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DEPARTMENT OF ENERGY, MINES AND RESOURCES

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Part I - Temperature and Current Structure in the Niagara River Plume

Part II - The Mixing of the Niagara River Plume in Lake Ontario

H.S. WEILER and C.R. MURTHY

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Abstract

A descriptive study off the mouth of the Niagara River was carried out in 1968 to obtain information on the dynamic behaviour of the river's plume, both in terms of gross movement as well as diffusive properties.

Part I of the report encompasses the results of temperature surveys, drogue tracking experiments, and infrared line scanner mosaics. These results show that the river's plume is strongly influenced by the dominant winds of the day before the experiment, and to a lesser extent those of the preceding day. Response time of the plume to persistent changes in wind, was estimated to be between 1 and 2 days. Surface currents in the lake, driven by over-lake winds, controlled the motion of the plume; the motion was quite varied and complex, depending on the wind fields encountered, a fact that showed up most clearly on the infrared line scanner mosaics.

Part II of the report encompasses the diffusion studies carried out in the same area. The mixing of the river's plume with the main body of the lake was found to take place in two stages. Fairly close to the river's mouth, very strong river-type mixing was found. Beyond this area, buoyant surface spread of the warmer river water over the colder lake water occurred. These findings are consistent with the results of Part I.

Part 1 - Temperature and Current Structure in the Niagara River Plume

H.S. WEILER

1. INTRODUCTION

Studies were conducted in 1968 in Lake Ontario off the mouth of the Niagara River to obtain preliminary information for a description of the river plume, as well as some idea of its dynamic behaviour in terms of gross movement and diffusive properties. This information would then be used in later interpretation of current meter records collected in the study area.

The detailed field study was carried out between May 23 and November 26, 1968, with the studies being carried out in a piecemeal fashion. The studies themselves fell into four groups:

(1) studies carried out from launches and using drogues, temperature measurements and diffusion measurements

(2) temperature studies carried out using a major vessel

(3) current studies using moored, self-recording current meters and data packages to acquire background meteorological information, and

(4) infrared imagery studies using an instrumented aircraft (Carried out in the summers of 1968 and 1969).

Since the third study provided a large mass of data to allow a more quantitative, as compared to a more descriptive, analysis of currents in the river plume to be made, they will be described separately in a future report. The rest of the studies, encompassing 1968 summer data, as well as some data in 1969, will be treated in this report. The report itself will be divided into two general parts, the second part encompassing the diffusion studies carried out by C.R. Murthy.

2. DESCRIPTION OF THE EXPERIMENTAL SITE

The study area was bounded approximately by latitude 43°20'N, the south shore of Lake Ontario, and longitudes 79°00'W and 79°10'W.

As seen in Figure 1, topography of the area just outside the river's mouth is characterised by a shallow bar extending about 3.5 miles in a direction close to northeast from the shore at Four Mile Point, the point of land jutting out into the lake at the extreme left of the figure. This feature is called the "Niagara Bar", and appears to be a bedrock formation

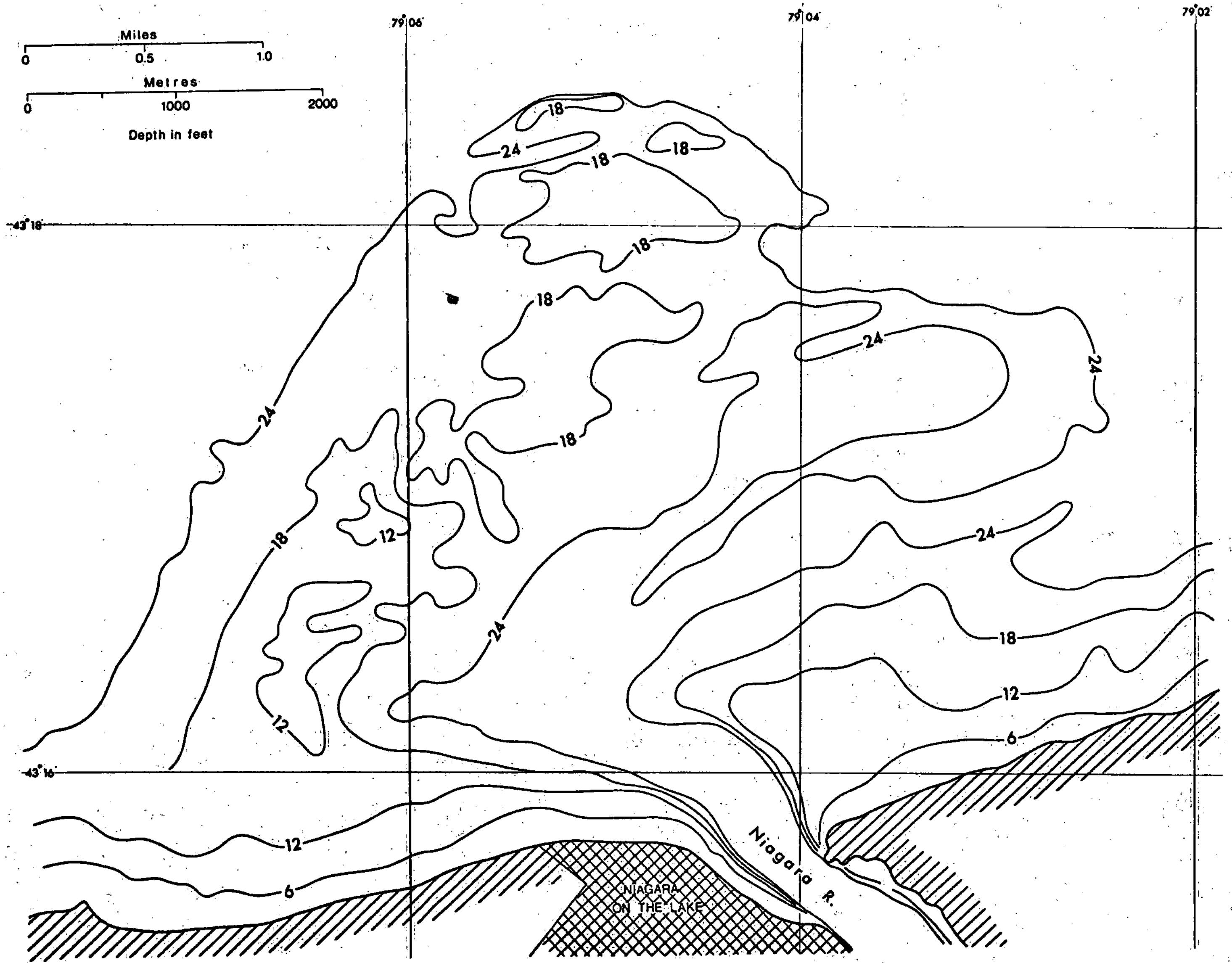

Figure 1. Bathymetry at the mouth of the Niagara River (after USLS chart 256).

partially covered by deposition of erosion material carried by the river's flow (Sly, 1970, pers. com.).

