THE FLOW AND CIRCULATION CHARACTERISTICS IN THE EASTERN LAKE ERIE AND UPPER NIAGARA RIVER

January 1989

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Mr. F.J. Philbert
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March 23, 1989

Dear Mr. Philbert:

Enclosed for your information are five copies of the report on "The Flow And Circulation Characteristics In The Eastern Lake Erie And Upper Niagara River Area". This report was prepared by the Ad Hoc Group on Physical Limnology and Hydraulics consisting of Dr. C.R. Murthy, Mr. A. Coniglio and myself. We have also made a presentation of this report at a meeting of your working group on January 10, 1989. This completes our assignment which we enjoyed working on during the past six months.

Yours sincerely,

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Enclosures: as stated

THE FLOW AND CIRCULATION CHARACTERISTICS IN THE EASTERN LAKE ERIE AND UPPER NIAGARA RIVER AREA

A Report

to the

River Monitoring Group

by the

Ad Hoc Group on

Physical Limnology and Hydraulics

January 1989

Section 1
Purpose and Scope

An ad hoc group of limnology and hydraulics experts was formed on October 19, 1988 to address the following:

a. Is the water at the Fort Erie station representative of the water in eastern Lake Erie?

b. Is water at the Buffalo Water Intake representative of the water in eastern Lake Erie?

c. Recommend a list of other possible station locations that would best be suited for collecting water samples from eastern Lake Erie.

d. Recommend sampling sites in eastern Lake Erie where waters can be considered representative of eastern Lake Erie.

Some guidance/assumptions were given to the group as follows:

(1) Actual loadings from eastern Lake Erie do not include those originating from Smoke's Creek and the Buffalo River. Loadings coming from these two tributaries are included, for analysis purposes, directly as point sources in the Niagara River itself.

(2) The head of the Niagara River is defined by a line drawn from the Fort Erie station, running southward and along the middle of the river and terminating at the mouth of Smoke Creek.

This report was prepared for the River Monitoring Group of the Niagara River Toxics Committee. The report represents the group's findings on the above points.

The geographic area of this study is eastern Lake Erie and the head of the Niagara River. The scope of this study is limited to the consideration of the physical processes of the Lake Erie-Niagara River system. Chemical sampling techniques and data analysis are excluded from the study.

The ad hoc group consists of: P.P Yee, Senior Water Resources Engineer, Water Planning and Management Branch, Ontario Region, Environment Canada; Dr. C.R. Murthy, Research Scientist, Lakes Research Branch, National Water Research Institute, Environment Canada; and A. Coniglio, Chief, Hydrologic Investigations, U.S. Army Corps of Engineers, Buffalo District. Technical assistance were provided by K. Kuntz and L. Falkiner of Environment Canada.

Section 2
Description of the Study Area

2.1 Hydrology and Hydraulics

Lake Erie is situated fourth in the chain of the Great Lakes system, and receives about 85 percent of its water supplies from the upper lakes. The remaining 15% comes from Lake Erie's own drainage basin. The lake has a surface area of 9,900 square miles, a maximum depth of about 210 feet and a total water volume of 116 cubic miles. The eastern basin of the lake has a surface area of about 2,000 square miles, and is the main focus of this study.

The Niagara River, about 36 miles in length, is the natural outlet of Lake Erie linking it with Lake Ontario. The average river flow is about 205,000 cubic feet per second (cfs). A small portion of the Lake Erie outflow is carried by the Welland Canal located about 17 miles to the west of the natural outlet. Figure 1 is a map of the study area.

The flows entering the Niagara River are not regulated but depend on the levels of Lake Erie. Seasonal water level fluctuation on the lake is quite regular, with the peak generally occurring in June and the low in February. Hence, the seasonal maximum and minimum flows also generally occur in these months, respectively. Since the seasonal water level fluctuation seldom exceeds 1.5 feet, the mean monthly flow fluctuation likewise seldom exceeds 25,000 cfs within any given year.

The total range of long-term fluctuation on Lake Erie, however, is about six feet. Persistently high water supplies to the Great Lakes can cause their water levels to increase steadily to extreme highs, such as those occurring in 1985-86. Lack of precipitation, on the other hand, will cause the lake levels to drop to extreme lows such as those in 1964-65. As discussed above, these level fluctuations cause the lake's outflows to fluctuate also.

Due to the east-west orientation of Lake Erie, this relatively shallow lake is sensitive to the prevailing westerly wind. Strong south-westerly winds can cause a large set-up in eastern Lake Erie and raise the water levels at Buffalo Harbor by up to eight feet during the storm, with a drop in water level by about the same amount at Toledo, Ohio, the opposite end of the lake. An all time instantaneous high river flow of more than 400,000 cfs occurred on December 2, 1985 when a severe storm acted on the then already very high lake level situation.

Flows can also be very low if given the right combination of low lake level situation and strong north-easterly winds. Flows as low as 100,000 cfs have been observed in the past.

Due to its shallow characteristic, Lake Erie is usually ice-covered in the winter. Ice normally begins to form in late December in shallow areas and along the north shore. The ice cover grows progressively to cover the entire eastern basin of the lake by early January or February. In severely cold winters, the entire lake might be ice-covered. Ice dissipation (melting) normally begins in late March or April and generally by late April the lake is ice free.

It should be noted that the process of ice formation and melting depends entirely on the timing for the arrival/departure of the cold weather, and the severity of the weather and storm activities in between. Since the weather conditions are seldom the same among the years, it is safe to say that no two ice seasons on the lake are exactly alike.

River flow retardation (also termed deceleration or reduction) due to ice, is a common winter event. Under conditions of high winds from the south-west, ice from Lake Erie can enter the river and becomes grounded in shallow areas such as the shoals near the head of the river and in the Chippawa-Grass Island Pool. Also, during severe winter weather, ice which is generated in the river often adds to the problems caused by lake ice. These ice groundings can affect the distribution of flow in that portion of the river. If the grounding becomes severe, ice jams can form which may significantly retard river flow. Since the winter of 1964-65, an ice boom has been placed across the head of the Niagara River to reduce the frequency and duration of lake ice runs in the river. The placement of the boom has reduced the lake ice runs significantly when compared with the pre-boom era. On clear cold winter nights, anchor ice may form on the shoals near the lake outlet, reducing the flow area and retarding flows.

Weed growth in the river can also retard flows. The extremely hot and sunny summer of 1988 encouraged high weed growth, with the result that up to 35,000 cfs temporary flow reduction was noticed. In an average summer, maximum flow retardation is about 5,000 cfs.

2.2 Circulation and Flow Patterns

The eastern basin of Lake Erie has a mean depth of about 80 feet with a maximum depth of 210 feet in the centre of the basin. It is separated from the shallow central basin by the Pennsylvania Ridge running southerly from the north shore west of Long Point (Figure 2). The eastern basin is also isolated in its dynamical characteristics from the rest of the lake, and behaves very much like Lake Ontario, although it is only a quarter its size.

Stratification and geostrophic effects are very important in determining the circulation features in the eastern basin. During the summer stratified season, a shallow thermocline of more or less constant depth is established in the eastern basin. This feature coupled with the geostrophic effects due to the earth's rotation sets up cyclonic flows, that is, anti-clockwise circulation. This is extensively verified by long-term current meter observations (Hamblin 1971, Saylor and Miller, 1987). During the winter season, the eastern basin exhibits the characteristic two-cell circulation pattern, typical of any deep lake circulation under homogeneous conditions. Figure 3 illustrates the generalized two cell circulation pattern observed from long-term current meter observations in Lake Erie (Saylor and Miller 1987). This dominant circulation feature is further substantiated from model results (Gedney 1971, Simons 1976) as shown in Figure 4. The strength of the two cells differs somewhat since Long Point interrupts the full development of the northern cell. To compensate for this, the southern half of the cell grows stronger and larger than the northern half. This two-cell circulation feature no doubt enhances mixing of the different water masses with the eastern basin both in the horizontal direction as well as vertical direction.

