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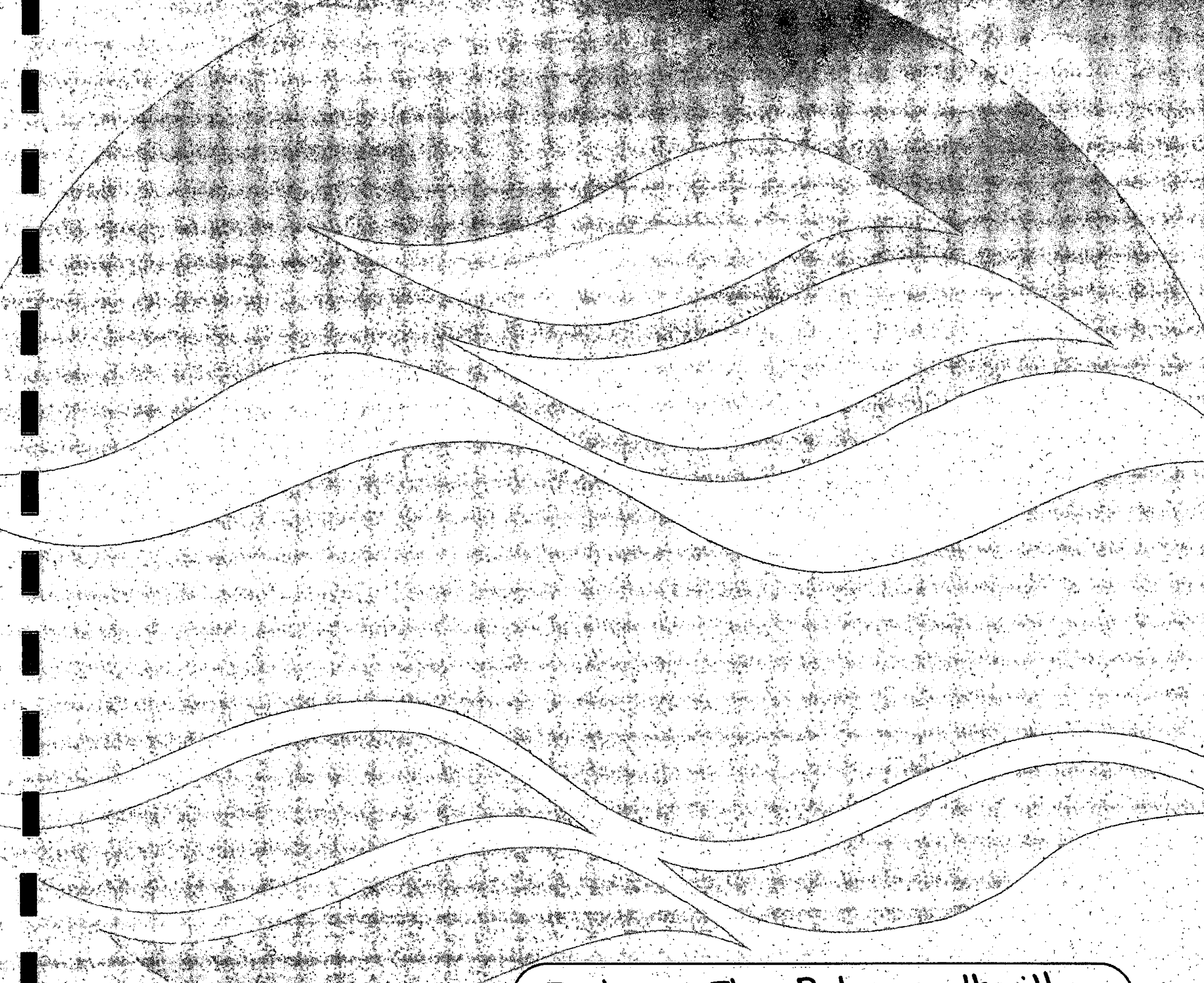

Exchange Flow Between Hamilton Harbour and Cootes Paradise

BY:

