this problem did not occur during the initial, *in situ* test is unclear. The most likely explanation is the difference in cable routing for the two moorings.

The problem was solved in May of 1975 by addition of a $1K\Omega$, $5nF$ integration circuit on the counter input line (see Fig. 5). The data produced since modifications of all packages appear to be correct.

7. Current-meter Moorings (Warm Weather)

Current-meter moorings for the spring and summer of 1974 were installed on April 30. Three mooring locations in water depths of 6.7, 9.4 and 15.8 m were selected. The moorings were positioned on a range line determined by a silo and the meteorological tower of the Point Beach nuclear generating station. Mooring stations were located approximately 390, 1,080, and 3,760 m offshore (Fig. 23).

The current meters were positioned either about 4 m or 7 m below the lake surface. Table 4 shows the station and depth associated with each record.

Each of the warm-weather mooring arrays consisted of a taut line sub-surface mooring for the current meter and a redundant recovery mooring. The redundant mooring consisted of a slack-moored spar buoy connected to a steel anchor (~ 70 kg). This redundant recovery mooring was connected to the taut-

TABLE 4. Current Meter Record Identification -
Warm-weather Moorings at Stations I-III
(Figure 23)

Time Period	Depth	Station I	Station II	Station III
Starting 4/30/74	3.6 m		B98741	
	4.3 m	B96741		
	4.6 m	Q1741 ^c		
	7.0 m		B97741	
5/2/74	3.6 m		B98742	
	4.3 m	B96742		
	4.6 m	Q1742 ^c		
	7.0 m		B97742	
6/17/74	3.6 m	Q1743 ^c	B98743	B96743 ^a
7/16/74	3.6 m	Q1744 ^c	B98744	B96744 ^a
	7.0 m		B97743	
8/27/74	3.6 m	Q1745 ^c	B98745	B96745 ^b
	7.0 m		B97744	
10/9/74	3.6 m	Q1746 ^c		B96746
	7.0 m		B97745 Q4741 ^c	

^aThe current meter was attached upside down to the mooring wire.
The data were bad.

^bOnly the last portion of the record had any value as the meter was
reinverted in mid-September.

^cThe data from the Bendix Q-15 meters were all bad due to design
problems in the recording system.

line mooring by a messenger line. The taut-line mooring consisted of another of these anchors, a current meter (or two), a subsurface float, and a slack-tethered, surface marker float. All lines used in these moorings were 3/8" braided nylon rope (breaking strength 18,700 N). The buoys were chosen so that in the worst case of total submergence, the net buoyancy would be substantially less than the anchor weight. Calculations of the drag exerted by the maximum expected currents showed that drag was negligible. All lines were terminated by clove hitches on shackles, stopped by a bowline above the clove hitch with the free end of the rope whipped to the standing part of the line. The line termination was then covered with vinyl tape to reduce chafing.

Two mooring configurations were employed for warm weather: the "U" mooring (Fig. 24) and the "N" mooring (Fig. 25). These configurations differ in the placement of the messenger line between the two vertical lines. In the "U" mooring, the messenger runs between the two anchors. The "N" mooring was designed to make recovery from the boat easier. In this case, it is only necessary to unclip the crossline from the spar buoy and to lift the assembly with this line. The spar mooring does not have to be lifted and may be used to moor the boat during the operation, which eliminates the problem of anchoring the boat when both the spar and the taut-line mooring must be pulled.

All the deployment, servicing, and recovery of warm-weather moorings were performed from a 6-m-length boat. From August onward, an electric capstan was used in place of the manual one used originally. Current meters were retrieved by divers as well as from the boat during this period. When recovered from the boat, two rope clamps were employed in a "hand-over-hand" fashion, using the electric winch. This technique is reliable but is very slow and tends to tip the boat toward the side from which the anchors are being lifted. The retrieval operation is difficult to perform when the waves are greater than about 0.3-m in height.

The wave-height restriction is not as important when divers are used to recover the meters. However, the availability of three trained divers may be a problem and scuba diving can be very exhausting when the waves are high or the air and water are cold.

The "N" mooring (Fig. 25) is serviced most easily from a boat. Both the "N" and "U" moorings are serviced equally well by divers.

Fig. 24. Schematic Diagram of a "U" Mooring.

Fig. 25. Schematic Diagram of an "N" Mooring

During this period, all warm-weather moorings were recovered successfully. No lines had parted, but in one instance there had been significant chafing of the taut-line mooring rope. This occurred on an "N" mooring where the crossline apparently had rubbed against the taut line, totally fraying the outer covering of the nylon rope.

The shackles showed no signs of wear but in some instances the "mousing" wire on the shackle pins was worn through. None of the terminations showed serious signs of wear.

The buoys held up well, although the subsurface floats tended to compress too much and to admit water. This tendency was not serious, as the flotation in these buoys is a type of plastic foam which maintains its buoyancy. There was a possibility that the outermost buoys had been run over at various times by barges or tugboats. (The run-down of a buoy was in fact observed in one instance when the servicing boat had to unmoor due to the approach of a tugboat and barge, whereupon the barge ran over a surface marker from the taut-line mooring. The barge was being pushed by a tug, from the Hannah Corp., which refused to change course in the presence of a moored vessel.)

The current meters showed no signs of damage. A large amount of periphyton, most likely *Cladophora* (Sp), had grown on the housing. Periphyton must be cleaned off periodically to maintain smooth functioning of the impeller bearing.

The warm-weather moorings operated very successfully, with the exception of the chafing problem when the "N" mooring was used. There was and is a very real danger presented by coastal shipping in the lake of running down moorings.

The following recommendations are made for future moorings:

1. "N" moorings should not be used, at least in the form described above,
2. a redundant mooring should be employed where practicable, because of the danger from shipping,
3. current meters should be serviced by divers, whenever practicable,
4. antifouling paint should be used to prevent fouling by periphyton,

5. the taut-line marker buoy should be as small as practicable, because of its possible effects in aliasing of the current record, and
6. stouter subsurface floats should be employed.

8. Current-meter Moorings (Cold Weather)

Cold-weather mooring conditions in the nearshore region can be severe. Typical problems include the formation of ice rafts, the buildup of frazil ice on anchors and lines, and the effects of strong wave motion, strong currents, ice formation on buoys, strong wind drag on buoys, and drifting material.

Ice rafting occurs when slabs of surface ice are blown into stationary ice, sliding upon or underneath the fixed ice. Such rafts can grow to considerable thickness. In Lake Erie, ice rafts may be ten meters or more in thickness (Foulds, 1974). Such ice rafts have been known to scour the lake bottom in the vicinity of power-plant intakes, causing severe damage to permanent structures.

Under certain circumstances, frazil ice will form on metal objects immersed in the water. Hoglund (personal communication) relates an instance in which an automobile engine block used as an anchor was buoyed to the surface by attached frazil ice.

Severe wave motion occurs during winter storms in Lake Michigan. There is evidence that during some of the worst storms of the century, sediments in sixty meters of water have been mixed by either current or wave action (Edgington, personal communication). In water as shallow as 10-20 m, longer period waves begin to "feel bottom" and the surge may cause scour around the anchors with attendant sinking into the bottom. Of greatest significance to mooring integrity are high waves that cause surging of the mooring assemblies.

Strong currents, winds, ice on buoys, and floating objects other than ice, probably are not as important to mooring longevity as the above factors. Currents are rarely above 0.5 m/s and the effects of wind stress on the buoys are about the same as the strongest currents. Floating objects are sufficiently rare that the probability of their encountering a mooring array is small [but not negligible -- one mooring array was destroyed off the Donald C. Cook power plant by a submerged log (Hoglund, personal communication)].