The volume outflow from the Niagara River is variable, depending on the season, as well as on planned diversions* by the Hydro Electric Power Commission of Ontario and the Niagara Mohawk Power Corporation in New York State. Since all observational programs undertaken by staff of the Canada Centre For Inland Waters lasted for periods varying from many hours up to a few days, the picture obtained from field observations of the plume have to be considered as "smeared" or averaged conditions, without considering the effects of these diversions, or other changes in the river's volume flow.

However a few crude calculations can be made. During the spring - summer - fall months, the average river flow is about 190,000 cfs or 5,500 m^3/sec (International Joint Commission, 1969, p.145). Using 70,000 square feet as the approximate cross-sectional area of the river's mouth (from U.S.L.S. chart no. 256), then by continuity, the average velocity at the mouth is about 2.7 feet/second or about 83 cm/second. This is close to values measured just outside the river's mouth as noted later.

3. EFFECT OF METEOROLOGICAL CONDITIONS ON THE NIAGARA RIVER PLUME

The overlake wind in the area is of primary interest in the study of the dynamics of the Niagara River plume. This information was obtained from a variety of sources, including a launch, a large research vessel (C.S.S. LIMNOS) used by the Canada Centre For Inland Waters, and regular meteorological stations on land in New York State (U.S. Coast Guard at Youngstown, N.Y.) and in Ontario (Vineland; Burlington Pier; Hamilton Marine Police; and Malton).

For purposes of evaluating the effect that the overlake wind would have on the behaviour of the river plume, it was felt that the winds for the week previous to the day of observation would be sufficient (Ayers, 1962). Since the observations were taken over a long period of time (up to a large fraction of a whole day), then the supporting meteorological observations were reduced to a daily average to make them more representative. The average was computed as a vector average in all cases and was expressed in knots and in terms of the eight ($\pm 22\frac{1}{2}^\circ$) compass points. Ship observations gave directional readings of better than 10 degrees; however, for uniformity, these observations were also expressed in the same units as the rest of the data. These wind observations are outlined in Table 1. In this table under "Assessment", "A" refers to observations taken within 10 km. of the river's mouth, "C" outside this area; the numbers 1 to 3 refer to decreasing levels of accuracy.

4. WATER TEMPERATURE STRUCTURE OUTSIDE THE MOUTH OF THE NIAGARA RIVER

A fairly large volume of information exists on the temperature structure of the river plume or parts of it. However, a study of all the temperature data showed a large number of common features, so that summaries will be discussed rather than each set of measurements.

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* These diversions are used to regulate the flow needed to generate electric power, as well as to ensure the scenic beauty of Niagara Falls. Hence, it is not too realistic to consider the flows on an hourly or day-to-day basis without detailed records of diversions. The diversions can amount to a sizable fraction of the mean flow on any one day in the spring to fall period when measurements were made.

TABLE 1. LIST OF METEOROLOGICAL OBSERVATIONS USED

Date	Day of Obser-vation	Wind Vector		Assessment*	Source**
		Speed Knots	Direction		
		1968			
May 17		14	SW	C2	M
May 18		4	S	C2	M
May 19		5	E	C2	M
May 20		11	NW	C2	M
May 21		9	NW	C2	M
May 22		7	S	C2	M
May 23	x	12	NE	C2	M
May 30		7	SW	A1	C
June 1		8	SW	A1	C
June 2		12	SW	A1	C
June 3		7	NW	A1	C
June 4		6	W	A1	C
June 5		9	SW	A1	C
June 6	x	12	SW	A1	L
June 7	x	5	W	A1	C
June 8	x	7	E	A1	C
June 18		3	S	A1	C
June 19		12	W	A1	C
June 20		11	N	A1	C
June 21		8	SW	A1	C
June 22		8	W	A1	C
June 23		1	SE	A1	C
June 24	x	3	NW	A1	C
June 25		6	SE	A1	C
June 26	x	11	E	A1	C
June 27	x	3	E	A1	C
June 28	x	13	SW	A1	C
July 2		4	NW	A1	C
July 3		8	NW	A1	C
July 4		7	SW	A1	C
July 5		6	S	A1	C
July 6		4	W	A1	C
July 7		8	SW	A1	C
July 8	x	14	SW	A1	L
July 9	x	10	SW	A1	C
July 10	x	6	E	A1	C
July 11	x	2	SE	A1	C
July 12	x	4	S	A1	L
July 13	x	4	SE	A1	C
July 14		5	SW	A1	C
July 15	x	14	SW	A1	L
July 16	x	8	SW	A1	L
July 17	x	8	SW	A1	L
July 18		11	SW	A1	C
July 19		14	NW	A1	C
July 20		6	NW	A1	C
July 21		8	SW	A1	C
July 22		9	SW	A1	C
July 23	x	4	NE	A1	L
July 24		6	W	A1	C
July 25		5	N	A1	C
July 26		4	E	A1	C
July 27	x	10	SW	A1	L
Aug. 7		7	NW	A1	C
Aug. 8		2	S	A1	C
Aug. 9		4	W	A1	C
Aug. 10		12	NE	A1	C
Aug. 11		6	NW	A1	C
Aug. 12		7	SW	A1	C
Aug. 13		6	SW	A1	C
Aug. 14		5	NW	A1	C
Aug. 15	x	4	E	A1	C
Aug. 22		4	E	A1	C
Aug. 23		3	SE	A1	C
Aug. 24	x	3	W	A1	C
Aug. 25		15	NW	A1	C
Aug. 26		14	NW	A1	C
Aug. 27		12	NE	A1	C
Aug. 28	x	5	NE	A1	C
Aug. 29		4	NW	A1	C
Aug. 30		5	NW	A1	C
Aug. 31		2	E	A1	C
Sept. 1		4	E	A1	C
Sept. 2		3	NE	A1	C
Sept. 3		1	SE	A1	C
Sept. 4		9	E	A1	C
Sept. 5		9	SW	A1	C
Sept. 6	x	15	W	A1	C
Sept. 7		9	NW	A1	C
Sept. 8		5	E	A1	C
Sept. 9	x	10	NE	A1	L
Sept. 10		5	E	A1	C
Sept. 11		12	NE	A1	C
Sept. 12		7	NW	A1	C
Sept. 13	x	12	NW	A1	L
Sept. 14	x	4	NW	A1	L
Sept. 15		5	W	A1	C
Sept. 16		2	E	A1	C
Sept. 17		6	E	A1	C
Sept. 18		7	E	A1	C
Sept. 19		6	E	A1	C
Sept. 20	x	6	E	A1	L
Oct. 2		13	W	A1	C
Oct. 3		17	W	A1	C
Oct. 4		16	NW	A1	C
Oct. 5		11	NW	A1	C
Oct. 6		1	W	A1	C
Oct. 7		4	NW	A1	C
Oct. 8	x	5	E	A1	C
Oct. 9	x	10	E	A1	L

* Assessment: See test in part 3.