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NWRI Contribution No: 98-248

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Management Perspective

Title:

Exchange Flow between Hamilton Harbour and Cootes Paradise

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NWRI Publication #: 98-248

Citation (to be submitted to the Journal of Great Lakes Research)

EC Priority/Issue:

Nature: The Hamilton Harbour Remedial Action Plan (Can-US GLWQA)

Background:

A fish control structure (fishway) was built at the outlet of Cootes Paradise to control the entrance of carp into the wetlands. Understanding of the flow conditions at the fishway will assist in the development of an operational plan for the fishway. The flow was monitored during 1997 and analyzed, in conjunction with the local meteorological conditions and water level records at the west end of Lake Ontario.

Next Steps

The results of the monitoring programme have being forwarded to the Dept. of Fisheries and Oceans, so that the information can be incorporated into an operaional plan.

J. Great Lakes Res. 26(1):120–125
Internat. Assoc. Great Lakes Res., 2000

NOTE

Exchange Flow Between Hamilton Harbour and Cootes Paradise

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ABSTRACT. The flow between Hamilton Harbour and Cootes Paradise was monitored from April until December 1997 to provide background information for the operation of a fishway in the connecting channel. The flow was highly variable, and changed direction several times each day. Comparison with local meteorological and water level data revealed several interesting features. Outflow events of 4 hours or greater in duration were typically preceded by winds from the east usually lasting at least 6 hours. Similarly inflow events longer than 4 hours were typically preceded by westerly winds for at least 6 hours. There was evidence of diurnal and semi-diurnal flow reversals and of free surface oscillations of Lake Ontario, but not of Helmholtz resonance between Hamilton Harbour and the lake nor of exchange flow resonance between the harbor and Cootes Paradise.

INDEX WORDS: Cootes Paradise, Hamilton Harbour, exchange flows.

INTRODUCTION

At the west end of Lake Ontario, Hamilton Harbour is connected by a 200-m-long channel to Cootes Paradise, a marsh of some 2.5 km^2 in area. A fish passage control structure or fishway was built at the outlet of Cootes Paradise into the channel connecting it to Hamilton Harbour. The fishway is not aligned perpendicular to the channel axis, which is relatively straight, but is at an angle of some 20° off the perpendicular. The fishway became fully operational in 1997. The purpose of the fishway is to prevent carp from entering the wetlands and destroying aquatic vegetation. However, many other fish species use the marsh as spawning, nursery, and feeding habitat. An operational plan is needed to facilitate the movement of these desirable species past the fishway. Knowledge of the flow conditions at the fishway is fundamental in developing the operational plan.

Anticipating that the flow changes direction often each day, the focus of the investigation has been to identify and seek a means of predicting extended periods of flow (either outflow or inflow). It is expected that the extended periods would be useful to conduct work activities to be detailed in the operational plan for the fishway. Therefore, the fishway was instrumented to monitor the flow and other relevant variables from April to December 1997. This paper describes the findings of the flow monitoring program, with emphasis on the extended periods of unidirectional flow.

INSTRUMENTATION

The flow through the fishway and canal connecting Cootes Paradise and Hamilton Harbour is not controlled. That is, there is no natural or man-made constraint to the flow, so conventional discharge methods (such as stage-discharge relations) cannot be used. Therefore a two-axis (horizontal) current meter that would simultaneously measure magnitude and direction of the flow was used. The meter was deployed from April until November 1997, approximately in the middle of the deeper section of the fishway, as indicated in Figure 1. Data from the current meter were logged every 20 minutes. Each value represented a 5-minute average of data collected at one sample per second. The meter was retrieved for service every 4 weeks, and deployed again usually within 2 days.