The above problems had to be considered when designing cold-weather moorings that would permit accurate current measurements and also possess a high probability of recovery.

The cold-weather mooring assembly possesses triply redundant capabilities. The primary location and recovery component is a surface spar buoy. This buoy is attached to an auxiliary anchor, which, in turn, is attached to the main anchor by a messenger and secondary-recovery array, consisting of a bottom line connecting the two anchors and a buoyed line attached to the bottom line (Fig. 26). The buoyed line constitutes the secondary location/recovery assembly. In the event that the primary assembly is lost, the secondary assembly is employed for recovery by dragging with a grappling hook. The tertiary location assembly consists of an electronic pinger attached to the current meter. The third assembly can be located by a scuba diver using a manual locator. The current meter is attached to the main anchor line and buoyed by a taut-line subsurface buoy. The entire mooring system is shown in Fig. 26.

The lines used in the mooring assembly consist of 3/8" GOLD-BRAID nylon rope. The rope is attached to standard shackles with a clove hitch and stopped with a bowline. The free end is whipped to the standing part of the line and the whipping is wrapped with vinyl tape. Even under the most severe conditions, this termination has shown no signs of significant wear. (The worst case observed consisted of the fraying of 4 to 5 strands of the outer braid at the clove hitch.) Where the worst wear would be expected, chain was used. The chains showed no sign of wear over the winter period.

Two types of shackles were used -- the *standard pin* and the *repair link*. In spite of careful "mousing" of the standard shackles, several were found to have loose pins when the assemblies were recovered. All the link-type shackles were found to be tight upon recovery.

The surface float was attached to the anchor line (Fig. 26) through a breakaway link. We feared that, in the event of strong easterly winds and extreme cold, ice rafting might occur, which could drag the entire mooring system from its known position or totally destroy it. It was necessary, therefore, to provide a mechanism whereby the surface float could break free if caught in ice and the stress on the anchor line exceeded the weight of the anchors. A weak-link was designed (Fig. 27) that would break if the force on it exceeded 445N. The link consisted of two semi-circular brass cylinders

Fig. 26. Schematic Diagram of the Cold-weather Mooring

Fig. 27. Schematic Diagram of the Weak Link

with two positioning pins which were wrapped with three turns of monofilament nylon line that was tied and melted to form a solid bond. Two holes were drilled in the cylinder to allow the attachment of shackles. These breakaway links worked too well. When it was time to recover the current meters, no surface float remained. Inspection of the recovered anchor lines showed that the weak links had failed. (Two surface buoys were subsequently recovered across the lake at Great Sable Point.)

The subsurface, current-meter floats consisted of large mooring buoys. These are about two feet in diameter and have a lifting capacity of 85 lbs (378 N). Upon recovery, they were found to be damaged and full of water but still possessing considerable buoyancy, as they are filled with polyurethane foam.

The cold-weather, current-meter moorings were deployed during the week of December 15, 1974. The farthest station was implanted on December 17, using the *R. V. AHA*, and was accomplished with considerable difficulty owing to waves and subfreezing conditions. For the deployment of the other meters, another boat, the *SHIRLINDA* was hired. Three more arrays were deployed on December 18.

The location of the moorings is shown in Fig. 23. All cold-weather moorings were positioned so that the secondary recovery line (the ground line) was perpendicular to and intersecting a range line formed by the Point Beach nuclear generating station's meteorological tower and a farm silo several miles back. The outermost mooring was located with a Motorola "Mini-Ranger" positioning system that failed before the inner two moorings could be positioned. These were surveyed with transits after deployment. (The accuracy was one minute of arc, which was quite sufficient.)

Anchors for the cold-weather moorings were lowered by means of auxiliary lines passing through a small sheave tied to each anchor. After the anchor was on the bottom, the line was pulled out of the sheave. This technique worked quite well with a minor problem of freezing of the line as it was removed from the water.

The day after deployment the surface buoy was observed to have the bell-shaped collar of ice surrounding it above the water line. This ice collar caused the buoy to tilt significantly.

The second Q-15 current-meter electronics package failed to transport the tape when it was stored. As the failure was obvious, we did not deploy the Q-15; thus, three Braincon current meters and one Bendix Q-15 current meter were deployed.

The first recovery of the cold-weather moorings was attempted on March 11, 1975. Both the Two Rivers and Manitowoc launching ramps were blocked with over four inches of ice. A crane was hired and the Great Lakes Research Project's new boat, the *R.V. ERDA I*, was lifted into the river opposite the Two Rivers Coast Guard Station. The boat then proceeded to the station site. No surface buoys were found. Due to a loss of transmission cooling fluid, the mission had to be cancelled before a search for the moorings could begin.

The second attempt at mooring recovery fared somewhat better. The first day's effort scheduled for April 8 was cancelled due to strong easterly winds. On the second day, the station nearest shore was located and marked with buoys. The moorings could not be recovered, however, due to high waves. On the third day, stations "A" and "B" were recovered and stations "C" and "E" were located and marked with buoys. The next day produced strong easterly winds and bad icing conditions. The boat was left in Two Rivers over the weekend and a new field crew drove up on Tuesday, April 15, to effect the final recovery.

The secondary location system performed very well. Transit fixes positioned the boat nearly over the mooring. On the average, only about 3-4 passes were required to grapple the buoyed mooring line. The grapnel was attached to a line several times as long as the water was deep and was weighted with a 6-kg lead block. The hook became tangled in the mooring of Station A (Fig. 23) and had to be left overnight with a buoy attached. No serious tangling problems occurred with the recovery of the other stations. At this point, it may be desirable to review the reliability of the hardware used in the cold-weather moorings.

The ropes, with one exception, fared very well. The exception was the cross-bottom line at station B (Fig. 28) at its point of attachment with the lead weight. We suspected that wave heave on the rope buoy either slid the lead weight back and forth across the rope or lifted the weight and dropped it repeatedly on the rope (Fig. 29). One of the lead weights showed severe deformation, lending credence to the second suspicion (Fig. 30).

Fig. 28. Bottom Profile and Cold-weather, Current-meter Locations, Point Beach, Wisconsin

Fig. 29. Worst Case of Rope-fraying - Cold-weather Mooring

Fig. 30. Effect of Winter Motions on a Lead Anchor

Fig. 31. Normal Rope Termination - No Fraying Evident

Knots and whippings held up very well. The electrical tape wrappings of the knots attaching the shackles and rings were intact in all cases. The clove hitches also were intact with very little apparent wear (Fig. 31). However, the electrical tape of the knots attaching the floats to the secondary recovery line became unwrapped in some cases. This indicates that a lashing/whipping should have been used to ensure that the knot did not "work." The string whippings were still intact.

The surface buoys that were blown across the lake have not yet been returned to Argonne, and no evaluation of the effect of the winter can be made until they are returned. That they survived the winter lake conditions to reach the eastern shore of Lake Michigan (with the ANL identification intact) indicates that any damage could not have been too severe.

The subsurface buoys did not fare as well. In the shallowest station, the small buoys were apparently intact and in good condition, whereas in the deeper stations they were damaged, apparently, by pressure (Fig. 32). On the other hand, even in the shallowest station (Fig. 33) the subsurface mooring buoys were damaged and had significant amounts of water inside.

The anchors showed no signs of deterioration. In some of the stations, a considerable amount of clay was attached to the steel block upon recovery, indicating that they had settled well into the bottom.