** Source:
L - launch
V - major vessel, CCIW
B - meteorological station, Burlington pier
C - meteorological station, U.S. Coast Guard
M - meteorological station at Malton

TABLE 1 (Cont.)

Date	Day of Obser-vation	Wind Vector Speed Knots	Wind Vector Direction	Assessment*	Source**
1969					
May 15		2	W	A3	V
May 16		5	NE	A3	V
May 17		12	SW	A3	B
May 18		13	NE	A3	B
May 19		11	SE	A3	V
May 20		10	SW	A2	V
May 21	x	8	N	A3	V
May 22		7	NE	A3	V
May 23	x	2	S	A2	V
May 24		7	SW	A2	V
May 25		16	N	A2	V
May 26	x	8	E	A2	V
May 27	x	2	NE	A2	V
July 8		6	NE	A3	V
July 9		11	E	A2	V
July 10		5	E	A2	V
July 11		3	SW	A3	B
July 12		6	SW	A3	B
July 13		6	NW	A3	V
July 14	x	3	SW	A3	B
July 15	x	4	W	A3	B
Aug. 28		3	NW	A3	V
Aug. 29		8	SW	A2	V
Aug. 30		4	SW	A3	B
Aug. 31		5	W	A3	B
Sept. 1		5	NW	A3	B
Sept. 2		8	NE	A3	B
Sept. 3	x	6	NE	A3	B
Sept. 4		7	NE	A3	B
Sept. 5		3	SW	A3	B
Sept. 6	x	15	W	A2	V

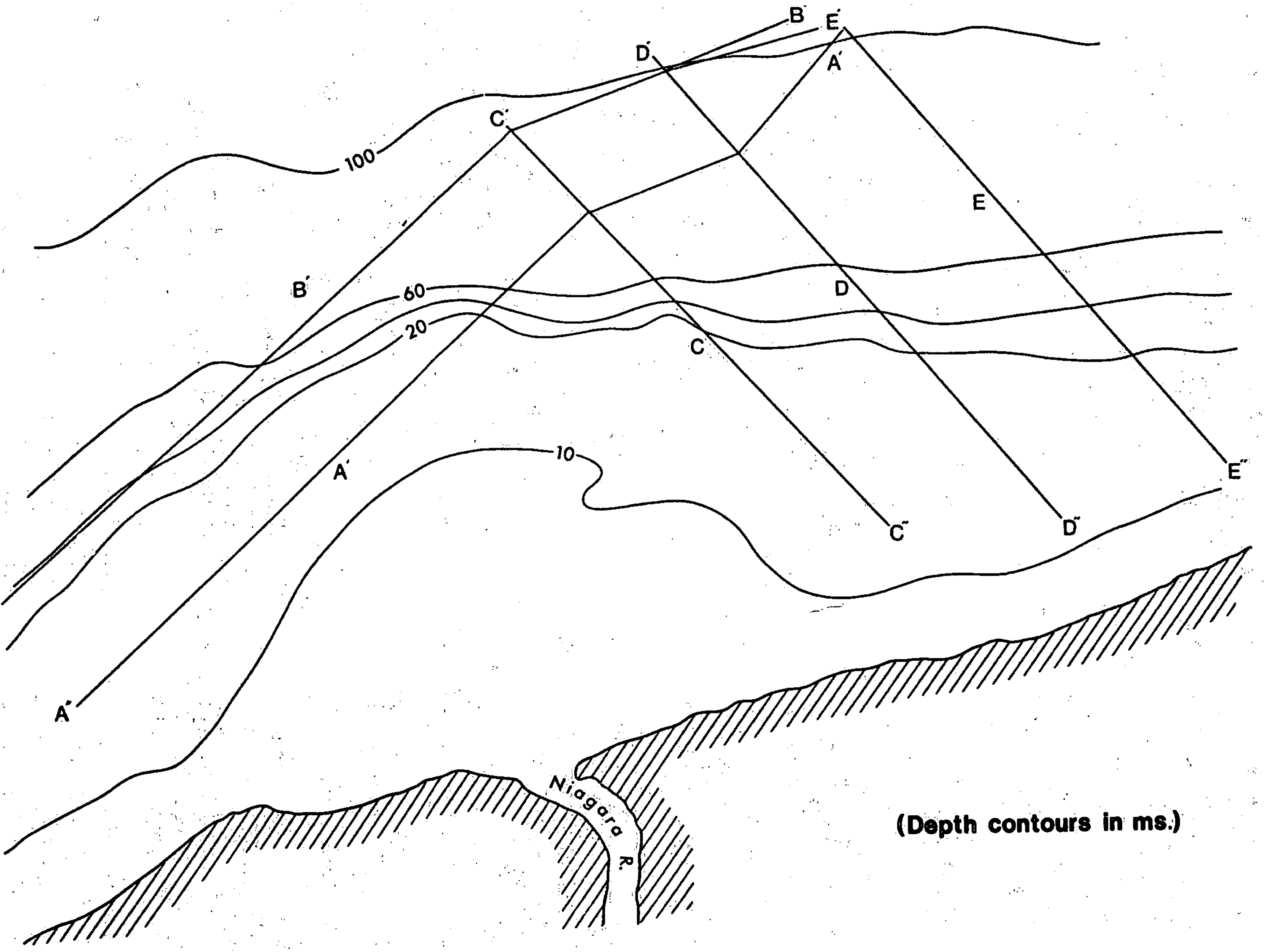
* Assessment: See text in part 3.

** Source: L - launch
V - major vessel, CCIW
B - meteorological station, Burlington pier
C - meteorological station, U.S. Coast Guard
M - meteorological station at Malton

In early spring, the temperature field was pretty well isothermal, with little structure. From about July onward, the thermocline in the lake close to the river's mouth becomes progressively more well developed, with the incoming river water being close to and above the temperature of the epilimnion. This can be seen from the series of detailed vertical temperature sections (Figs. 3, 4 and 5, see Figure 2 for location plan of sections) measured between August 26 and September 3, 1968, when the thermocline is quite sharp. The thermocline outside the bar area is well developed, while inside the bar it is more poorly defined; fairly weak stratification exists. This arises from rapid turbulent mixing. However, stratification is not wholly absent on the outer edge of the bar, away from the river's mouth. The studies by Anderson and Rodgers (1959) point to a probable movement of deeper lake water toward the western edge of the bar, and subsequent entrainment of this water by the outward flowing plume. This would aid in preserving the fairly sharp temperature gradient observed in the area. Figures 4 and 5, especially Figure 4, indicate this probable intrusion of colder lake water onto the shallower bar.