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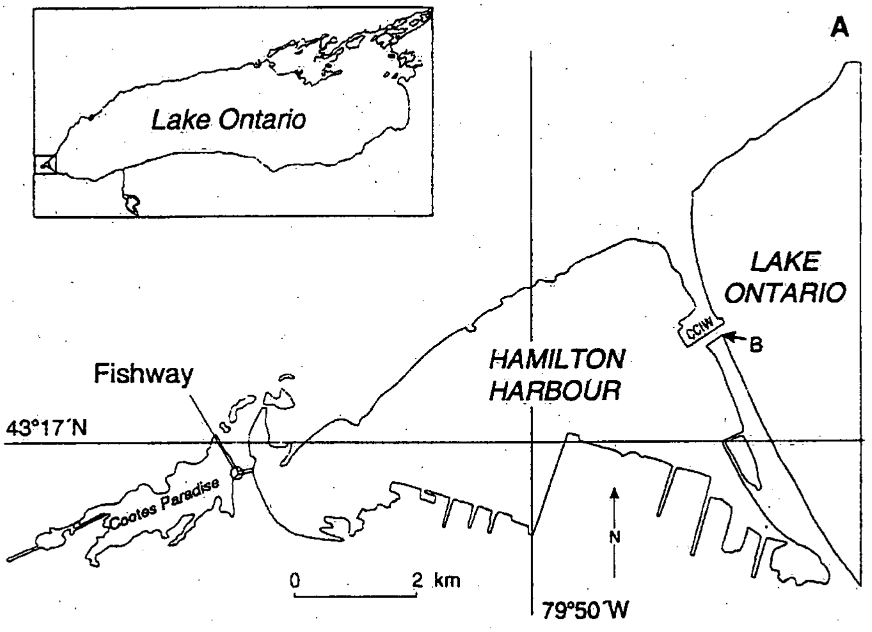

Figure 1a. Location map. The fishway structure is at the west end of the channel between Cootes Paradise and Hamilton Harbour. The wind and water level data were collected on the lake side of the ship canal between the harbor and the lake (B).

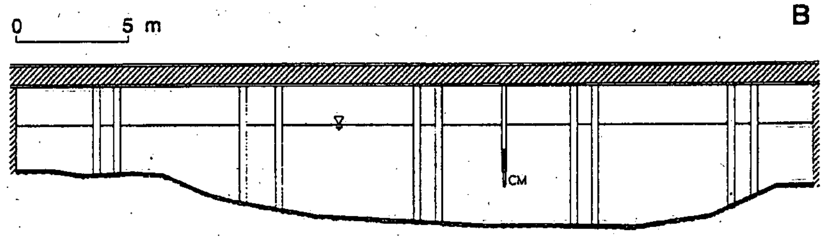

Figure 1b. View of the fishway looking toward Cootes Paradise, showing the location of the current meter (CM) at 0.6 times the depth below the water surface.

Other Data Sources

Meteorological data and Lake Ontario water level data were obtained from stations on the Lake Ontario side of the ship canal connecting Lake Ontario and Hamilton Harbour. The meteorological data were available every 10 minutes and the water level data every 15 minutes.

RESULTS

Time Series Data

To get an overview of the flow in the fishway, histograms of the number of flow occurrences, as a function of direction, were plotted from the time series. The histogram for July is shown in Figure 2. It is clear the current was strongly bi-directional. The two dominant directions are not exactly 180° apart because the fishway is not aligned with the axis of the channel. The spread about the dominant directions probably reflects the positioning of the current meter at the fishway one end of the channel, rather than along a straight central section of the channel.

Detailed examination of the time series of all the variables confirmed the frequent reversals of current direction at the fishway. Although variable in number, there were often six to eight flow reversals a day. Numerous small (less than 3 cm) variations in the water level at the Burlington Canal were also noticed. Most occurrences of outflows were linked to falling water level or a decrease in the rate of rise of water level. Outflow events appeared to lag the water level drop events by up to about half an hour, with considerable variability. Water temperature data showed indications of flow reversals only early in the season when the temperature difference between the harbor and the marsh was significant.