The current meters survived the winter reasonably well. There was some minor damage to the vanes of the Braincon current meters (Fig. 34), probably caused during recovery, but all impellers were working properly and no leakage was detected in any of the housings. The impellers were all turning freely. There was a small accumulation of sediment on the outer surface of the current-meter housings. A determination of how the fine suspended sediment affected the operation of the impeller bearings must await a recalibration of the current meters.

The weak links all parted. We suspect that this occurred during one week in January when one of the worst storms of the century passed directly over the mooring site. The links probably failed due to repeated flexing of the monofilament line, which finally parted.

In conclusion, the cold-weather moorings functioned adequately. Some hardware was lost but no instrumentation was lost or severely damaged. Despite

Fig. 32. Effect of Pressure on a Subsurface Buoy
(Secondary Recovery System)

Fig. 33. Effect of Pressure on a Subsurface Buoy
(Primary Current-meter Flotation)

Fig. 34. Crack in a Braincon Vane

the good results, we make the following recommendations for any future cold-weather moorings:

1. stronger, uncrushable subsurface floats should be used,
2. no surface buoys should be used,
3. a timed release should be used to deploy a marker-recovery buoy in the spring,
4. the secondary backup system should be kept as is,
5. an acoustic pinger should be attached to the recording package as a tertiary back-up system,
6. light chain should be used for the cross-bottom messenger line,
7. only the repair-link type of shackles should be used and these should be tightened very well, and
8. the small plastic spheres should be replaced by solid vinyl or glass spheres. These are more expensive than the buoys presently used, but will not crush.

B. DATA REDUCTION

After the film from the Braincon current meters is developed, it is read by the ALICE image-processing computer in Argonne's Applied Mathematics Division. ALICE produces a 9-track, magnetic tape that can be read by the IBM 370-195. One record is produced for each speed and direction average.

This tape is read by a preprocessing routine that converts the angular readings to calibrated velocity components, computes the times for each reading, and creates a data file in a standard data format (sdf), for use on the Great Lakes Research Project. This format (Table 5) is designed as a card-image record for ease in data exchange with other institutions.

The fields in the sdf record do not always contain data. The data in columns 69-70 are used to denote the temperature scale and the speed units, depending on whether the data are for winds or water currents. The default is for water-current data, in which case the code is CC. For raw wind data, the code is WF, and the speed is in miles/hr; the temperature is in °F.

TABLE 5. Standard Data Format (Fortran Convention)

Columns	Format (Fortran Convention)	Contents
1- 2	I 2	Last 2 digits of the year
3- 5	I 3	Day of the year
5- 8	I 3	Hour
9-10	I 2	Minute
11-15	I 5	X - position (m) in local coordinate system
16-20	I 5	Y - position (m) in local coordinate system
21-26	I 6	Northward velocity in mm 5'
27-32	I 6	Eastward velocity in mm 5'
33-37	F 5.1	Temperature in deg. C
38-40	I 3	Depth (m)
41-43	A 3	Instrument code
44-47	I 4	Run No.
48-51	I 4	Fluorometer Reading
52-55	F 4.1	Dissolved SO ²
56-59	I 4	Sequence Number
60-61	I 2	Reliability code
62-65	F 4.1	Speed
66-68	I 3	Direction (deg)
69-70	A 2	2 Letter use code
71-80	Blank	Reserved

After the data are in the standard format, the basic statistics are computed and the data are plotted in component form, as speeds and directions, as progressive-vector diagrams, as histograms, and as spectra. These data have also been used to determine the degree of predictability that may be obtained by linear optimal filters. Work on cross-spectral analysis between the current meters at different positions is now underway, as is the development of a program to obtain spectral estimates from unequally-spaced data. The general data processing system is illustrated in Fig. 35.

Fig. 35. Summary of Wind and Current Data, April 1974-April 1975

III. RESULTS

A. DATA RETURN

Four current meters were deployed in the Point Beach area in the period April 1974 through April 1975: three Braincon, histogram-recording current meters and one ANL-Bendix Q-15R system.

Due to problems with electronic circuitry, the Bendix Q-15R did not return valid current data. It did provide a good temperature record.

The Braincon current meters behaved reliably over most of the summer. Current meter no. B96 was removed for servicing after the first two weeks of operation. When reinstalled, it was moored upside down, resulting in 2-1/2 months loss of data. Current meters B97 and B78 performed satisfactorily over the entire spring, summer, and autumn.

Of the cold-weather moorings, only meter no. B96 returned reliable data. B97 was returned with a broken film-drive-spline shaft, and B98 had silt in the magnet housing and the bearings were fouled.

The MRI meteorological station functioned well except for a two-week period when the tail arm had been destroyed by a storm. While the instrument reliably returned data, the stability of the time base is open to doubt. This is discussed in more detail in the section on the prediction of currents by optimal filtering techniques (Sec IV.B.2). The data return is summarized in Fig. 36.

B. CURRENT AND WIND DATA

The data from the current-meter moorings at Point Beach, and the associated wind records, are presented in Appendices I and II. For each record, four plots are shown. The first plot is for the separate north and east components of the velocity and the instantaneous specific kinetic energy of the flow at each current meter. The second plot presents the same information, but in terms of speed and direction. The third plot provides a scatter diagram of each velocity vector in the record, along with histograms of each velocity component. The last plot shows the current data as a progressive vector diagram. These are all basically equivalent ways of representing the data, but some are more useful in certain contexts than others.

ANALYSIS SECTION

MODELS & SYNTHESIS

Fig. 36. General Current Meter Data Processing System

Although each record is not examined in detail, those features of the data that are common to all the records are pointed out. The most striking of these is the "burst" nature of the kinetic energy plots. We can see that most of the kinetic energy in the currents appears as short intense episodes, separated by relatively long periods of quiescence. That these current events are strongly coupled to the winds may be seen by comparing record B98743 with the wind record for the same period. In almost every instance, a peak of kinetic energy in the wind record may be associated with a corresponding peak in the current record. This is one of the best correlations. Comparing record B98744 with the wind record for the same period, the relationship between the current and the wind is not as clear. In this case, the peaks in current kinetic energy are more likely due to wind-direction variations than to wind-speed variations, the peak near day 206 probably resulted from the sudden shift of the wind toward the north (from a former easterly direction) and then damped as the wind again shifted toward the south (about noon). This record (see Fig. II.26) is distinguished from the previous one (see Fig. II.22) by its relatively constant wind speed, as opposed to the strongly varying speed of the former record and its more stable directions.

While we do not go into each record in detail, it is probably advantageous to consider the records in their entirety for the construction of statistical models that will assess the importance of the local wind on the nearshore circulation. These considerations are presented in the last section of the report.

One common feature of the data should be noted. In all cases, the velocity scatter diagrams (for example, Fig. I.3) show a strong relation between the current components. The strongest correlation is between north and west components. This is a very clear example of the effect of the shore and local topography on the currents in the area of the study. These elements force the currents into a shore-parallel mode, as observed by Sato and Mortimer (1974), Monahan (1975), and Frye et al. (1975).

Record B96745 is a peculiar record and is included as a warning to others who might wish to study currents in lakes or oceans. This record originated with a current meter that was installed in an inverted position, causing the compass to become locked to the speed mechanism. As a result, the directions are distributed almost uniformly on 0-360° while the velocity

component histograms have an unusual symmetry. The most revealing aspect of the data, however, is in the progressive-vector diagram (Fig. I.8). The rapid loops are obviously not associated with inertial period motions and clearly show that something is very wrong with the current meter. Actually, the problem was not first discovered from the vector representations of the current, but from the odd spectra that were produced by this motion. These spectra were almost flat at all frequencies.