The plume also tends to flow and spread out on the surface of the lake, so that, in effect, one can consider it a weakly "buoyant" plume.

A comment should be made at this point on the plume's behaviour between August 26 and September 6. Although the measurements stretched from August 26 to September 6, all of the measurements of Sections A to D (Figure 2) were done on September 5 and 6. During these two days the flow in the plume moved northeastward and then eastward, so that the warmer



(Depth contours in ms.)

Figure 2. Temperature sections, Niagara River bar, 1968.

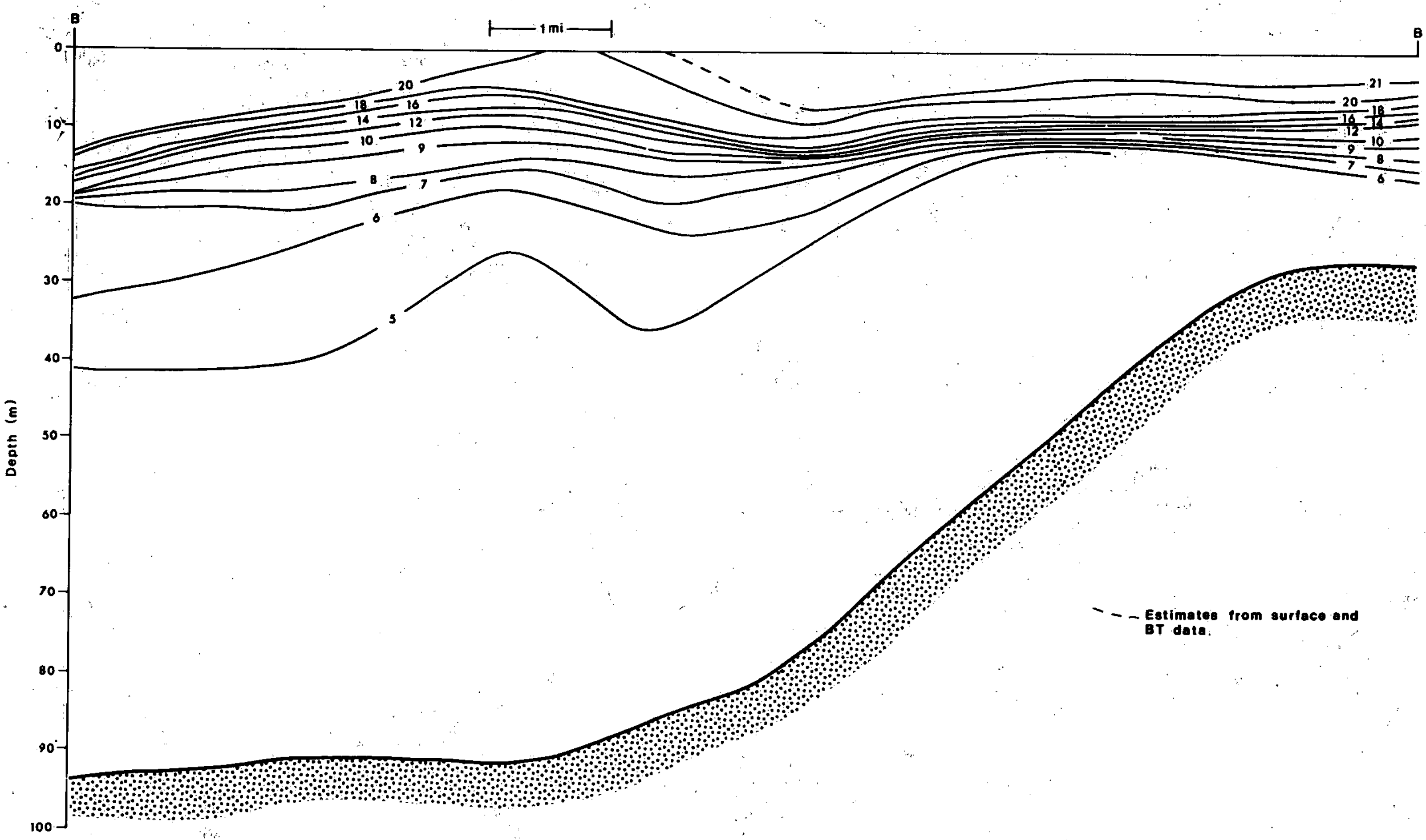


Figure 3. Temperature section B, Niagara River Bar, August 26 - September 3, 1968. (temperatures in °C)