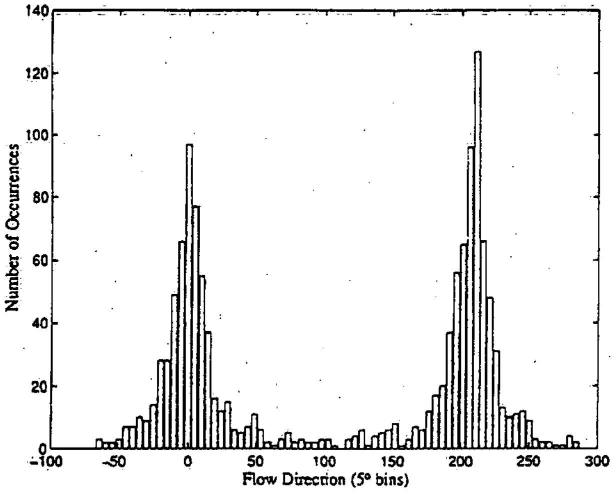

FIG. 2. The numbers of occurrences of velocity events greater than 1 cm/s, for the July deployment of the current meter, are plotted against direction (the peak at zero degrees is flow into the marsh and at about 210° is outflow).

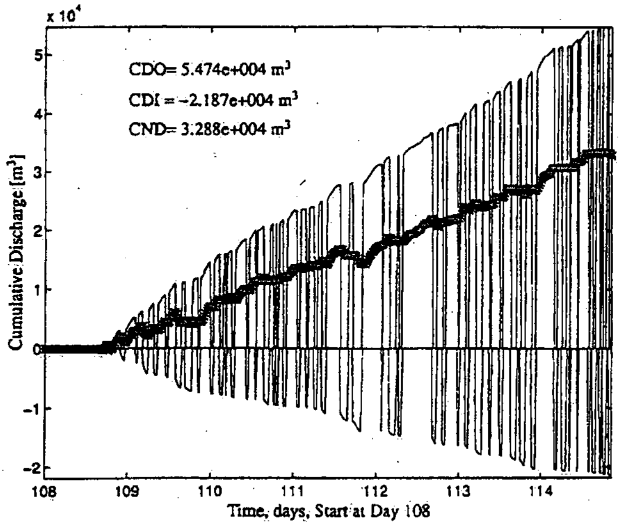

*FIG. 3. Cumulative discharge for April deployment: CDO (positive – cumulative outflow); CDI (negative – cumulative inflow); CND (***, net cumulative discharge).*

The time series of the velocity, taken with the cross-sectional area of the water at the fishway, can be used to estimate the cumulative discharge at the fishway. The flow was only measured at one point in the cross-section, and the flow was assumed to be normal to the plane of the fishway, so there is considerable uncertainty in the estimates. Nevertheless, the estimates give some guidance as to the discharge. Both the outflow and inflow cumulative discharges, as well as the net cumulative discharge, are plotted versus time in Figure 3. This plot depicts the oscillatory nature of the flow at the fishway and, although there is considerable flow in both directions, shows there is substantially more outflow than inflow.

Extended Outflow and Inflow Events

As indicated in the introduction, predicting periods of either inflow or outflow which persist for extended time periods would be useful in developing operational strategies for the fishway. For this exercise, a time of 4 hours or more was selected as being significantly long. The time series plots of all the variables were examined visually to choose the events. Outflow events along with the corresponding information on water levels, wind, and rainfall are given in Table 1. An important feature that emerges from this study is that the water level at the Burlington Pier was usually dropping during an outflow event (about 80% of the events) but steady for 20% of the events. The wind conditions were more variable. Broadly speaking, the wind came from an easterly direction for about 62% of the events and from a westerly direction for the remainder. However, even *before* events started, winds were from an easterly direction 80% of the time and they often persisted for more than 12 hours beforehand. This level of occurrence was the same as that of falling water level during an outflow event. Rainfall during an event occurred only for about one quarter of the events. Less than 10% of the events started during the daytime.