Figure 5 shows vertical circulation features in the eastern basin predicted by the hydrodynamic model and compared with measured currents (Lam et al 1982). As can be seen there is good vertical mixing of water masses throughout the entire water column.

Because of the prevailing westerly winds, currents along both the northern and southern shores of the eastern basin tend to flow easterly with the wind stress. Return flow occurs westward along the axis of the basin like in any deep lake circulation such as Lake Ontario during winter homogeneous conditions. Figure 6 shows depth averaged Lake Erie circulations predicted by the homogeneous model for easterly and westerly wind impulses (Simons 1976). Heavy arrows indicate directions and relative magnitude of the wind stress. The two cell circulation pattern in the eastern basin was observed whether the stress impulse was easterly or westerly, although of course the currents along the coasts were reversed for the two different directions. As discussed earlier, the prevailing winds in Lake Erie are westerly (Saylor and Miller 1987 and Simons 1976).

In the eastern basin, the strong eastward transport along the shore is followed by a compensating westerly return flow. Since only a fraction (about one-tenth) of the local eastward transport leaves the eastern basin through the Niagara River, the bulk of the eastward flowing water recirculates in the deep westerly current. This unique re-circulation feature, no doubt, enhances thorough mixing of different water masses throughout the eastern basin. Figure 7 shows a schematic representation of the inlet conditions of the head waters of the Niagara River inferred from long-term current meter observations and from results of comprehensive hydrodynamic models.

When a lake enters a river, a transition takes place where the movement of water changes from one of very slow inter-lake circulation to a gradually well-streamlined feature normally expected in open channel flows. Hydraulically speaking, the exact location of the head of the Niagara River can only be loosely defined. It is physically impossible to have a sudden or rapid change in the flow condition between the lake and the river, nor is there any sharp change in the lake-to-river geometric feature. Rather, this flow transition takes place over a fairly large distance extending from an area where lake circulation occurs (well above the Peace Bridge) to just below the International Railway Bridge, about two miles from the Peace Bridge.

It is worthwhile at this point to mention that one suggestion made in a report by the Data Interpretation Group is that the mouth of the river be defined by a line originating at the Fort Erie station, and running upstream along the middle of the river and terminating at the mouth of Smoke's Creek at Lackawanna, New York. It follows then, that eastern Lake Erie would terminate south-west of this line. This assumption was made to simplify the procedure in estimating the loadings from eastern Lake Erie using existing/available data collected at the present Fort Erie station, and is only a conceptual tool.

In entering the river, water from Lake Erie converges into a funnel-shaped inlet to the river. The water picks up speed as it approaches the Peace Bridge due to the narrowing of the channel, and drops rapidly in the Peace Bridge area. It is in this area that the rock ledge at the bottom of the river acts as a submerged weir in dictating the conditions of the flow. At the Peace Bridge, surface water velocities are as high as twelve feet per second. After passing the Peace Bridge area, the river slows down slightly on its way towards the International Railway Bridge. There, the velocity picks up again due to the reduced cross-sectional area caused by the numerous massive bridge piers.

Because of the high flow velocities within the river reach discussed above, significant secondary (cross channel) flows are not possible. Hence, cross-channel mixing is also not possible. This is evident in examining a number of air photos (Figures 8 and 9). Figure 10 shows the flow lines in the river based on interpretation of the past air photos. These photos show that flow lines begin to establish well before the water enters the Peace Bridge area. These pictures also show the plume originating from Smoke's Creek and the Buffalo River. However, this plume hugs the U.S. shore as it travels down river. Mixing of this plume with the lake water is not evident.

Immediately below the present Nicholl's Marine site (see Figures 10 and 11), the local flow lines seem to have been deflected sharply by the tip of the protrusion into the main channel where the flow is fast and the water is deep. The flow lines then quickly recovers in speed and direction before it reaches the Fort Erie station. However, this process in effect causes the formation of a small but localized secondary flow, or an embayment in the river. The fast and constant circulation of the water in this area ensures mixing of its water with that in the main stream.

2.3 Shoreline Development

The Canadian shoreline on Lake Erie is mostly agricultural land, with sporadic cottage communities and recreational beaches in between. There are no major urban or industrial centers except the city of Port Colborne where the Welland Canal is also located.

The upper-most part of the Niagara River is park land which extends just past the Peace Bridge. Immediately below the Peace Bridge, there are several commercial establishments (marine equipment sales and service, restaurants, etc). The Niagara Parks Commission, the Town of Fort Erie and the Ontario Ministry of Government Services maintain ownership to much of the rest of the shore land between the Peace Bridge and the International Railway Bridge. Much of these lands are not developed and in some areas, shore protection in the form of large stones are evident.

Immediately upstream of the Fort Erie station (Figure 11), there are several lots owned by Serv-a-Station, the Town of Fort Erie and a numbered Ontario company. The Serv-a-Station lot is a product of past landfills which occurred quite sometime ago. Although the lot is protected by a vertical concrete wall, this land has been left undeveloped and is now being used as a parking lot. The extent of past shoreline modifications at this site has been rather significant, and has over-shadowed the Fort Erie station. However, since the sampling intake is located about 100 feet from shore (see Figure 12), this land-fill site is considered not to have affected the ability of the intake to collect water from the main stream.

The United States shoreline in Lake Erie is a mix of urban, agricultural and industrial land. There is a high concentration of industrial activities in the Lackawanna and southern Buffalo areas. As noted above, the conceptual model assumes that local sources from this area are point sources directly to the Niagara River. Also the evidence of the plume suggests it hugs the U.S. shoreline of the river. At the east terminus of Lake Erie, the Bird Island Pier begins to extend along the upper Niagara River, separating the main river from the Black Rock Navigation Canal. The pier terminates at the southern tip of Squaw Island where the Buffalo Sewage Treatment Plant occupies much of the island.

The flows in the Black Rock Canal are very low except during vessel transits at the lock. The pier consists of large rocks and boulders, and is porus in nature. This plus the fact that the canal is higher in water surface elevation than the river, a continuous but very small leakage of flow into the river occurs.

Section 3
Water Quality Sampling Station at Fort Erie

3.1 Station Location

The water quality sampling station is located at the Customs Dock beside the Niagara River at Fort Erie (Figure 11). It is about 700 feet downstream of the International Railway Bridge, and about three miles downstream of the head of the Niagara River. The location was chosen in 1984 with the intention of monitoring the chemical loadings entering the river from Lake Erie.

Factors used in locating the site include: close proximity to eastern Lake Erie, land acquisition, accessibility, security and the availability of electrical power. Based on these factors, the Customs Dock site was selected.

3.2 Intake Structure

The intake line is composed of three 3/4 inch I.D. polyethylene tubes, encased in a protective sleeve placed in the river. The line is held in place by a heavy anchor. The polyethylene tube is connected to a stainless steel frame anchored in the bedrock. The total depth of water at the intake is about 10 feet. The intake itself is about 7 feet below the water surface, and about 3 feet above the river bed. It is located about 100 feet from the shore. Figure 12 shows the general layout of the intake system.

3.3 Flow Conditions at the Intake

While the intake is located only 100 feet out into the river where the total river width is about 1,600 feet, water velocity at the intake is quite high (about 3-4 feet per second). There are no secondary flows or in-bay circulations at the site. Thus, the possibility of collecting stagnant water can be ruled out.