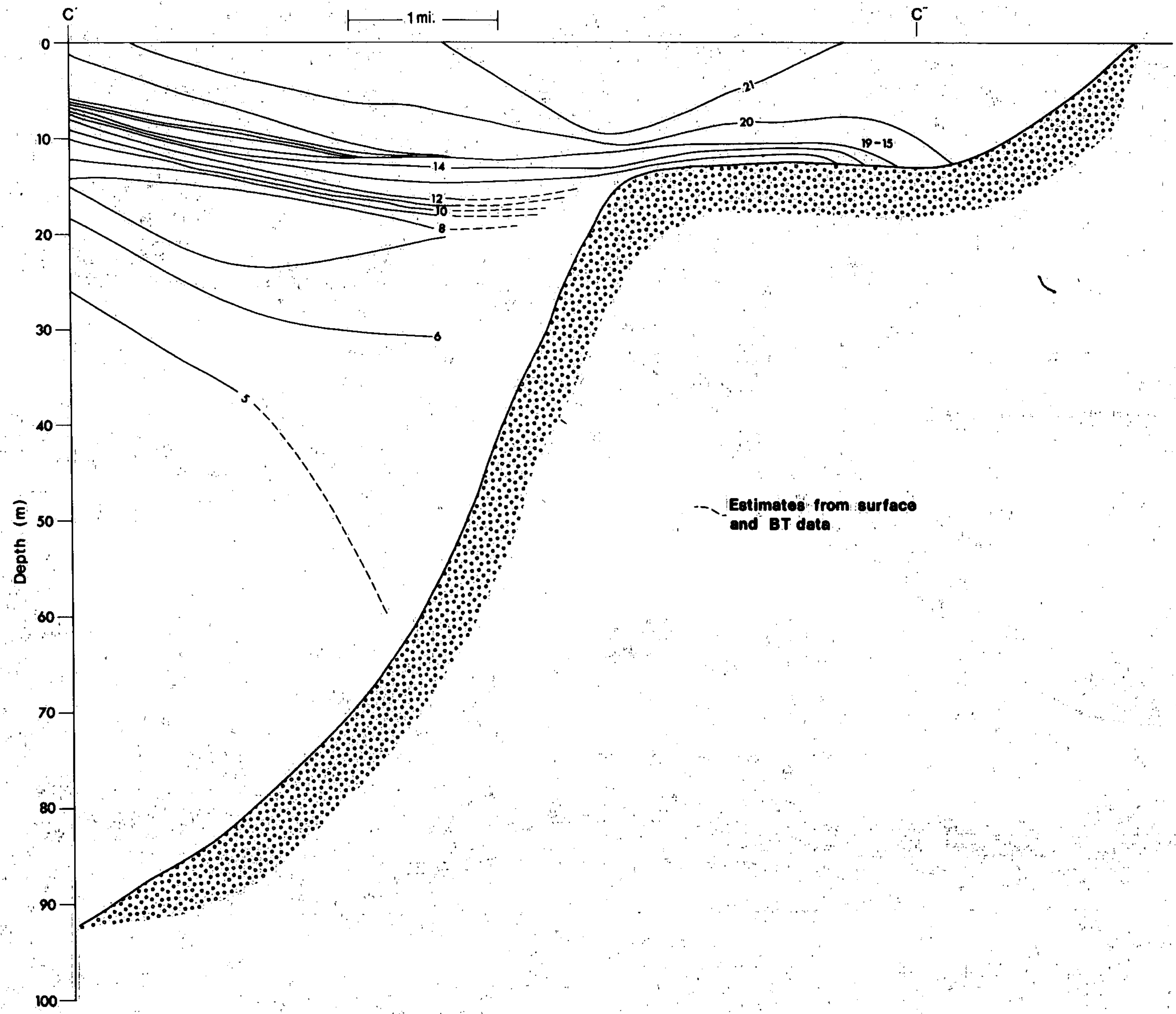


Figure 4. Temperature section C, Niagara River Bar, August 26 - September 3, 1968. (temperatures in °C)

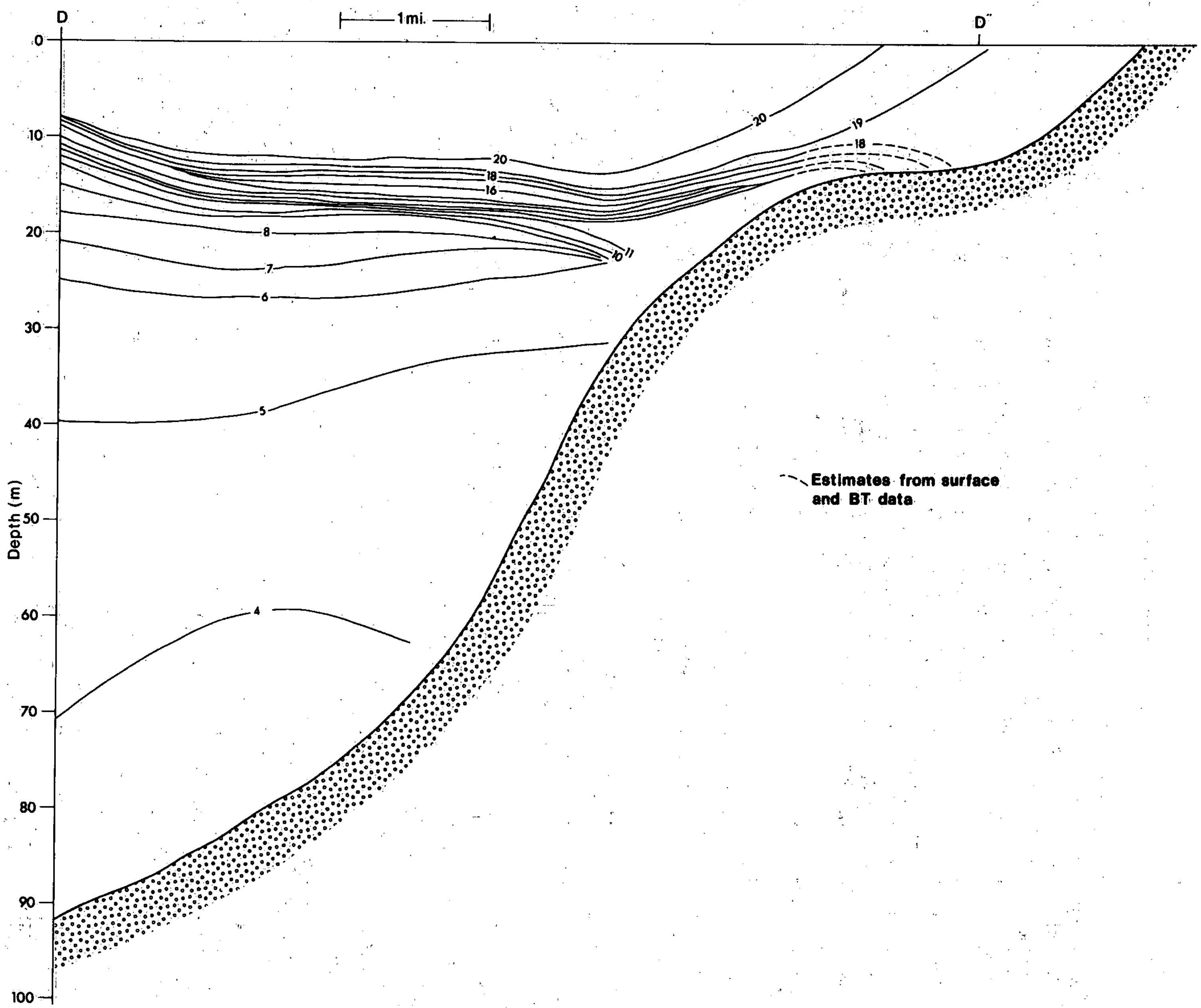


Figure 5. Temperature section D, Niagara River Bar, August 26 - September 3, 1968. (temperatures in °C)

water of the river was confined fairly close to the shore some miles east of the river's mouth. However, the general temperature structure was similar for other midsummer and early fall river flow conditions.

5. CURRENT STRUCTURE IN THE PLUME

To understand fully the movement of the Niagara River plume, one must consider the general circulation dynamics in the western end of Lake Ontario. A review of the near-surface circulation in the western end of the lake, compiled from all sources available at the time, is given in Volume 1 of the Report of the International Joint Commission (1969, Section 4.6, Fig. 4.6.1). The seasonal net flow in the western end of the lake during the summer season is counterclockwise; offshore lake currents thus are eastward near the river's mouth. However, an understanding of the detailed movement of the plume is incomplete without considering the dynamic behaviour of these offshore currents under variable wind conditions. Information on this is sparse, with the most complete coverage to date being provided by Casey (1967, pp. 6-8 to 6-12, and Figs. 6-10 to 6-19.) An analysis of these results, shows that the offshore currents in the Niagara River area behaved as follows:

(1) with winds from north and northeast; currents flow northwestward and westward

(2) with winds from the east, southeast, south and southwest; currents flow northeastward

(3) with winds from the west; currents flow eastward

(4) with winds from the northwest; currents flow eastward and southeastward (further from the river's mouth).