Extended inflow events were similarly extracted from the time series and are listed in Table 2. The events were less numerous than the extended outflow events and were of shorter duration. The strongest correlation is with water level rising at the Burlington Pier. Of the 20 events the water level was rising for 19 and steady for the other one. The wind direction during an event did not show a strong pattern, but the wind for at least 6 hours *before* the event was from a westerly direction for 15 of the 20 events (75% of the events). A striking feature was that the events typically started around mid-day (12 times at about 1600 GMT (1200 EDT) and three times at about 1800 GMT: 75% of the events).

TABLE 1. Extended outflow events (more than four hours) at the fishway in 1997.

Date (Julian Day), Start Time (GMT)	Event Duration, hrs	Water Level	Wind Direction[1]	Wind Direction before Event[2]	Rainfall, mm/day	Maximum Outflow, m/s
3 May (123), 1500	12	falling	ENE → NW	E for 12 hrs	18.6	0.4
6 May (126), 0800	8	falling	W → NNW	E > 12 hrs	0	0.3
9 May (129), 1200	6	steady	ENE → WNW	W for 6	0	0.4
12 May (132), 0900	8	falling	W	W > 12	0	0.3
15 May (135), 0900	8	falling	ENE → W	E > 12	15.6	0.3
16 May (136), 0600	6	falling	W → NW	W > 12	2.4	0.4
28 June (179), 0300	6	falling	SSE → WNW	E for 6	0	< 0.1
30 June (181), 1800	6	falling	NE → W	E for 12	0	0.1
31 July (212), 0400	8	falling	SSE → WNW	E for 12	0	0.2
13 Aug (225), 0200	8	falling	ENE → NW	E > 12	18.2	0.3
15/16 Aug(227/228) 1800/0100	6 / 8	falling	NE → WNW	E > 12	15.2 / 0	0.5
18 Aug (230), 0900	6	falling	NNE	E > 12	0	0.3
19/20 Aug (231/232), 2200	6	falling	E → NE	E > 12	0 / 11.2	0.3
21 Aug (233), 0600	12	falling	ESE	E > 12	0	0.3
23 Aug (235), 0000	8	falling	NE → NW	E > 6	0	0.3
25 Aug (237), 2200	12	falling	NW → E	E for 6	0	0.2
26 Aug (238), 1800	8	falling	E	E > 12	0	0.2
27 Aug (239), 1700	8	falling	E → W	E > 12	0	0.3
28 Aug (240), 0000	6	falling	W	W > 12	0	0.3
1 Sept (244), 1600	8	falling	SE → W	E > 12	0	0.2
2 Sept (245), 0600	8	falling	W	E > 12	0	0.2
6 Sept (249), 0000/1200	6 (X2)	falling	W	W > 12	10.5	0.2
7 Sept (250), 0100	6	falling	W	W > 12	0	0.3
11 Sept (254), 0400	6	falling	SE → NW	E > 12	0	0.2
13 Sept (256), 0500	6	falling	NW	W > 12	0	0.2
15 Sept (258), 0800	6	falling	NW	E for 12	0	0.3
4 Oct (277(1)), 0000	6	steady	NE	E for 4	0	0.3
4 Oct (277(2)), 0900	6.	steady	W → NE	E, W, then E	0	0.2
14 Oct (287), 0600	8	falling	NE → NW	E > 12	0	0.4
15/16 Oct (288/9), 1900	8	falling	N → S → NE	E > 12	0	0.3
17 Oct (290), 0600	8	falling	S→NE	E > 12	0	0.3
17/18 Oct (290/1), 1900	8	steady	NE → S	E > 12	0	0.2
18 Oct (291), 0900	8	steady	NW	E > 12, then W	0	0.3
18/19 Oct (291/2), 2200	8	falling	SSE→NW	E > 12	0	0.3
27 Oct (300), 0300	24	falling	SE →NW	E > 12	35.1(299); 11.6	0.8
1/2/3 Nov (305/6/7), 2200	30	falling	E → W	E > 12	24.6(305)	0.6
3 Nov (307), 1200	8	steady	SSW → WNW	W > 12	24.6(305)	0.3
12 Nov (316), 0400	8	falling	W → NW	W > 12	0	0.3
14/15 Nov (318/9), 1800	8	falling	SE→ NE	E > 12	20.2	0.2
16 Nov (320), 2200	8	falling	NW → W	W > 12	0	0.2
22 Nov (326), 1400	8	falling	E → NE	E > 12	0	0.2
24 Nov (328), 0300	8	steady	NW	W > 12	0	0.1
26 Nov (330), 1500	8	steady	W	W > 12	0	0.2

[1] Direction during the event, *or* the arrow indicates the wind direction changed from the first to the second direction before or during the event.