3.4 Potential Local Inputs

Previous transect sampling by Environment Canada and the Ontario Ministry of the Environment at the Peace Bridge site has indicated apparently uniform chemical concentrations from samples taken across the width of the river except for a plume that hugs the river's east bank. (more information to be added). This is a clear indication that eastern Lake Erie water is already well-mixed before it enters the river. The plume originates from the Buffalo River and Smokes Creek farther to the south, both considered as a part of the head of the Niagara River. While the flow volumes from these streams are relatively small due to the small drainage areas they serve, the chemical pollutants could be very substantial as they run through some of the most heavily industrialized areas.

As discussed in Section 2.2, this plume does not mix with the water in eastern Lake Erie as lake circulation takes place in the deeper part of the lake. In addition, examination of past air photos shows that this plume does not mix with the water in the head of the river, due to the high velocities in this reach as discussed earlier. Chemical substances originating from this plume cannot find their way across the river towards the sampling station. In other words, the water samples collected at the station are not affected by this plume. This should not be a matter of concern since earlier in the report, we have assumed that these point sources are a part of the Niagara River.

There are no tributaries in the Canadian portion of the upper Niagara River above the Fort Erie station. Although there are several commercial establishments, none of these have any outfalls to the river. The Town of Fort Erie, on the other hand, has several storm sewers that discharge into the river. They are generally located at the city's water lots located at the end of city streets. The newest of these outfalls is the one installed in 1985 immediately upstream of the water quality sampling station. None of these outfalls have any steady effluent except in times of storms, and even then, the flows can not be high because of the small residential drainage areas they serve.

The Fort Erie station is located a short distance downstream from the City of Buffalo's principal sewage treatment plant. Because of the high velocity of the river and the large width at this site, effluents from the treatment plant do not cross-over to the station.

3.5 Sampling Schedule

The following table lists the frequencies and durations used in collecting water samples for analysis.

	1983-86	1986-87	1987-88
1. Nutrients:			
frequency	7/week	3/week	3/week
duration	<5 min	<5 min	<5 min
2. Major Irons & Trace Metals:			
frequency	1/week	1/week	1/week
duration	<5 min	<5 min	<5 min
3. Organics:			
frequency	2/month	1/week	1/week
duration	15 min grab	24 hr extract.	24 hr extract
4. Susp Sed:			
frequency	2/month	1/week	1/week
duration	24 hr composite	24 hr composite	24 hr composite

An automatic timer was installed at the site and has been programmed to collect the water samples at pre-specified frequencies and duration. All sampling is carried out in the late morning or early afternoon. To collect samples for nutrient analysis, for example, the routine is as follows. The automatic timer initiates the pumping at 1330 hours to flush the system for 30 minutes. Sampling starts at 1400 hours and stops at 1402 hours. Pumping stops at 1430 hours and the whole procedure is repeated two/three days later.

In the case of organics sampling which occurs only once a week, the pump works continuously for 24 hours and pumps at a rate of 6 litres/minute into an overflowing reservoir. From the reservoir, an extractor collects water at a rate of 35 ml/min such that at the end of the period, 50 litres of water will be collected for analysis. Further details on this sampling methodology can be found in the Niagara River Sampling Protocol document (1988).

Section 4
Findings and Conclusions

Based on the discussion presented in the previous sections, the ad hoc group has arrived at the following findings and conclusions in addressing the issues raised:

A. Is the water at the Fort Erie station representative of the water in eastern Lake Erie?

The water collected at the Fort Erie station is representative of the water in eastern Lake Erie. Based on our knowledge of the limnological and hydraulic processes of the system, we believe that the continuing circulation of the water in eastern Lake Erie provides a well-mixed water mass before the water enters the Niagara River. Once entering the Niagara River, further cross-stream mixing is very difficult if not impossible because of the high velocities and the absence of any significant secondary (cross current) flows or circulations in the river.

The effluent from the Buffalo River and Smoke's Creek do not mix with the water in eastern Lake Erie nor with the water in the upper part of the Niagara River. Therefore, water samples collected at the Fort Erie station are not affected by the presence of this plume. Geographically and even hydraulically speaking, the mouths of these two tributaries are located on the eastern Lake Erie shore. As such, they could be considered as point source pollution in eastern Lake Erie. The assumption that the head of the Niagara River include these two tributaries invalidates this argument. However, they are then considered as point sources to the Niagara River.

While there are a number of local storm sewer outfalls located upstream of the sampling station in Canada, their discharges are nil most of the time except possibly during and after a storm event. Considering that these outfalls drain very small residential areas, it is doubtful that the effluent from these outfalls will have any serious impacts on the water quality of the samples collected at the Fort Erie station.

B. Is water at the Buffalo Water Intake representative of the water in eastern Lake Erie?

The water at the Buffalo Water Intake is representative of the water in eastern Lake Erie. The water passing the intake site has undergone complete mixing while in eastern Lake Erie. The intake site is located sufficiently far out in the lake away from the plume that comes from Smoke Creek.

C. Recommend a list of other possible station locations that would best be suited for collecting water samples from eastern Lake Erie.

Because of the presence of the plume as discussed above, all land-based U.S. shore stations should be ruled out. In Canada, any shore location from the existing station to Lake Erie would be suitable. The most ideal location would be above the Peace Bridge. But this location would pose other problems such as availability of shelter, power, security and accessibility, etc.

Another alternative is to install the sampling intake at one of the Peace Bridge or International Railway Bridge piers. But this would pose a rather serious hazard to the installers and the operators who would need to inspect and service it up to three times a week.

D. Recommend sampling sites in eastern Lake Erie where waters can be considered representative of eastern Lake Erie.

Because of the continuous water circulation in the eastern basin of the lake, the water within it is well mixed. Any sites far away from the shore would be suitable. To be consistent, the group would recommend that a net work of four fixed locations on the lake be selected. If the high cost of analyzing these samples is a prohibiting factor, the group would suggest that a minimum two fixed locations be selected where samples should be collected at least twice every year.

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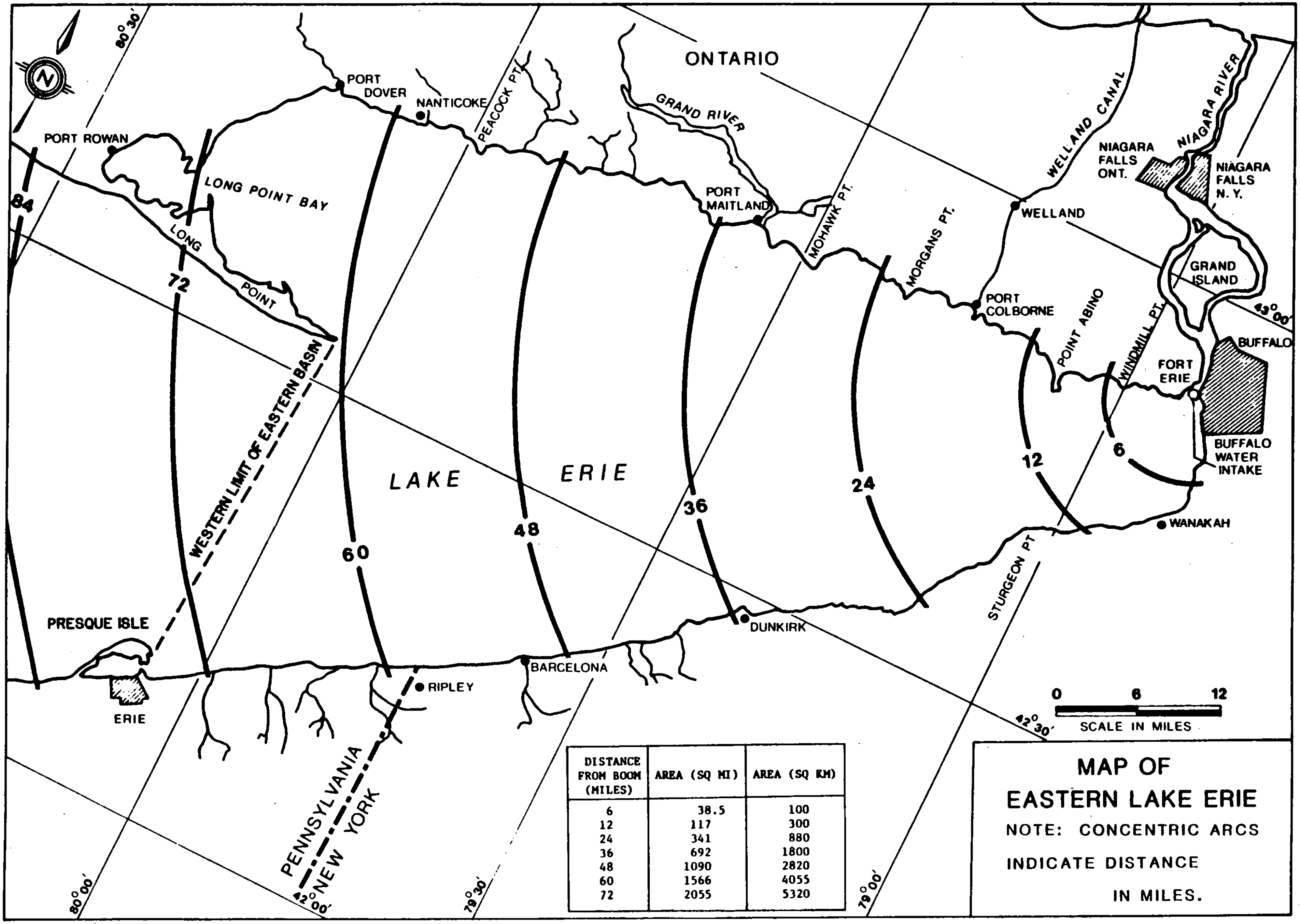
9. Environment Canada, United States Environmental Protection Agency, New York State Department of Environmental Conservation and Ontario Ministry of the Environment, Niagara River Sampling Protocol, 1988.