In case (2) (currents flowing northeastward) there appears to be a counterclockwise gyre in the western end of the lake, bounded by Hamilton on the west, and approximately the Niagara River on the east, (or slightly to the east under conditions of direct easterly winds).

During 1968 currents in the area of the Niagara River plume were measured by means of "roller-blind" drogues tracked by radar and sextant from a launch or major vessel. The "roller-blind" drogues consisted of a vertical sheet of polyethylene film weighted on the bottom by a metal bar, and supported on the top by a bar attached to a surface float equipped with a marker light, flag, and radar reflector. The "blinds" stayed perpendicular to the currents, as observed and expected, and were placed normally at a depth of about 3 meters. During any one "run" or experiment, a group of 4 - 6 drogues was released and tracked, with their positions being calculated using a simple computer program.

To allow a consistent evaluation of the motion of the plume, the drogue tracks were grouped according to the prevailing wind direction during the day of the observation. As well, drogue tracks in each grouping were averaged where more than one followed along approximately the same path. For each drogue, average velocities were calculated between each set of position fixes, and these velocities were then used to give curves of constant speed in the plume for each grouping considered.

The results of the drogue measurements are shown in Figures 6-9 grouped with winds coming from the NE-E, S-SSW, SW and NW sectors. Unfortunately, no observations were recorded during northerly or south-easterly winds, or for calm conditions.

The initial conclusion that became apparent was that the motion of the plume was highly variable, but was dependent on the wind conditions. The plume also appeared fairly insensitive to wind speed, depending primarily on the wind direction. Reference to past wind data also showed that the winds one day prior to the day of observation have a strong influence on the plume's behaviour, while winds two days prior and possibly to a small extent three days prior also may influence the plume. Effects of winds more than 3 days before the day of observation did not appear to influence the plume's behaviour.

As observed from our data, the plume moved as follows:

(1) Winds from northeast and east (Fig. 6).

The plume moves northwestward, its velocity decreasing with distance from the river's mouth, spreading fanwise with somewhat higher velocity as it passes over the far edge of the bar. Some eddies appear on the western edge of the plume; the westward leading edge of the plume is sharp, with a large horizontal velocity gradient.

(2) Winds from the south, south southwest (Fig. 7).

The plume moves northwest, with a fairly symmetrical shape, and detaching eddies on both edges of the plume. The plume itself spreads out fanwise, with velocities decreasing with increasing distance from the river's mouth.

(3) Winds from the southwest (Fig. 8).

Initially, the plume moves approximately northward, and then curves toward northeast and east as it spreads out; the velocity steadily decreases with distance from the river's mouth. The western edge of the plume is also sharper than the eastern edge, which is more diffuse, except near the river's mouth where the plume is fairly symmetrical in cross-section.

(4) Winds from the northwest (Fig. 9).

The plume moves northeastward, spreading out fanwise and with somewhat larger horizontal velocity gradient on the western side of the plume as compared to the eastern side. Where the plume passes over the bar almost directly north of the river's mouth, the velocities show a small increase.

Under the wind conditions studied, with the exception of case (2) (winds from the south and south southwest), the plume's direction conforms fairly well with the direction of the surface currents some distance from the river's mouth, as inferred by Casey (1967). Case (2), with winds from the south, south southwest on July 12 and 27 is, however, anomalous. According to Casey's results, the southerly and southwesterly winds should produce a surface current in the bar area which flows northeastward or at best, northward (the data are not sufficiently detailed in the area to give completely firm delineations of direction). But during the two runs, the plume moved northwestward.

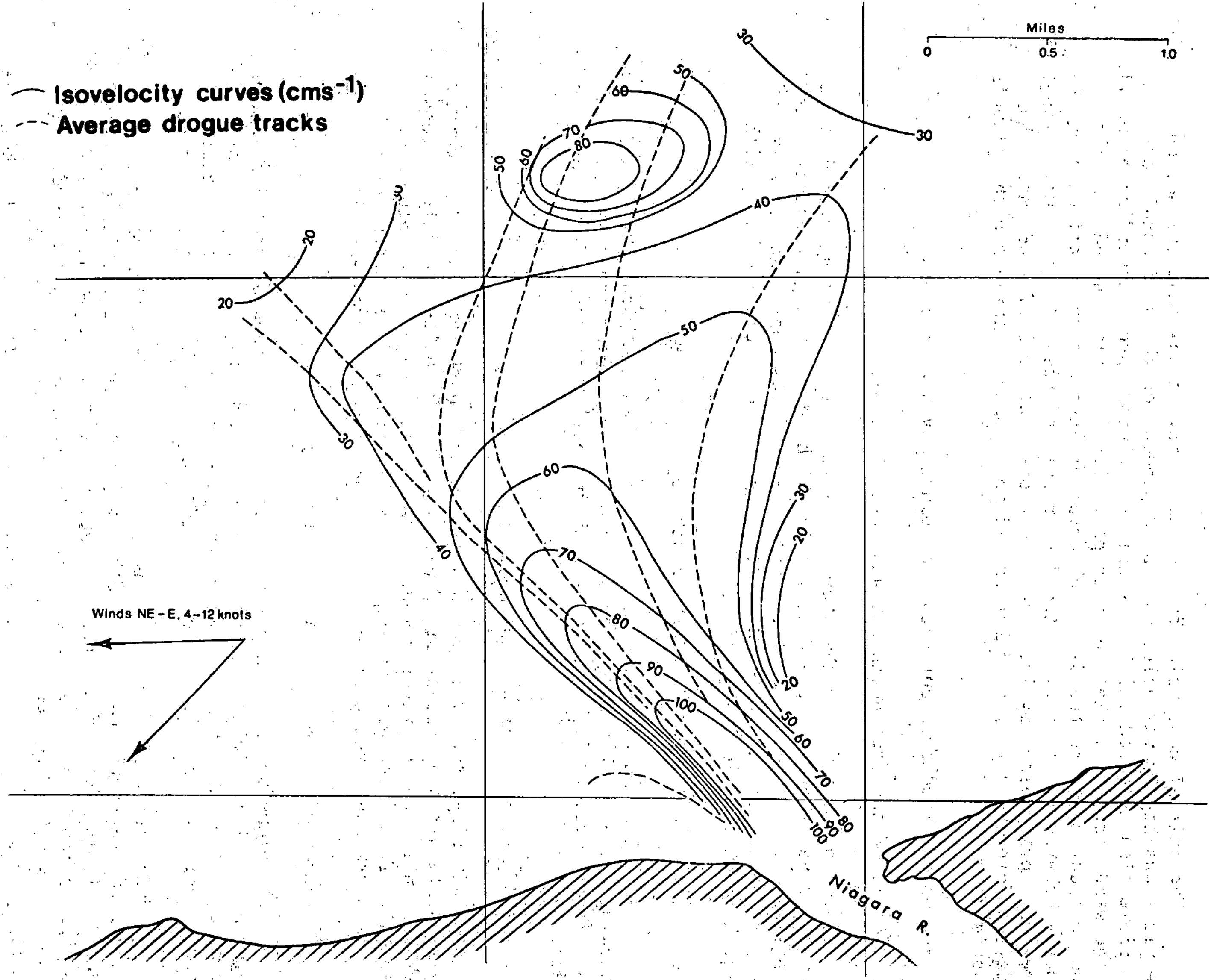


Figure 6. Niagara River plume under winds from NE-E, range 4-12 knots. (4 runs from September 9 to October 9, 1968)