[2] Direction conditions before event ('E' means with easterly winds, 'W' means with westerly winds).

TABLE 2. Extended inflow events (more than four hours) at the fishway in 1997.

Date (Julian Day), Time (GMT)	Event Duration, hrs	Water Level	Wind Direction[1]	Wind Direction before Event[2]	Rainfall, mm/day	Maximum Outflow, m/s
29 June (180), 1600	4	rising	E	NNW for > 6 hr		0.1
1 July (182), 1600	4	rising	E	NE for 6		0.2
2 July (183), 1600	7	rising	E	WNW for 6	8.5	0.2
5 July (186), 1600	6	rising	W	WNW >12		0.2
7 July (188), 1800	4	rising	SE	N > 6	3.4	0.1
18 July (199), 0400	4	rising	WNW	W >12		0.2
18 July (199), 1300	4	rising	W	W >12		0.2
18 July (199), 1800	4	rising	NW	W >12		0.2
1 Aug (213), 1800	7	rising	W	W >12		0.2
2 Aug (214), 1600	5	rising	W	W >12		0.2
3 Aug (215), 1600	4	rising	S	W >12		0.3
8 Aug (220), 1600	5	rising	W	NW >12		0.2
12 Aug (224), 1100	8	rising	NE	NNE > 6		0.2
17 Aug (229), 1600	4	rising	ESE	NW→N > 6	0.9	0.2
19 Aug (231), 0400	4	rising	NE	S→NE		0.2
19 Aug (231), 1600	5	rising	E	N		0.2
2 Sept.(245), 1600	4	rising	W	W > 6		0.2
14 Sept (257), 1600	4	rising	W→S	W > 6		0.3
14 Oct (287), 1600	4	rising	W	NW > 6	0.6	0.3
15 Oct (288), 0200	5	steady	NW	W > 6		0.2

[1] Direction during the event, *or* the arrow indicates the wind direction changed from the first to the second direction before or during the event.

[2] Direction conditions before event ('E' means with easterly winds, 'W' means with westerly winds).

Spectral Analysis

The time series of the flow and the water levels were analyzed in the frequency domain to investigate any links to known driving processes. Cross-spectra were calculated between the water level at the Burlington Pier and the outflow at the fishway (Fig. 4). The predominant periods for both the flow in the fishway and the water level at Burlington Pier are at 21.8, 11.7, 5.2, and 3.2 hours (the frequency increment in the analysis is 0.0133 cycles per hour). The first two are, within the limits of the analysis, the diurnal and semi-diurnal periods. The peaks at 5.2 and 3.2 hours agree closely with the first and second modes of free surface oscillations of Lake Ontario (Rao and Schwab 1976, Hamblin 1982). The peak periods at 5.2 and 3.2 hours are the highest in the flow spectrum and indicate that the flow is responding to the free surface oscillations in the lake.

Two additional driving mechanisms were investigated which might cause peaks in the spectrum: Helmholtz resonance (Freeman *et al.* 1974) and exchange flows (Hamblin 1998). Freeman *et al.* reported the period of Helmholtz resonance for Hamilton Harbour and the open lake to be 2.5 hrs. The method of Hamblin allows an estimation of the period of exchange flow oscillation between two enclosed bodies of water connected by a channel. In