DISTANCE FROM BOOM (MILES)	AREA (SQ MI)	AREA (SQ KM)
6	38.5	100
12	117	300
24	341	880
36	692	1800
48	1090	2820
60	1566	4055
72	2055	5320

FIGURE 1

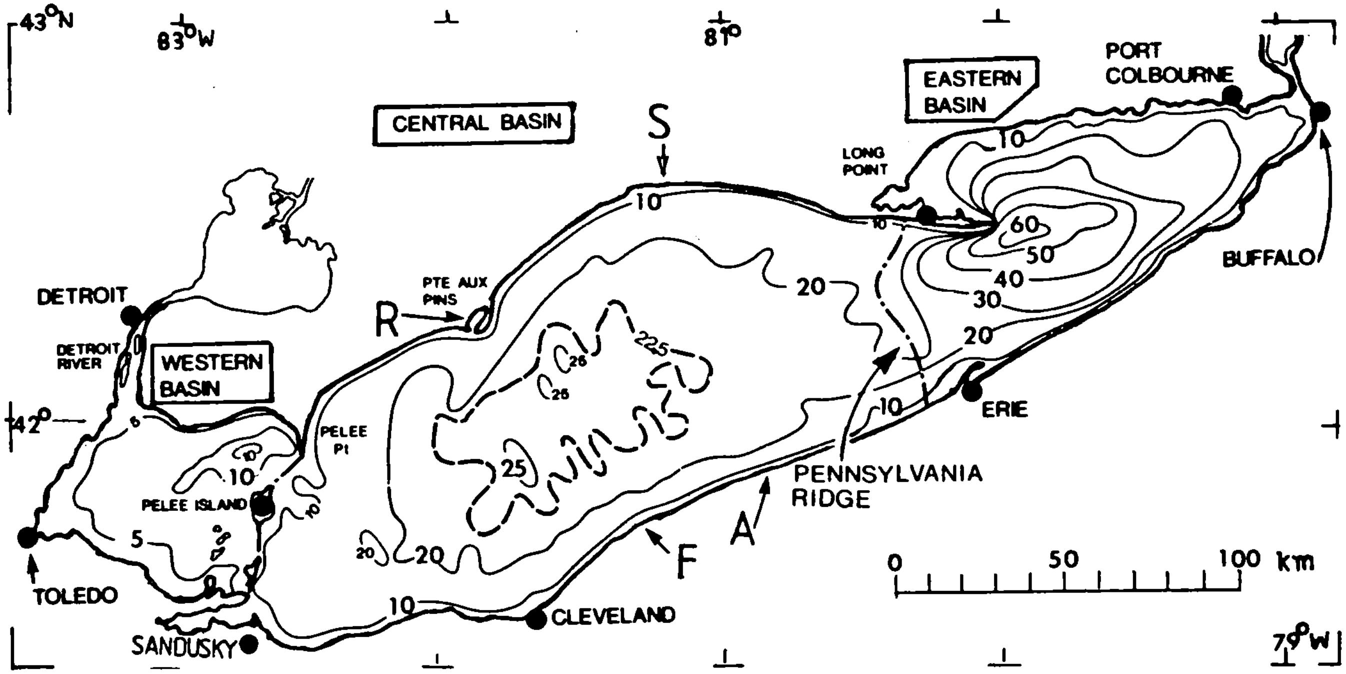


FIGURE 2 Lake Erie bathymetry, contours in metres. (Mortimer, 1987)

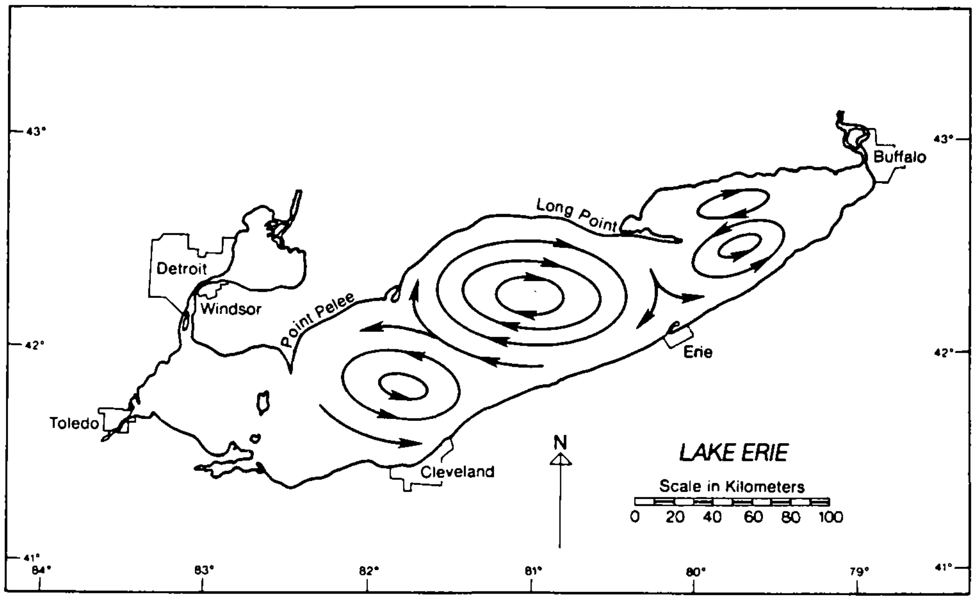
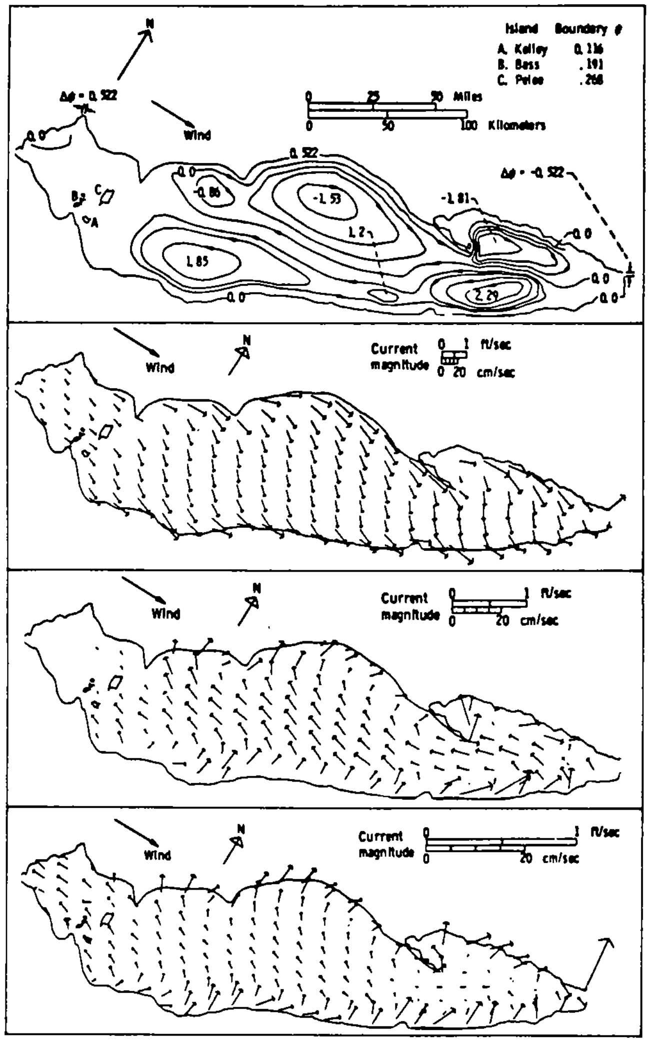