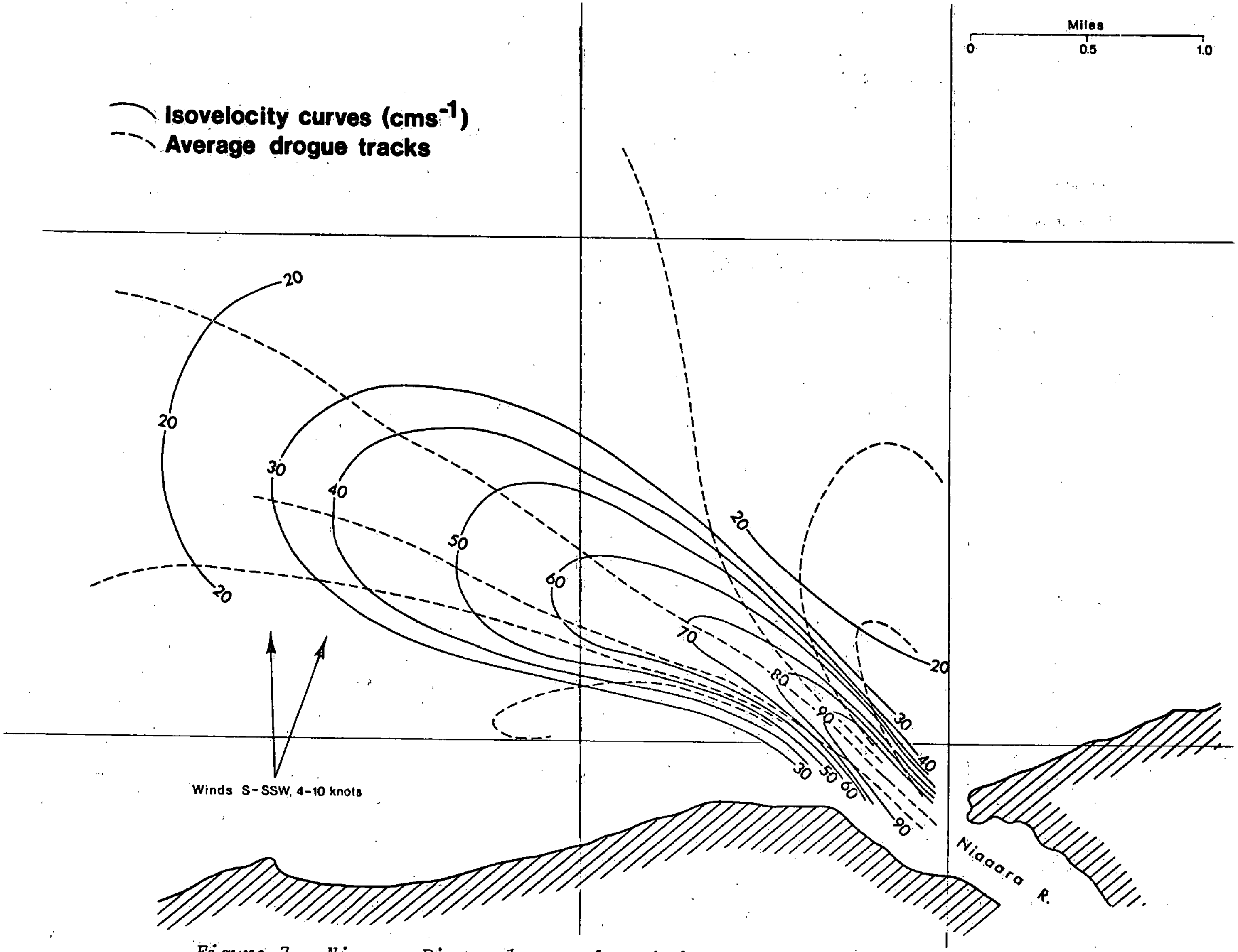


Figure 7. Niagara River plume under winds from S-SSW, range 4-10 knots. (2 runs, on July 12 and 27, 1968)