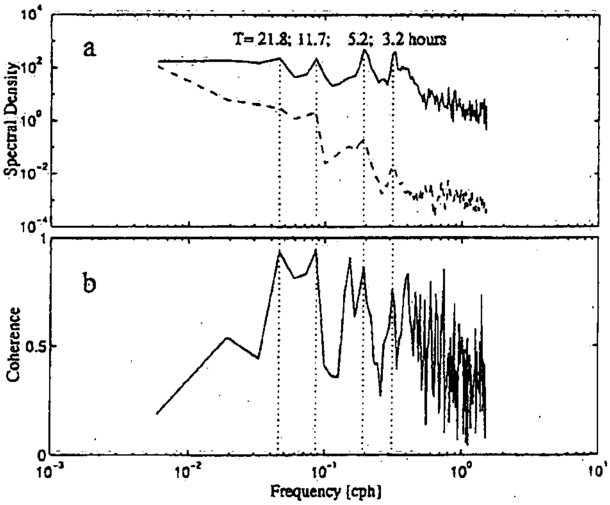

FIG. 4. a) Spectra of the outflow for the August deployment (—: $[(m/s)^2/cph]$) and water level (- -: $[m^2/cph]$); b) Coherence.

this case Hamilton Harbour, Cootes Paradise, and the connecting channel were used, and the period of oscillation was estimated to be about 1.8 hrs. Neither of these mechanisms appears to have a signature in the spectrum.

DISCUSSION AND CONCLUSIONS

From April to November 1997, the flow at the fishway was predominantly bi-directional, and was characterized by many reversals each day. The histogram plots show that the flow was in and out of the fishway and that there are more outflow occurrences than inflow. One explanation for this is that the meter takes a record every 20 minutes and many outflow events last longer than that so they are recorded as multiple occurrences.

Examination of the time series provided a useful tool in analyzing the data and in delineating events. The relationship of the flow with possible driving forces was complex. While major rainfall events appeared to have an effect (primarily in prolonging outflow events), wind direction and water levels clearly played major roles in the extended events.

Extended outflow events were well correlated to the occurrence of easterly wind events. About 80% of outflow events longer than 4 hours duration were preceded by easterly winds for at least 6 hours, and were accompanied by falling water levels. The latter appear to be caused by wind direction changes at or during the event (usually to west wind). In simple terms it appears that extended wind events from the east set up the west end of the lake and harbor. A shift to westerly winds causes the lake and harbor levels to drop, promoting a significant outflow event at the fishway. Only 10% of the events occurred in the daytime.

A similar observation can be made for inflow events longer than 4 hours. In this case, 75% of the events are preceded by westerly winds for more than 6 hours. It appears that such winds set down the western end of the lake and help to drive water out of Cootes Paradise. When the westerly wind relaxes (either by a drop in speed or change in direction) the water in the lake and harbor rises forcing water into the wetlands. Most (75%) of the events occurred around mid-day.

To put the frequency of the occurrence of these extended events into perspective, during the period of instrument deployment of about 186 days, there were 46 outflow events and 20 inflow events of 4 hours duration or longer. Therefore, on average, either one or the other only occurred about once every 3 days. Knowledge of persistent wind directions alone could be used as a predictor of extended outflow and inflow events.

The frequency domain analysis revealed that there were diurnal and semi-diurnal components to the oscillations. Furthermore there was a strong response to the first two modes of free surface oscillations of Lake Ontario. It is apparent that strong, persistent winds are necessary to overcome the response to the lake surface oscillations and produce flow in one direction for an extended period.

ACKNOWLEDGMENTS

The author gratefully acknowledges the efforts of Ken Stewart, SUNY at Buffalo and Dave Schwab, NOAA/GLERL, whose suggestions and advice on the first draft greatly improved the manuscript. This project was initiated and strongly supported by Victor Cairns, GLLAFS, Fisheries and Oceans Canada. Bob Rowsell, NWRI, provided the meteorological data and support for the current meter deployment. Ron Solvason, Canadian Hydrographic Service, provided the water level data. Doug Doede, NWRI, provided deployment and data analysis support. Staff of the Royal Botanical Gardens kindly provided access to the site and assisted in maintaining the meter.