Time Series Analysis

By their very nature, current meter data constitute a continuous vector time series. From this series, the current meter records averages of the current speed and direction every twenty or forty minutes for periods ranging from weeks to several months. By applying standard methods of time series analysis, we can obtain information about the energy content of the currents in various frequency bands, the typical times over which the currents remain correlated, the partitioning of energy between alongshore and offshore flow and the variation of energy as a function of space and time. Other information is also possible to obtain, such as the spatial coherence of the currents and the transfer mechanisms between the wind and the currents. Spatial coherence is not discussed in this report and the treatment of the transfer mechanism between the winds and the currents is considered in the last section, using the methods of optimal filtering.

Several difficulties stand in the way of obtaining good information through the techniques of time series analysis: the averaging processes and the nonlinearities of the current meters contaminate the data. The fundamental assumption upon which our standard techniques are based, that of second order stationarity, (and hence, ergodicity) is not verifiable and probably not valid. The data are sampled at finite, regularly spaced times that lead to the problem of aliasing, and, finally, the data records are of limited extent, which introduces uncertainty in the estimates of the spectrum (equivalently, truncation of the auto-correlation functions). These difficulties are very real and must not be minimized if one is to make valid use of the spectral data (see, for example, Jenkins and Watts - *Spectral Analysis and its Applications*, Holden-Day, 1968, pp. 209-318, for a discussion of spectral analysis and examples of some of the problems that may be encountered).

Nevertheless, if one is willing to take the above caveat into account, spectral analysis can be a useful tool for gaining insight into physical processes, as long as it is used only for that purpose and in conjunction with other methods to verify and study possible processes brought to light.

For this study, we have used only the simplest methods. The data are screened before processing to remove current speeds that are impossibly high and other unrealistic records. The currents are then separated into components, either north-south and east-west or, as used almost exclusively in this study, alongshore and offshore. The components are then input to a packaged program developed by the University of California, which computes estimates of the spectral components at various frequencies. This is a rather inflexible system, as it permits little or no modification (the source code is not available). A revised spectral analysis code will be used in later studies. The data are plotted in the following graphs as the variance of the current speed component in mm/sec versus the frequency in reciprocal hours. Both the alongshore and offshore components of the spectra are plotted.

The most striking feature, common to all the spectra, is the difference in the alongshore and offshore components, the alongshore component exceeding the offshore by nearly an order of magnitude. This excess is in agreement with observations in other lakes.

The second feature common to all the spectra is the rate at which the variance falls off with the frequency. An argument, presented in Appendix III, shows that under a few assumptions, the spectrum should fall off as the negative 2nd power of the frequency. The plots that follow neither contradict nor prove this argument as the error band is too wide. Other features of the spectra include weak peaks at the diurnal and uninodal seiche frequencies, but these are within the 90% error bounds and are not to be trusted. Aliasing is evident, as the spectra tend to flatten at frequencies near $0.3\text{--}0.4\text{ hr}^{-1}$. No strong evidence of inertial motion is found in the spectra, indicating that the current-meter records are all well within the coastal zone where inertial motions have been severely damped.

Something is to be gained by intercomparison of various spectral plots for current-meter records taken over the same time period. Consider records

B98744 and B97743 (Figs. 37 and 38). Here, both meters were located at the same station, meter no. 98 positioned below the surface about 4 m and meter 97 about 8 m. The depth of the water at this station was about 9 to 10 m. Here we can see that there was about four times as much energy in the currents at 4- as at the 8-m depth, in frequency bands ranging from 0.01 to 0.05 hr^{-1} .

If we consider records B96742, B97742, and B98742 (Figs. 39, 40, and 41), we can glean additional information. In this case, meters 96, 97, and 98 were positioned in locations of increasing distance from shore, respectively. Meters number 96 and 98 were set at a depth of about 4 m and number 97 at about 8 m. The spectrum from record B98742 shows a slightly larger amount of variance than from record B96742, although it is not statistically significant. On the other hand, both of these records show considerably more variance at low frequencies than record B97742, which was taken between the other two and at a greater depth. These features may be seen more clearly in Table 6.

Table 6. Total Variance of the Current for Each Period

Record	Total Variance ($\text{mm}^2 \text{s}^{-2}$)
B96742	3230.5
B96746	7571.9
B97741	1738.3
B97742	1422.1
B97743	1679.7
B97744	3590.0
B97745	1835.0
B98742	4952.9
B98743	5383.5
B98744	7003.9
B98745	8795.0

Fig. 37. Variance Spectrum of Current-meter Record 3-97-74

Fig. 38. Variance Spectrum of Current-meter Record 4-98-74

Fig. 39. Variance Spectrum of Current-meter Record 2-96-74

Fig. 40. Variance Spectrum of Current-meter Record 2-97-74

Fig. 41. Variance Spectrum of Current-meter Record 2-98-74

IV. PREDICTION OF NEARSHORE CURRENTS BY OPTIMAL LINEAR FILTERING TECHNIQUES

A. INTRODUCTION

Many numerical models for lake circulations use the linearized Navier-Stokes equations with a constant eddy diffusivity. These models are driven by an imposed wind stress at the surface, and, in some cases, thermal forcing is added. Little attention has been given to the ultimate possible performance of these models in predicting actual currents in the nearshore region. The work presented here addresses the question: What is the ultimate (or optimum) predictive capability of a linear model for nearshore currents, given the local wind at one point?

B. METHOD

1. General

Once the wind stress on the surface has been prescribed, a linear predictive model for currents behaves as a multiple input transfer function model. That is, the horizontal current components may be expressed by the relation:

$$U_i(t) = \sum_{k=1}^2 \int_0^t \tau_k(t - \xi) h_{ki}(\xi) d\xi; \quad i=1,2, \quad (1)$$

where τ_k are surface stress components and h_{ki} are the impulse-response function for the currents.

The method used here is to determine the optimal transfer function h_{ki} , given the wind at one location (and a relationship giving τ_k from the wind vector) and the current in the lake ($U_i(t)$). From these components, a predicted current may be obtained and compared with the observed current. Ideally, agreement would be perfect, and it would be possible to conclude that a linear model with constant eddy diffusivities could predict the currents. On the other extreme, if there were no relationship between the predicted and observed current, it could then be concluded that no linear model could predict the local currents, given only the local winds.

The technique for producing an optimal linear filter, given both the input and the output, was published as an appendix to Wiener's book *Time Series* by Norman Levinson (1949), which described single-input, single-output time series. This technique has been expanded for multiple input time series and is presented below.

Suppose we are given several inputs and one output time series represented by $\tau_k(t)$, $k=1, m$ (inputs) and $U(t)$ where t assumes integral values. Thus:

$$\hat{U}(t) = \sum_{k=1}^m \sum_{i=0}^L \tau_k(t-i) H_k(i), \quad (2)$$

where $\hat{U}(t)$ is the predicted output. (Note: this is the digital approximation to (1).) We wish to determine $H_k(i)$ ($i=0, \dots, L$) so that

$$I = \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^{t=N} (U(t) - \hat{U}(t))^2 \quad (3)$$

is minimized.