FIGURE 3 Two cell circulation pattern (Saylor and Miller, 1987)



Lake Erie stream function (top) for a 5.2 m s^{-1} west wind. Currents are shown for 0.4 and 9.9 m depths and for a constant elevation of 1.2 m above the lake bottom from the upper part of the figure to the lower part, respectively. (From Gedney 1971).

FIGURE 4

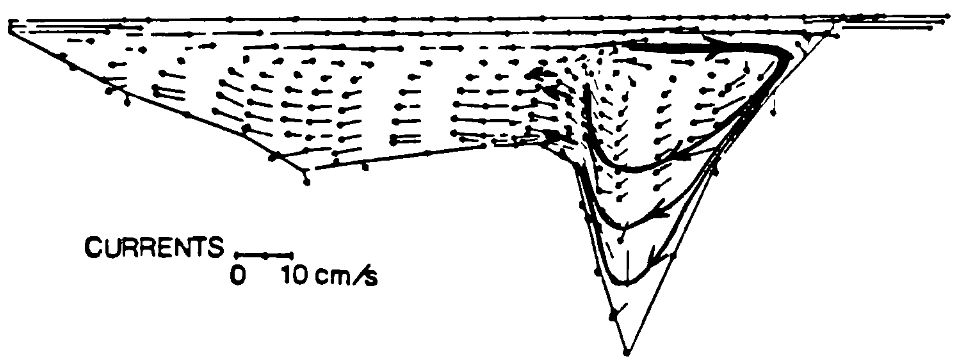


FIGURE 5 Vertical circulation characteristics (Lam et al)

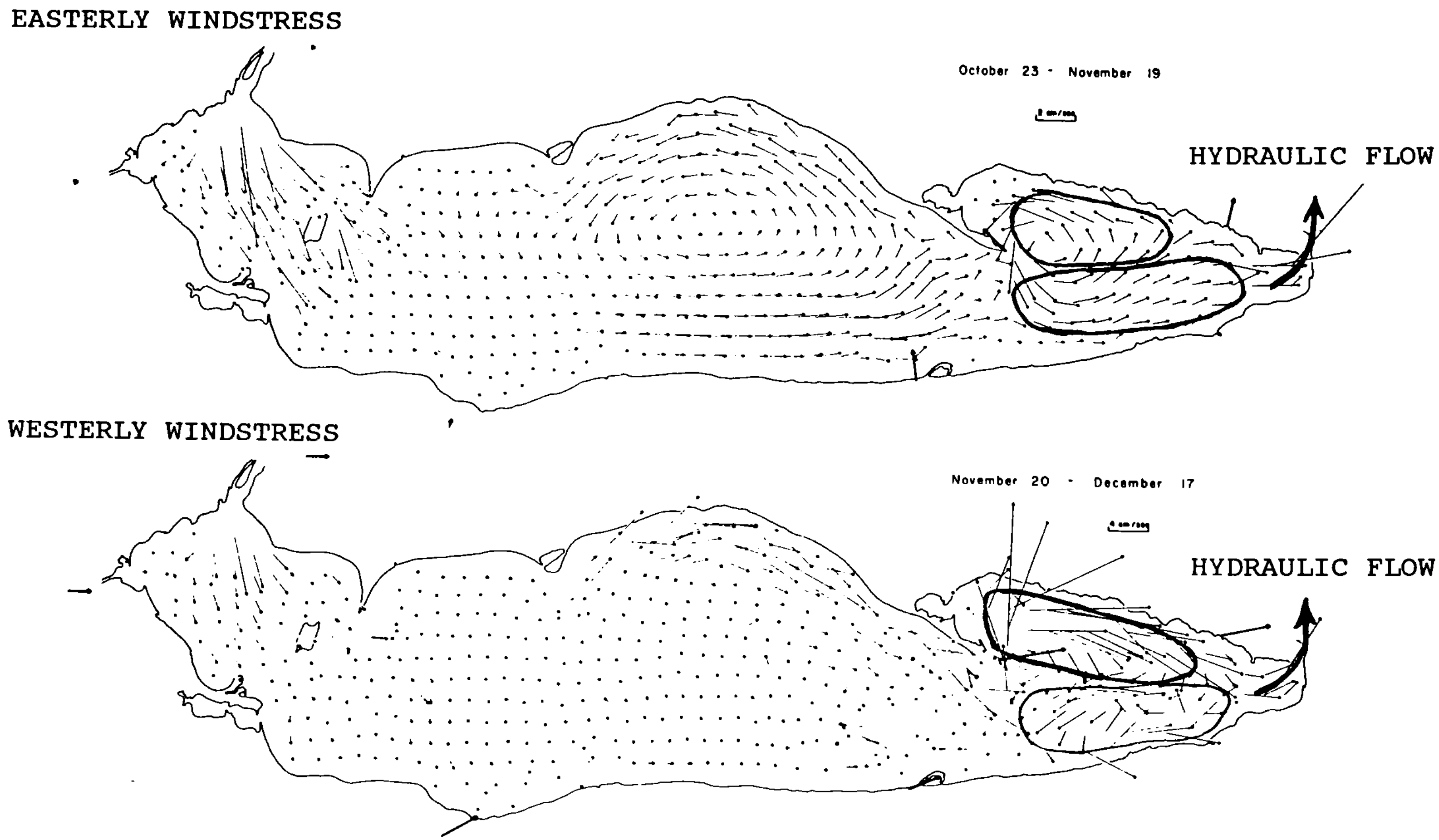


FIGURE 6 Depth-averaged lake Erie water circulations computed by homogeneous model for easterly and westerly wind impulses indicated by the dates above each map. Heavy arrows indicate directions and relative magnitudes of windstresses.