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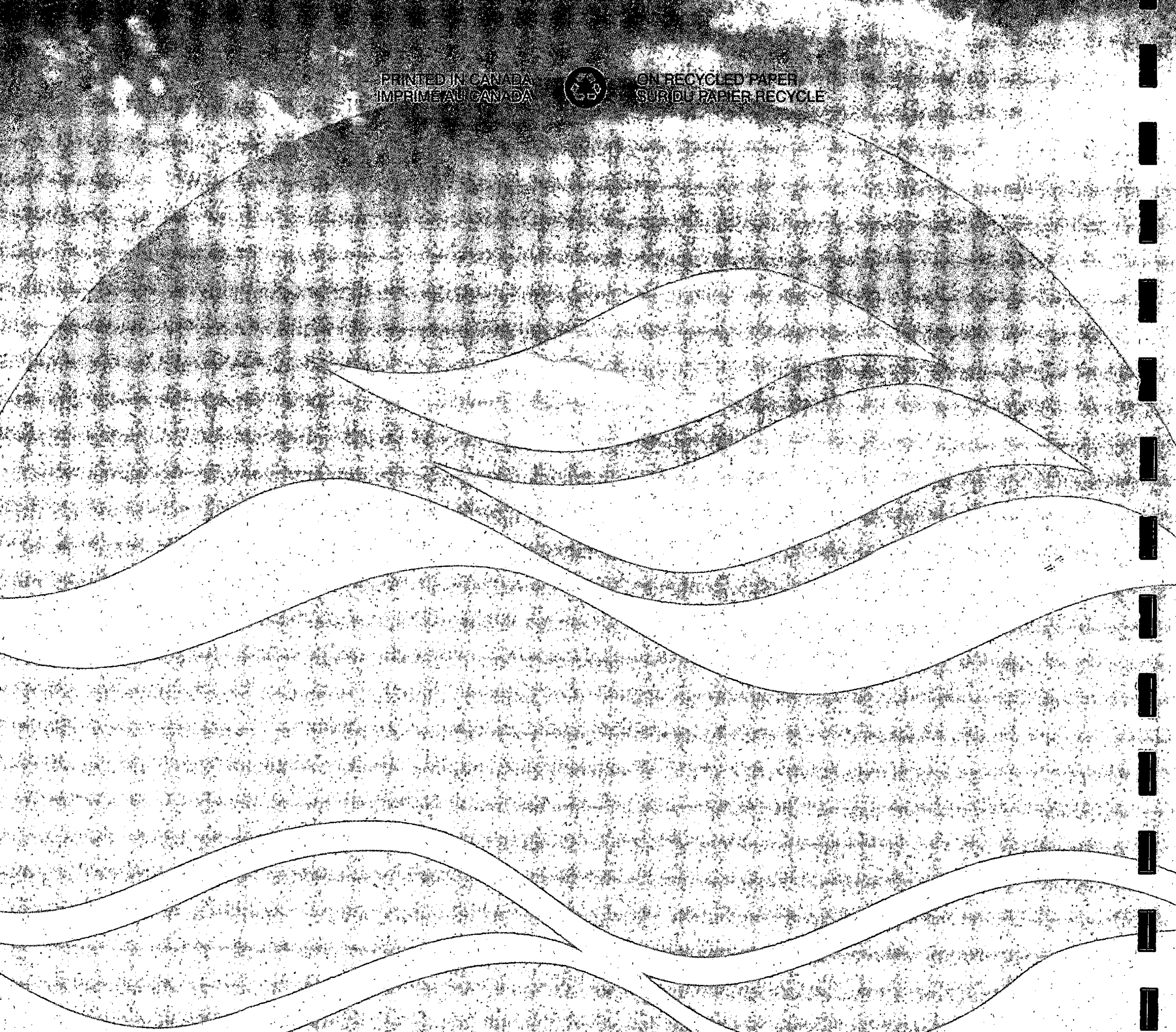
Submitted: 18 March 1999
Accepted: 11 October 1999
Editorial handling: David J. Schwab



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