Expanding Eq. 3, we have,

$$I = \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^{t=N} \left\{ U^2(t) - 2U(t) \sum_{k=1}^M \sum_{i=0}^L \tau_k(t-i) H_k(i) + \sum_{k=1}^M \sum_{i=0}^L \tau_k(t-i) H_k(i) \sum_{k'=1}^M \sum_{i'=0}^L \tau_{k'}(t-i') H_{k'}(i') \right\} \quad (4)$$

A necessary condition that I possess a minimum in $H_k(i)$ space is that

$$\frac{\partial I}{\partial H_k(i)} = 0 \quad ; \quad k=1, \dots, m; i=0, \dots, L, \quad (5)$$

or

$$\lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^N \tau_k(t-i) \left[U(t) - \sum_{k'=1}^M \sum_{i'=0}^L \tau_{k'}(t-i') H_{k'}(i') \right] = 0. \quad (6)$$

or

$$\lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^N \tau_k(t-i) U(t) = \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^N \sum_{k'=1}^M \sum_{i'=0}^L H_{i',(i')} \tau_k(t-i) \tau_{k'}(t-i') \quad (7)$$

Interchanging the order of summation, the right-hand side of the equation becomes:

$$\sum_{k'=1}^M \sum_{i'=0}^L H_{k',(i')} \left\{ \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^N \tau_k(t-i) \tau_{k'}(t-i') \right\} \quad (8)$$

Define

$$\phi_{\alpha\beta}^\varepsilon(i,j) = \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N-\varepsilon}^{t=N-\varepsilon} \alpha(t-i) \beta(t-j) \quad (9)$$

Thus Eqs. 7 and 8 may be rewritten as:

$$\phi_{\tau_k u}^0(i,0) = \sum_{k'=1}^M \sum_{i'=0}^L H_{k',(i')} \phi_{\tau_k \tau_{k'}}^0(i,i') \quad (10)$$

Note:

$$\sum_{t=-N}^{t=N} \alpha(t-i) \beta(t-j) = \sum_{\xi=-N-j}^{\xi=N-j} \alpha(\xi+j-i) \beta(\xi), \quad (11)$$

where

$$\xi = t - j \text{ or } t = \xi + j. \quad (12)$$

Thus,

$$\phi_{\alpha\beta}^0(i,j) = \phi_{\alpha\beta}^j(i-j,0). \quad (13)$$

If the time series are second-order stationary, $\phi_{\alpha\beta}^0(i,j) = \phi_{\alpha\beta}^0(i-j,0) \triangleq \phi_{\alpha\beta}(i-j)$. The governing Eq. 10 may be written:

$$\begin{aligned} \phi_{\tau_k} u(i) &= \sum_{k'=1}^M \sum_{i'=0}^L H_{k'}(i') \phi_{\tau_k \tau_{k'}}(i-i') \\ &; \quad k, k' = 1, 2, \dots, m \\ &; \quad i, i' = 0, 1, \dots, L. \end{aligned} \quad (14)$$

$$\text{In practice } \phi_{\alpha\beta}(i) \triangleq \frac{1}{2N+1} \sum_{t=0}^{2N} \alpha(t-i)\beta(t). \quad (15)$$

Thus the estimated coefficients of the impulse response function are given by:

$$\hat{\phi}_{\tau_k} u(i) = \sum_{k'=1}^M \sum_{i'=0}^L \hat{H}_{k'}(i') \hat{\phi}_{\tau_k \tau_{k'}}(i-i'). \quad (16)$$

The value of the minimizing functional, I , is given by:

$$\min[\hat{I}] = \hat{I}_m = \hat{\phi}_{uu}(0) - \sum_{k'=1}^M \sum_{i'=0}^L \hat{H}_{k'}(i') \hat{\phi}_{\tau_k \tau_{k'}}(i'). \quad (17)$$

This may be normalized by $\hat{\phi}_{uu}(0)$ to give

$$V_M = 1 - \sum_{k'=1}^M \sum_{i'=0}^L \hat{H}_{k'}(i') \frac{\hat{\phi}_{\tau_k u}(i')}{\hat{\phi}_{uu}(0)}, \quad (18)$$

$$\triangleq 1 - E_M, \quad (19)$$

To understand the meaning of V_M and E_M , recall that we can rewrite V_M as

$$V_M = \frac{\sum_{\text{all } t} [u(t) - \hat{u}(t)]^2}{\sum_{\text{all } t} [u(t)]^2}, \quad (20)$$

or if we define an error time series, $\varepsilon(t)$, by

$$\varepsilon(t) \triangleq u(t) - \hat{u}(t) \quad (21)$$

and the variance in the usual fashion, then

$$V_M = \frac{\sigma_\varepsilon^2}{\sigma_u^2} \quad \text{and} \quad E_M = 1 - \frac{\sigma_\varepsilon^2}{\sigma_u^2} \quad (22)$$

Now

$$\sigma_u^2 = \sigma_\varepsilon^2 + \sigma_{\hat{u}}^2 + \phi_{\varepsilon\hat{u}}(0) \quad (23)$$

If the errors and the estimated velocities are uncorrelated, $\phi_{\varepsilon\hat{u}}(0) = 0$. This can be computed as follows:

$$\phi_{\varepsilon\hat{u}}(0) = \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^N \hat{u}(t) [u(t) - \hat{u}(t)] \quad (24)$$

$$= \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^N (u\hat{u} - \hat{u}^2) \quad (25)$$

$$= \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{t=-N}^{t=N} \left[u \sum_{k=1}^M \sum_{i=0}^L H_k(i) \tau_k(t-i) - \sum_{k=1}^M \sum_{i=0}^L \sum_{k'=1}^M \sum_{i'=0}^L H_k(i) H_{k'}(i') \tau_k(t-i) \tau_{k'}(t-i') \right] \quad (26)$$

$$= \lim_{N \rightarrow \infty} \frac{1}{2N+1} \sum_{k=1}^M \sum_{i=0}^L H_k(i) \left[\sum_t u(t) \tau_k(t-i) - H_k(i) \sum_{k'=1}^M \sum_{i'=0}^L H_{k'}(i') \sum_t \tau(t-i) \tau(t-i') \right] \quad (27)$$

and, invoking second-order stationarity,

$$= \sum_{k=1}^M \sum_{i=0}^L H_k(i) \left[\phi_u \tau_k(i) - \sum_{k'=1}^M \sum_{i'=0}^L H_{k'}(i') \phi_{\tau_k \tau_{k'}}(i-i') \right] \quad (28)$$

The bracketed term is identically zero from Eq. 14, thus $\hat{u}(t)$ and $\varepsilon(t)$ are uncorrelated and therefore

$$\sigma_u^2 = \sigma_u^2 + \sigma_\varepsilon^2 \quad (29)$$

Thus:

$$E_M = 1 - \frac{\sigma_\varepsilon^2}{\sigma_u^2} = \frac{\sigma_u^2 - \sigma_\varepsilon^2}{\sigma_u^2} = \frac{\sigma_{\hat{u}}^2 + \sigma_\varepsilon^2 - \sigma_\varepsilon^2}{\sigma_u^2} = \frac{\sigma_{\hat{u}}^2}{\sigma_u^2} \quad (30)$$

Therefore, E_m is the fractional amount of the variance of the output time series, $u(t)$, that can be accounted for by the predicted time series, $\hat{u}(t)$; V_m is the fractional amount of the variance that cannot be accounted for by the optimal linear filter.

In this development, we have shown only that the necessary condition for a minimum of the functional, I , has been satisfied. It is still necessary to show that this is also sufficient.