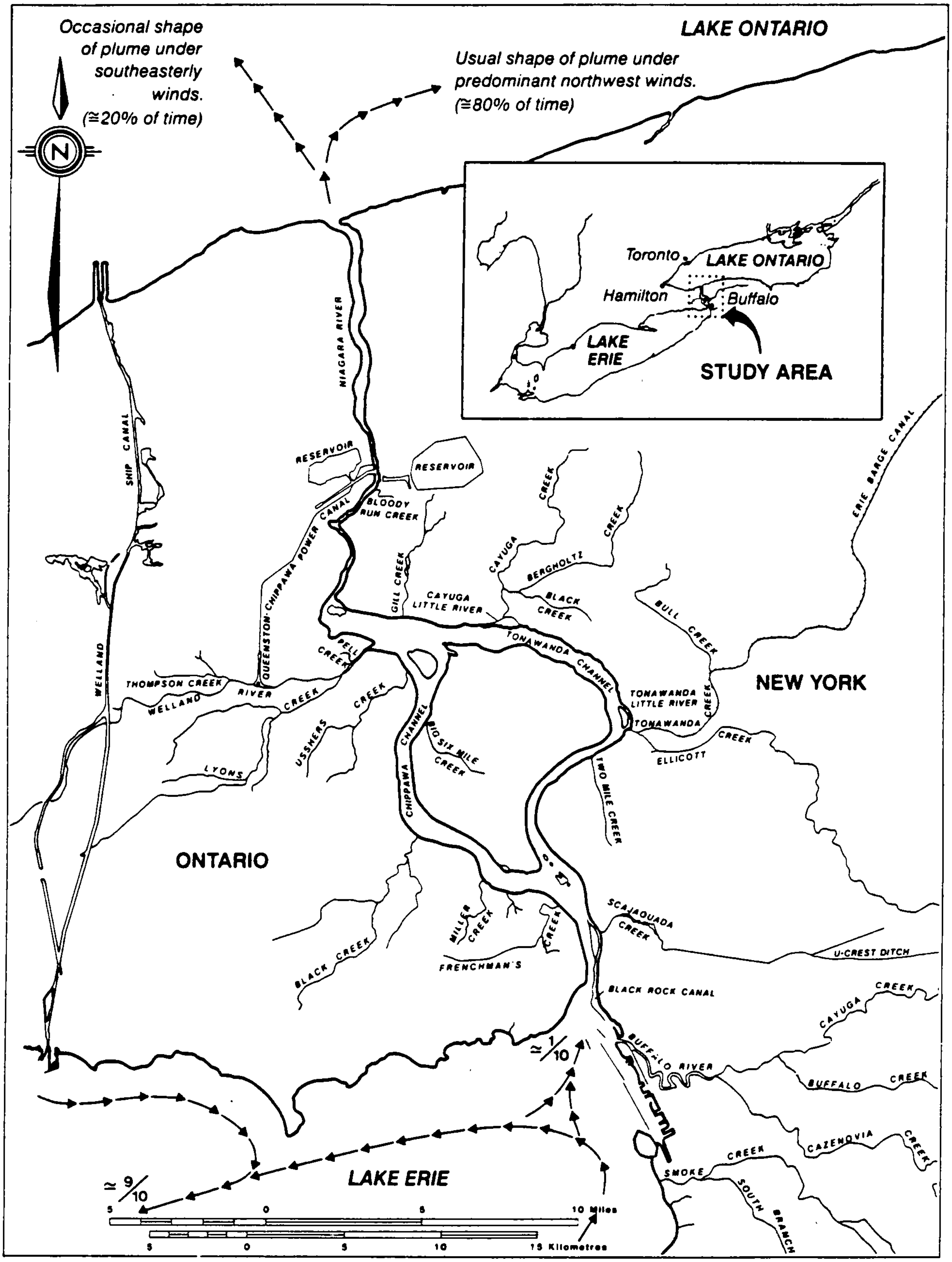


FIGURE 7 Inlet/outlet conditions of the Niagara River. (NRTC 1984)

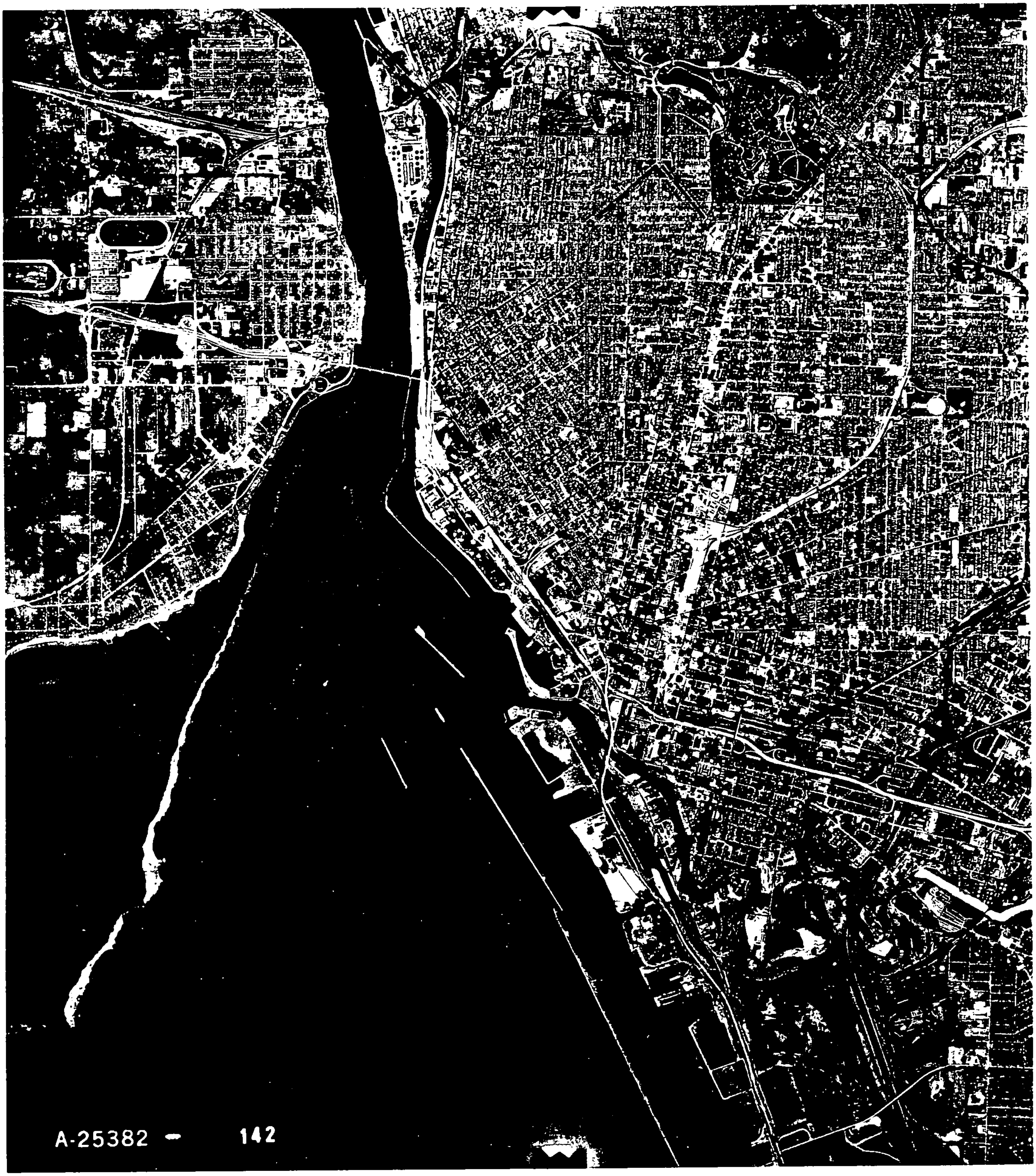


FIGURE 8 Air photo of the study area (head of Niagara River)