We can rewrite the expression for I as:

$$I = \sum_i [u(t_i) - \hat{u}(t_i)]^2.$$

Let

$$\hat{u}_i \triangleq \hat{u}(t_i) = \sum_k a_k \tau_{ki}, \quad (31)$$

where

$$\tau_{ki} \triangleq \tau_k(t_i).$$

By a Gram-Schmidt orthonormalization, we can always construct an orthonormal sequence of functions, $\phi_\ell(t_i) = \phi_{\ell i}$ so that

$$\phi_{\ell i} = \sum_k \beta_{\ell k} \tau_{ki}, \quad (32)$$

or

$$\tau_{li} = \sum_k \gamma_{kl} \phi_{ki}, \quad (33)$$

and

$$\sum_i \phi_{li} \phi_{mi} = \delta_{lm} = \begin{cases} 0 & \text{if } l \neq m \\ 1 & \text{if } l = m \end{cases}; \quad (34)$$

$$I = \sum_i u_i u_i - 2 \sum_i u_i \hat{u}_i + \sum_i \hat{u}_i \hat{u}_i \quad (35)$$

$$= \sum_i u_i u_i - 2 \sum_i u_i \sum_k a_k \tau_{ki} + \sum_i \sum_k a_k \tau_{ki} \sum_l a_l \tau_{li}. \quad (36)$$

For simplicity of notation, we shall now use the tensor summation convention so:

$$I = u_i u_i - 2 u_i a_k \tau_{ki} + a_k a_l \tau_{ki} \tau_{li}, \quad (37)$$

$$= u_i u_i - 2 u_i a_k \gamma_{lk} \phi_{li} + a_k a_l \gamma_{mk} \phi_{mi} \gamma_{nl} \phi_{ni}, \quad (38)$$

$$= u_i u_i - 2 u_i a_k \gamma_{lk} \phi_{li} + a_n a_l \gamma_{mk} \gamma_{nl} \delta_{mn}, \quad (39)$$

$$= u_i u_i - 2 u_i a_k \gamma_{lk} \phi_{li} + a_k a_l \gamma_{nk} \gamma_{nl}, \quad (40)$$

Let

$$b_l \equiv a_k \gamma_{lk}. \quad (41)$$

So

$$I = u_i u_i - 2 u_i b_l \phi_{li} + b_l b_l. \quad (42)$$

So

$$\frac{\partial I}{\partial b_p} = -2 u_i \phi_{pi} + 2 b_p, \quad (43)$$

$$\frac{\partial^2 I}{\partial b_p \partial b_q} = 2\delta_{pq}. \quad (44)$$

Thus, everywhere, the matrix $[\partial^2 I / \partial b_p \partial b_q]$ is positive definite. The critical point is located where

$$\frac{\partial I}{\partial \phi_p} = 0 = -2u_i \phi_{pi} + 2b_p,$$

or

$$b_p = u_i \phi_{pi}, \quad (45)$$

or

$$a_k \gamma_{pk} = u_i \phi_{pi}. \quad (46)$$

Multiplying by γ_{pq} ,

$$a_k \gamma_{pk} \gamma_{pq} = u_i \gamma_{pq} \phi_{pi} = u_i \tau_{qi}, \quad (47)$$

but

$$\gamma_{pk} \gamma_{pq} = \gamma_{lk} \phi_{li} \gamma_{pq} \phi_{pi} = \tau_{ki} \tau_{qi}. \quad (48)$$

So

$$a_k \tau_{ki} \tau_{qi} = u_i \tau_{qi}, \quad (49)$$

which is the equation for the critical point expressed in terms of the base functions, τ_k , proving that the functional I is a true minimum at the critical point.

The theory was developed under the assumption that the time series were infinite. In practice this is impossible, thus raising the question of what is the effect of truncating the time series. If we define

$$\hat{\phi}_{\alpha\beta}^{\text{EN}}(i,j) = \frac{1}{2N+1} \sum_{\tau=-N-\epsilon}^{N-\epsilon} \alpha(t-i)\beta(t-j), \quad (50)$$

all our results will carry over if

$$\hat{\phi}_{\alpha\beta}^{\text{ON}}(i,j) = \hat{\phi}_{\alpha\beta}^{\text{jN}}(i-j,0) = \hat{\phi}_{\alpha\beta}(i-j). \quad (51)$$

This is a somewhat stronger condition than second-order stationarity. For lack of a better term, we shall denote this condition by "finite second-order stationarity."

2. Filter Application

In a series of numerical experiments, optimal linear filters were computed using one or two components of wind stress as inputs and shore parallel current in the lake as the output time series.

The winds were measured as an hourly average at the intake crib of the nuclear generating station at Point Beach, Wisconsin. The instrument was located about 900 m from shore and about 4 m above the lake surface. The intake crib is sufficiently large and the wind sensor is mounted about 1 1/2 m above the crib structure so that the wind field is undoubtedly influenced by the crib. The time base of the wind recorder is not entirely reliable but has been corrected as much as possible (by linear interpolation) for the series of experiments described here.

The lake currents were measured with Braincon Corporation, Model 381, histogram, recording current meters. These were modified by the addition of ENDECO ducted impellers to reduce the rectifying effect that the original Savonius rotors had in the presence of a wave field. The current measurements were taken about 1 km south of the wind sensor. The current meters gave averaged currents and directions every twenty minutes. The effects of histogram averaging and of the nonlinear response of the current meters were not important at frequencies below about 0.25 cycles/hr. Above that frequency, these effects and aliasing cause an overestimation of the energy in this region of the frequency band. This led to the decision to use low-pass filtered winds and currents in some of the filter generation runs. In these runs, only the shore parallel component of the current was used as an output function.

The input or driving time series are not the winds but actually the wind stresses. A number of different stress "laws" have been used in air-sea interaction studies. In the present study three models for the wind stress are used:

$$1. \quad \tau_i \propto W_i, \quad (\tau_1),$$

$$2. \quad \tau_i \propto W_i |W|, \quad (\tau_2),$$

$$3. \quad \tau_i \propto W_i |W|^{1.5}; i=1,2, \quad (\tau_3),$$

where τ_i are the components of the wind stress and W_i are the components of the wind.

The optimal filters were computed according to the theory presented in the previous section, to accomplish which a FORTRAN program was written. Due to limitations of the matrix inversion subroutine employed, a maximum of about 32 (total number) coefficients could be determined, which limited the testing the applicability of the technique.

The results of 10 experiments are summarized in Table 7. From which we see:

1. Two wind components produce "better" filters than when the shore parallel component alone is used.
2. Different wind stress "laws" have little effect on the "goodness" of the filter, although linear "law" seems to give the best results.
3. When low-pass filtered wind data are used, the filter is unstable.
4. Increasing the number of coefficients (cases 8 and 10) has no effect on the goodness of fit.
5. Using only wind data as inputs, the largest value of E_m is about 0.80.

The major conclusion from these experiments is that: given the wind at one point, the current as measured nearby is not well predicted by an optimal linear filter. Possible causes for this discrepancy include:

TABLE 7. Summary of Numerical Experiments to Obtain Optimal Filters

Experiment Number	No. Inputs	Wind L.P. Filtered	Current L.P. Filtered	Stress Law	No. Coef.	E_m	σ_ϵ	Stable?
1	1	X	X	W	21	0.54	0.42	
2	1		X	W	21	0.54	0.42	X
3	1			W	21	0.55	0.48	X
4	1	X	X	$W W $	21	0.54	0.46	
5	2	X	X	W	11	0.81	0.52	
6	2	X	X	$W W $	11	0.75	0.32	
7	2	X	X	$W W ^{1.5}$	11	0.69	0.35	
8	2			W	11	0.80	0.32	X
9	2			$W W $	11	0.74	0.37	X
10	2			W	16	0.80	0.32	X

1. errors in the time base for the wind measurements,
2. effects of averaging in the anemometer and current meters,
3. digitizing error in the wind data,
4. superimposed lake currents not generated by local winds,
5. error in the choice of wind stress formula,
6. anisotropy of the drag coefficients for wind stress calculations, and
7. variations of the drag coefficient with atmospheric stability under rainy conditions.