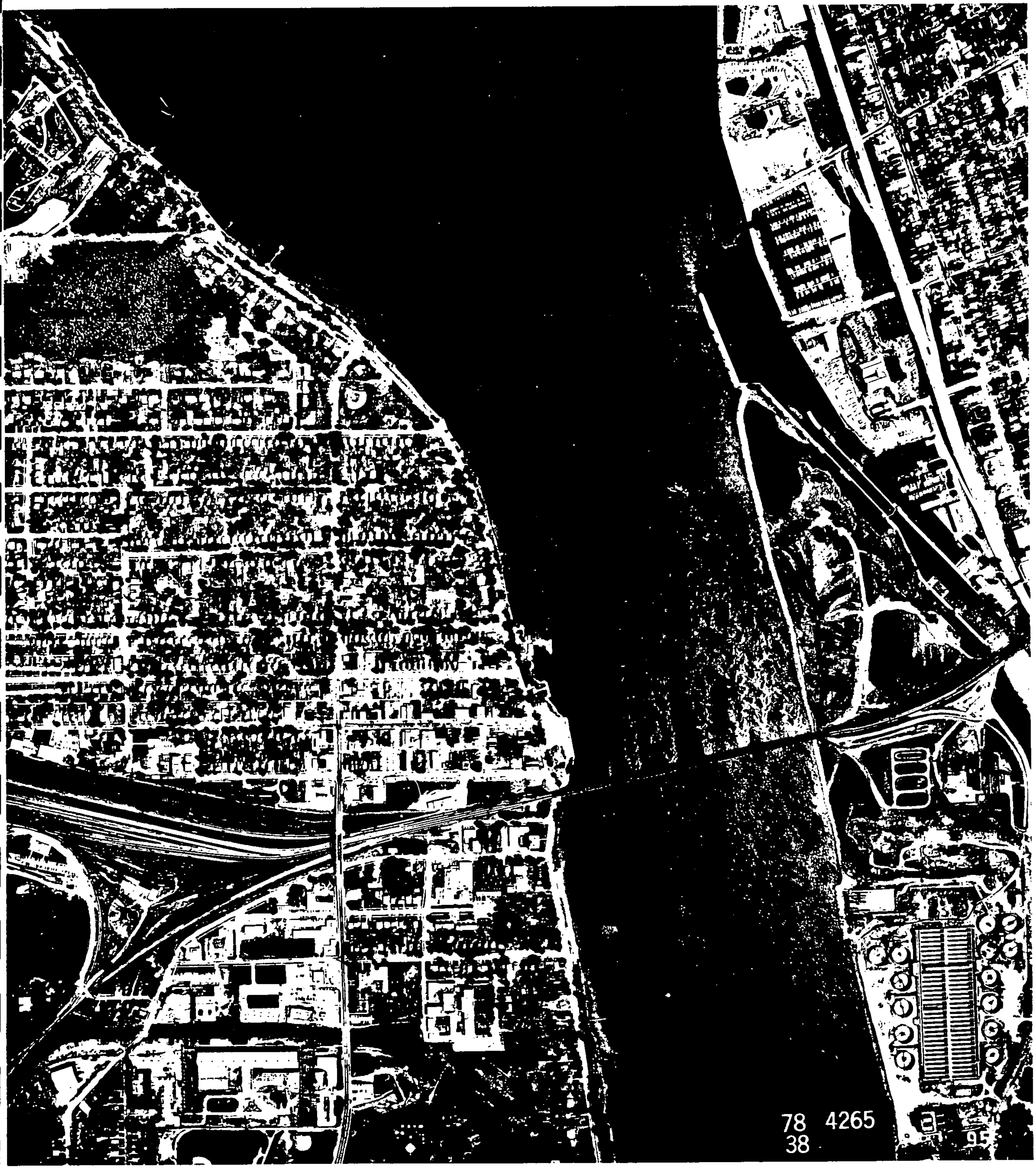


FIGURE 9 Air photo of the study area (site of the Fort Erie station)

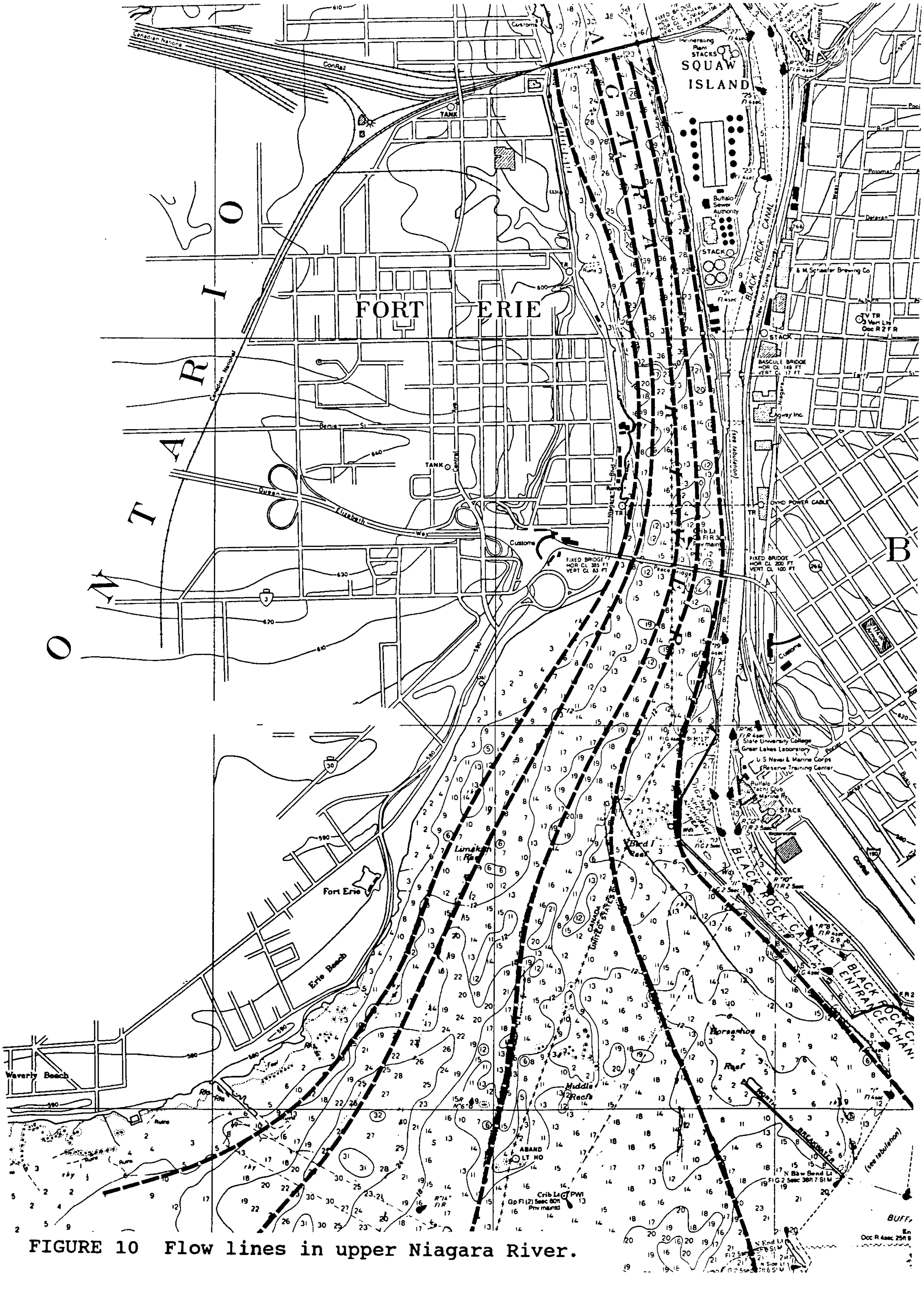


FIGURE 10 Flow lines in upper Niagara River.