These sources of error are discussed separately. The first three sources of error are instrumental and can be eliminated by a proper choice of instruments. The next is physical, and the last two depend on the relation of wind stress to the measured wind.

3. Time Base Errors

The wind instrument was an MRI Model 1071, mechanical recording anemometer. The wind speed and direction were recorded as an analog record on a strip chart driven by an electrically wound mechanical clock. The time base for these records has been found to be several days off at the end of the month. For the cases discussed here, the error was corrected by deleting about one hour of data per day. This correction method is probably not very good as it appears from the actual wind record that the variations in the time base were not uniform but, to the contrary, occurred in discrete jumps (on occasion). The only remedy for this source of inaccuracy is a better time base, which has been incorporated into the wind sensor to be used in future experiments.

4. Averaging Effects and Sensor Nonlinearity

The wind sensors and current meters act as histogram-averaging flow sensors: that is, they average the speed and direction separately over a given time interval. The results produced are quite different from those of a vector-averaging flow sensor wherein the two components of the (horizontal) velocity are averaged separately. To illustrate let $s = s(t)$ be the speed, $\theta = \theta(t)$ be the direction and express the velocity as a complex number

$$v = se^{i\theta} = s(t)e^{i\theta(t)} \quad (52)$$

such that $\text{Re}(v)$ and $\text{Im}(v)$ are the easterly and northerly components of the velocity, respectively. Let $\langle \phi \rangle$ denote an average of a random variable, ϕ . Furthermore, define

$$\begin{aligned} s' &= s - \langle s \rangle \\ \theta' &= \theta - \langle \theta \rangle \end{aligned} \quad (53)$$

$$v' = v - \langle v \rangle$$

$$\text{Furthermore define } \psi = e^{i\theta} \quad (54)$$

$$\text{and } \psi' = \psi - \langle \psi \rangle. \quad (55)$$

Then

$$\begin{aligned} \langle v \rangle &= \langle s \psi \rangle = \langle (\langle s \rangle + s') (\langle \psi \rangle + \psi') \rangle; \\ &= \langle \langle s \rangle \langle \psi \rangle \rangle + \langle s' \langle \psi \rangle \rangle + \\ &\quad \langle \langle s \rangle \psi' \rangle + \langle s' \psi' \rangle; \\ &= \langle s \rangle \langle \psi \rangle + \langle s' \psi' \rangle. \end{aligned} \quad (56)$$

Now

$$\begin{aligned} \langle \psi \rangle &= \langle e^{i(\langle \theta \rangle + \theta')} \rangle; \\ &= \langle e^{i\langle \theta \rangle} e^{i\theta'} \rangle; \\ &= e^{i\langle \theta \rangle} \langle e^{i\theta'} \rangle; \end{aligned} \quad (57)$$

so

$$\langle v \rangle = \langle s \psi \rangle = \langle s \rangle e^{i\langle \theta \rangle} \langle e^{i\theta'} \rangle = \langle s' \psi' \rangle, \quad (58)$$

or

$$\begin{aligned} v &= \langle s \rangle e^{i\langle \theta \rangle} = \frac{\langle v \rangle - \langle s' \psi' \rangle}{\langle e^{i\theta'} \rangle} \\ &= \frac{\langle v \rangle - \langle s' e^{i\theta'} \rangle}{\langle e^{i\theta'} \rangle} \end{aligned} \quad (59)$$

Now this is the velocity we measure by histogram averaging flow meter. If the current speed residuals are distributed independently of the direction residuals, then $\langle s'e^{i\theta'} \rangle = 0$ and

$$V = \frac{\langle v \rangle}{\langle e^{i\theta'} \rangle} . \quad (60)$$

A further effect that complicates the picture is the low-speed non-linearity of the flow sensors. The Braincon current meters do not sense flows of less than about 0.05 m/s and have a nonlinear response between about 0.05 and 0.10 m/s. The wind sensor has a threshold of less than 0.22 m/s speed and 0.33 m/s in direction. Simulation experiments (see Sec. II.A.3) indicate that the nonlinear effects in the current meters are of about the same order as the histogram-averaging effects. The nonlinear and threshold effects are less in the wind instrument due to the smaller relative threshold.

5. Digitizing Error

The digitizing errors are a third source of contamination. The winds were digitized manually to the nearest 1/2-1 mi/hr. For a typical wind of 5-10 mi/hr, this amounts to a maximum error of about 10%. The direction was estimated to the nearest 10°, thus the digitizing error is on the order of $5^\circ/360^\circ \approx 1\%$.

The resolution of the Braincon current meters is 0.3% for direction and about 0.0028 m/s which, for a typical speed of 0.10 m/s, is about 3%. The typical digitizing errors to be expected are given below:

	<u>Speed</u>	<u>Direction</u>
MRI wind sensor	10%	1 %
Braincon current meter	3%	0.3%

The error is negligible for the current meter, but could be significant for wind observations, particularly at the lower speeds.

6. Superimposed Lake Currents

The current regime in the lake is produced by the total wind stress field over the lake and by thermal forcing, and is modified by nonlinear interactions and by bottom and lateral boundary conditions. The nearshore currents may be decomposed into locally produced currents and those produced by forces acting elsewhere in the lake, whose effects, nevertheless, are felt in the nearshore region. As the transfer function model takes only local winds into account, currents produced by wind variation over the lake as a whole are treated as a residual error term.

7. Choice of the Wind-stress Formula

It is ordinarily assumed that the wind stress, τ , over the water obeys a law of the form

$$\vec{\tau} = \rho C_D \vec{U} |\vec{U}|,$$

where τ is directed in the direction of the wind, $\vec{U}$. Usually C_D is assumed constant with a typical value being 0.0015 - 0.003 (Roll, 1965). Several other relations have been assumed, though it is generally agreed that C_D is an increasing function of the wind speed.

For this reason, the three formulas, τ_1 , τ_2 , and τ_3 were tried. Little difference was found, though τ_1 gave slightly better results than the other two. Because of this, it seems that the choice of the wind stress formula will not account for the residual variance.

8. Anisotropy of the Drag Coefficient

As this study deals with currents in the nearshore region, the wave regime will depend on the direction from which the wind is blowing (and also on the recent history of the wind speed and direction). In turn, this will cause the surface roughness (and thus the drag coefficient) to be anisotropic.

The wind stress formulas used do not take this variation into account. At present the magnitude of this effect is unknown.

C. DISCUSSION OF THE RESULTS

That the "linear stress law" should provide a better filter may seem surprising. However, this is not unexpected. Ekman (1905) concluded from empirical data that the magnitude of the horizontal velocity was proportional to the wind speed:

$$V_o = \frac{0.019W}{\sqrt{\sin \phi}},$$

where ϕ is the latitude.

Witting (1909) indicates a proportionality of the form:

$$V_o = 0.48 \sqrt{W}.$$

Various forms for the surface wind stress have been reported. Some of these are summarized in the table below:

Table 8. Summary of Wind Stress Power Laws

Author	Wind Stress Formula
Taylor (1916)	$\tau = C_D \rho W^2$
Ekman (1905)	$\tau = 3.2 \times 10^{-6} W^2$
Hellström (1914)	$\tau = 9.3 \times 10^{-6} W_{(6m)}^{1.8}$
Bryson et al. (1952)	$\tau = 1.5 \times 10^{-4} W_{(5m)}^5$ (Smooth Water)
Van Dorn (1953)	$\tau = 1.2 \times 10^{-6} W_{(10m)}^2$ ($W_{(10m)} < 5.6$) $= 1.2 \times 10^{-6} W_{(10m)}^2$ $+ 2.25 (W_{(10m)} - 5.6)^2$ $(W_{(10m)} \geq 5.6)$

Several authors have observed that the eddy viscosity, A_z , is also a function of wind speed. Ekman (1905) suggests the form

$$A_z = 4.3 \times 10^{-4} W^2, W > 6 \text{ m/sec},$$

whereas Thorade suggests

$$A_z = 1.02 \times 10^{-6} W^3, W < 6 \text{ m/sec}.$$

If the Taylor stress formula and the Ekman formula are used, the condition of matching the surface stress in the air and water becomes

$$\tau = \frac{\partial u}{\partial z}$$

and

$$C_D \rho (W)^2 = C W^2 \frac{\partial u}{\partial z},$$

so:

$$\frac{\partial u}{\partial z} = C_0$$

Now, in the ordinary Ekman theory, we have

$$\frac{\partial u}{\partial z} \Big|_{z=\text{surface}} = C_1 V_o \frac{1}{\sqrt{A_z}}.$$

therefore:

$$V_o = \frac{C_0}{C_1} \sqrt{A_z} = \left[\frac{C_0}{C_1} \sqrt{C} \right] W = C_2 \cdot W,$$

$$(C, C_0, C_1, C_2 \text{ constants}),$$

which is what Ekman deduced from Colding's 1876 data.

In general, if the stress law is given as

$$\tau = (\text{const.})W^m,$$

and the eddy viscosity as

$$A_z = (\text{const.})W^n$$

then

$$V_o = (\text{const.})W^{m-n/2}.$$

The results of various stress and eddy viscosity laws are presented in the table below.

Table 9. Velocity Dependence on Eddy Viscosity and Wind Stress Power Laws

Eddy Viscosity Law	Wind Stress Law		
	Taylor $m=2$	Hellström $m=1.8$	Bryson et al. $m=5$
Ekman $n=2$	W	$W^{0.8}$	W^4
Thorade $n=3$	$W^{0.5}$	$W^{0.3}$	$W^{3.5}$

Thus the second result of this study appears to confirm the Ekman suggestion that the current speed is proportional to the first power of the wind speed (see Table 10 and Fig. 42).

Table 10. Summary of Variation of E_m with Power Law Wind Stress Exponent

n	E_m
0.5	0.760
0.8	0.791
1.0	0.801
1.2	0.804
1.5	0.794

$$\overline{\tau} = \hat{W} |W|^n, \quad \hat{W} \equiv \frac{\overrightarrow{W}}{|W|}$$

Fig. 42. Plot of E_m vs. n .

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APPENDIX I
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APPENDIX III

REPRESENTATION OF THE VELOCITY FREQUENCY SPECTRUM
IN THE INERTIAL SUBRANGE

APPENDIX III. REPRESENTATION OF THE VELOCITY FREQUENCY SPECTRUM IN THE INERTIAL SUBRANGE

- Assumptions:
- (1) That for a certain frequency range in the energy spectrum
    - a) there is no energy added, and
    - b) there is no energy dissipated (i.e., in the subrange, $S(\omega)$ is independent of viscosity);
  - (2) The frequency spectrum may be specified only by the viscosity and the dissipation rates as external parameters, $S(\omega) = f(\omega; \nu, \epsilon)$.

One nondimensional number may be extracted from ω, ν, ϵ {with the exception of its powers - these count as the same parameters}.

Proof: let $\omega^\alpha \nu^\beta \epsilon^\delta = \text{const}$ in their units,

$$\left(\frac{1}{T}\right)^\alpha \left(\frac{L^2}{T}\right)^\beta \left(\frac{L^2}{T^3}\right)^\delta = \text{const} \rightarrow 2\beta + 2\delta = 0 \rightarrow \beta = -\delta$$

$$\alpha + \beta + 3\delta = 0 \rightarrow \alpha - \delta + 3\delta = \alpha + 2\delta = 0 \rightarrow \alpha = -2\delta$$

Thus: $\omega^{-2\delta} \nu^{-\delta} \epsilon^\delta = \left(\frac{\epsilon}{\nu \omega^2}\right)^\delta$;

with the exception that $\frac{\epsilon}{\nu \omega^2}$ may be raised to any power, δ , this is the only nondimensional number arising from the 3 parameters.

The units of $S(\omega)$ are $\left[\frac{L^2}{T}\right]$. The possible ways of producing such units among the three parameters are

$$(\omega, \nu) \rightarrow \left[\omega^\alpha \nu^\beta\right] = \left[\frac{L^2}{T}\right] \rightarrow \begin{matrix} \alpha + \beta = 1 \\ 2\beta = 2 \end{matrix} \rightarrow \omega^0 \nu^1 = \nu$$

$$(\omega, \epsilon) \rightarrow \left[\omega^\alpha \epsilon^\beta\right] = \left[\frac{1}{T}\right]^\alpha \left[\frac{L^2}{T^3}\right]^\beta = \left[\frac{L^2}{T}\right] \rightarrow \begin{matrix} 2\beta = 2 \rightarrow \beta = 1 \\ \alpha + 3\beta = 1 \rightarrow \alpha = -2 \end{matrix} \rightarrow \left(\frac{\epsilon}{\omega^2}\right)$$

$$(\nu, \epsilon) \rightarrow \left[\nu^\alpha \epsilon^\beta\right] = \left[\frac{L^2}{T}\right]^\alpha \left[\frac{L^2}{T^3}\right]^\beta = \left[\frac{L^2}{T}\right] \rightarrow \begin{matrix} 2(\alpha + \beta) = 1 \rightarrow \beta = 0 \\ \alpha + 3\beta = 1 \end{matrix} \rightarrow \nu$$

Thus: The only dimensionally correct representation of $S(\omega)$ is

$$S(\omega) = \left(\frac{\epsilon}{\omega^2}\right) f\left(\frac{\epsilon}{\nu\omega^2}\right) + \nu g\left(\frac{\epsilon}{\nu\omega^2}\right),$$

by assumption (1)b,

$$\begin{array}{l} g \rightarrow 0 \\ f \rightarrow \text{constant} \end{array} \rightarrow \frac{\partial S(\omega)}{\partial \nu} = 0 \rightarrow S(\omega) = K_s \epsilon \omega^{-2},$$

where K_s is a universal constant.

Hence for any current meter record, $P_\epsilon = \omega^2 S(\omega)$ should be approximately constant and therefore $P_\epsilon = K_s \epsilon$. Hence, from one spectrum to another the ratios of the dissipation rate ϵ may be computed. But not the rate itself, i.e.,

$$r(\epsilon_1, \epsilon_2) \equiv \frac{\epsilon_1}{\epsilon_2} = \frac{P_{\epsilon_1}}{P_{\epsilon_2}} = \frac{S_1(\omega)}{S_2(\omega)}.$$

In this range we also know

$$\Gamma(k) = K^1 \epsilon^{2/3} k^{-5/3},$$

where $K^1 = 0.48 \pm 0.005$ (see Kraus, p. 34).

Thus:

$$\left[\frac{k^{5/3} \Gamma(k)}{0.48} \right]^{3/2} = \epsilon,$$

hence if $\Gamma(k)$ can be estimated from one or two values of k , ϵ may be determined.

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