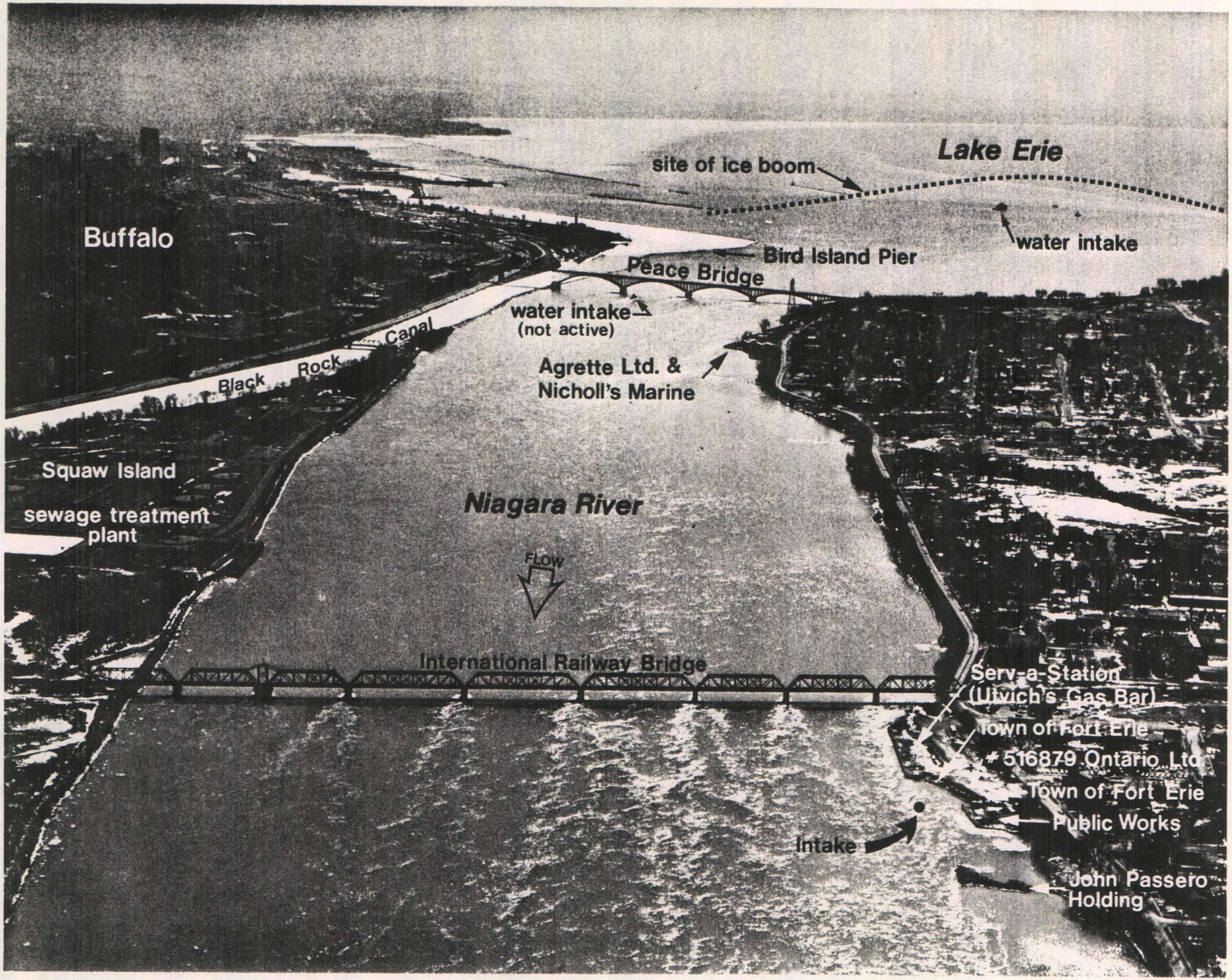


FIGURE 11 Site of sampling station.

NYPA photo

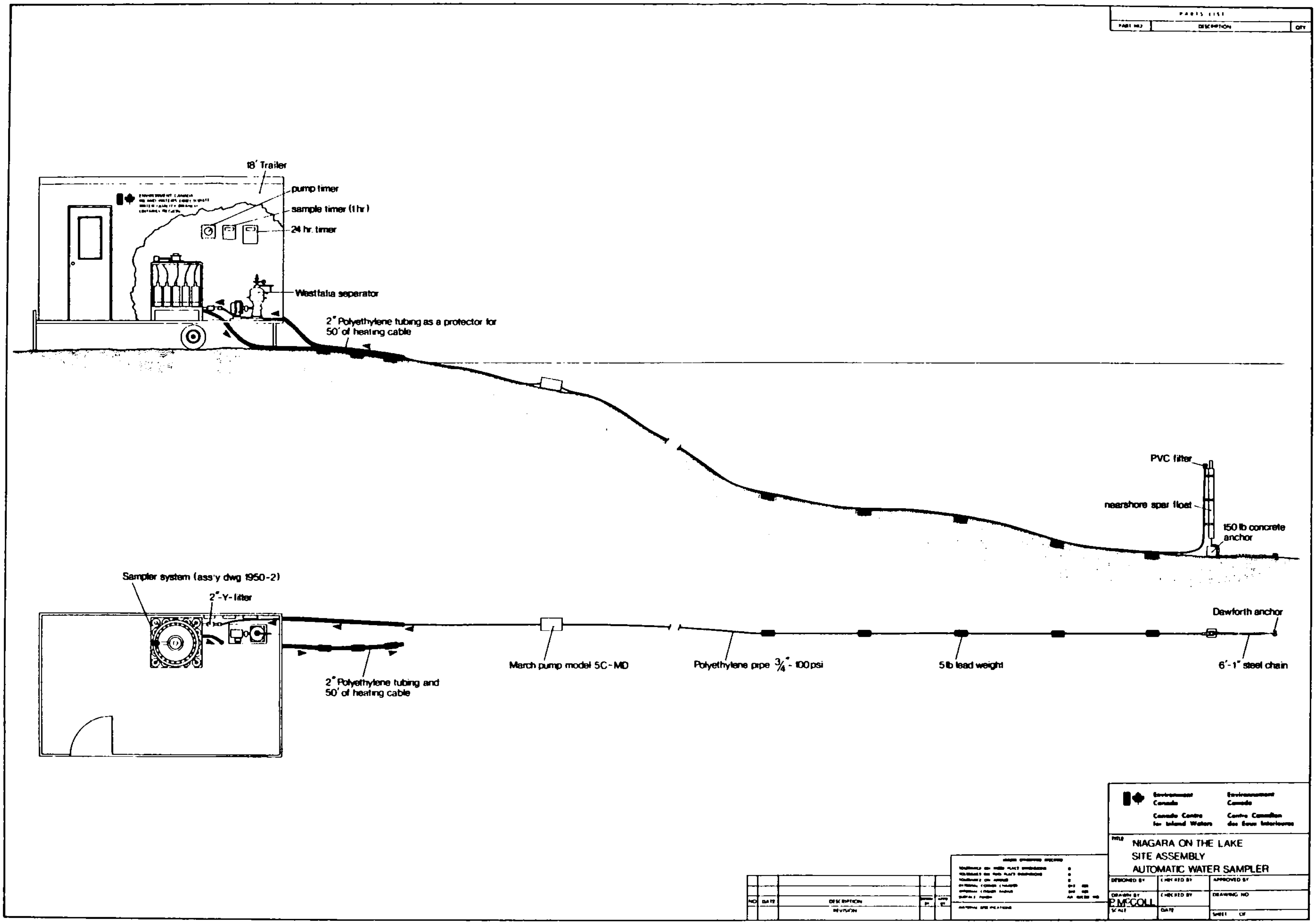


FIGURE 12 Niagara River intake assembly.