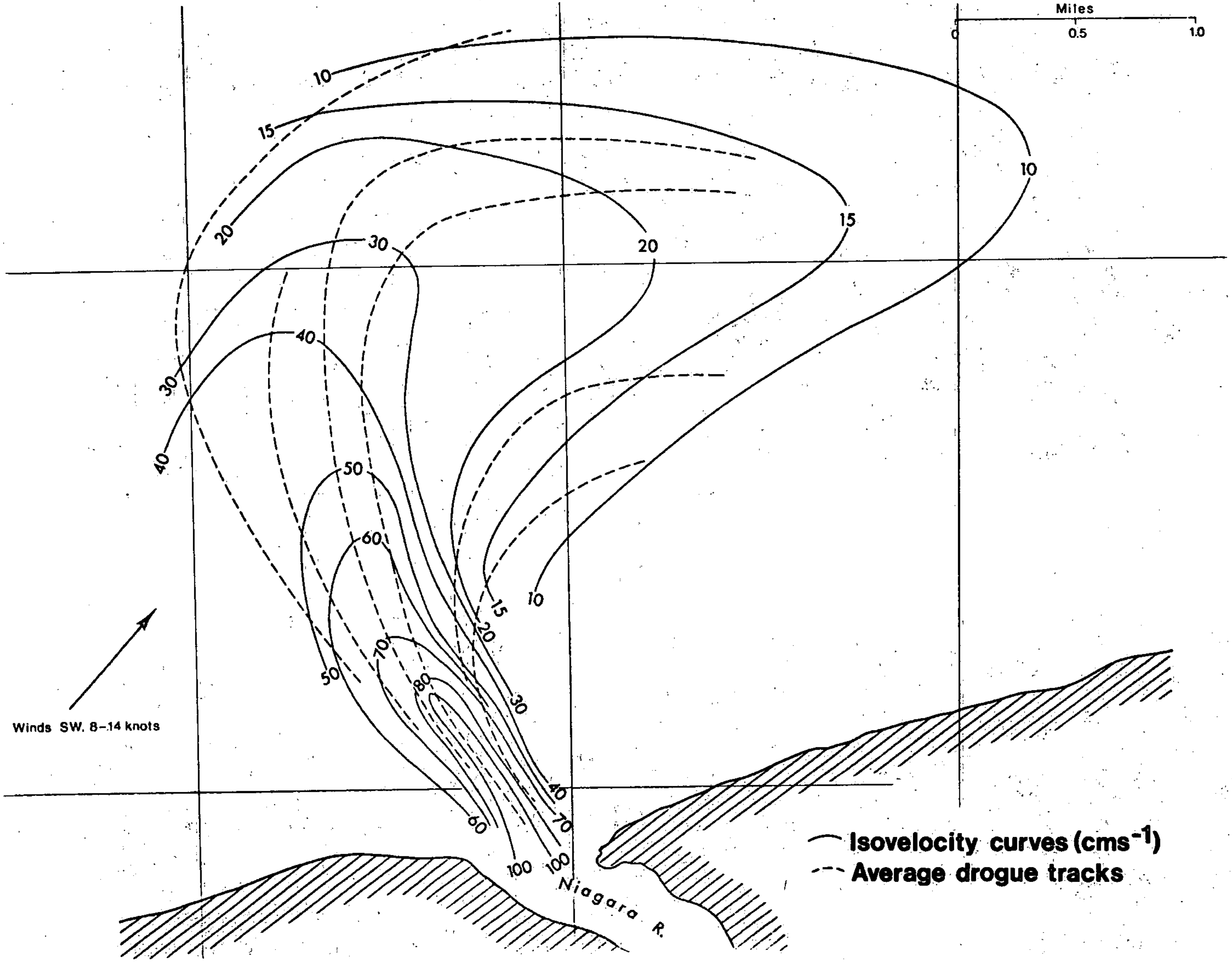


Figure 8. Niagara River plume under winds from SW, range 8-14 knots. (4 runs from June 6 to July 8, 1968)

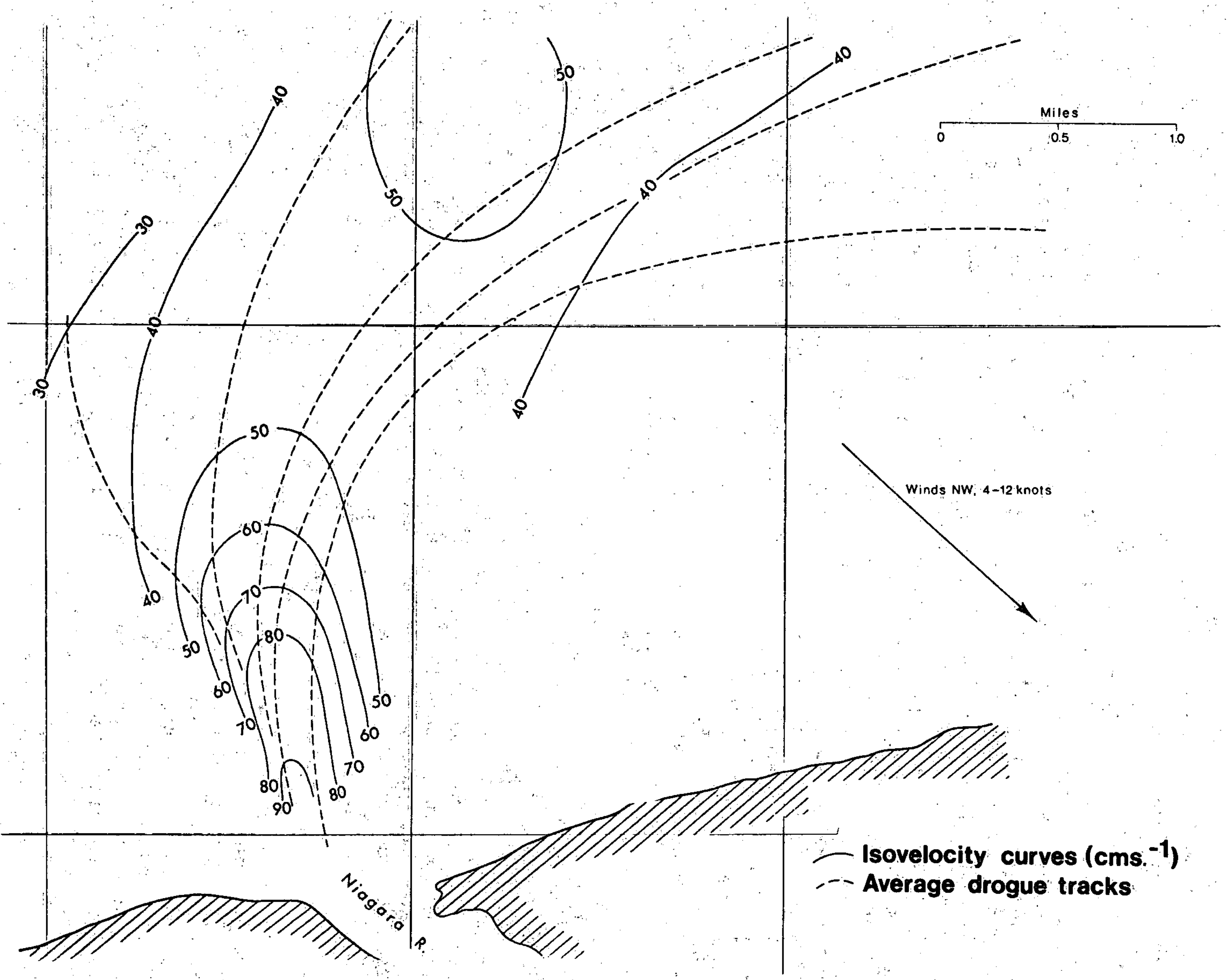


Figure 9. Niagara River plume under winds from NW, range 4-12 knots. (2 runs, on September 13 and 14, 1968)

An explanation of this anomaly was sought from the wind records in the area. As before, winds up to three days before the day of observation were considered. The results showed that for these two runs, the winds on the day of observation only were from the south or southwest; on the two previous days, they ranged from north to southeast. Further reference to the results from Casey (1967) shows that if one places greater weight on the wind velocity on the day before the observation, then the run of July 27 could be explained as before; the surface lake current would move northwestward and westward, driven by the northerly and easterly winds, with the currents not yet adjusted to a new change in wind direction. Reference to the run of July 12 produces a more mixed picture, although here again one could argue that the strong NE wind (12 knots) on the 10th, followed by weaker winds from the NW (6 knots) on the 11th and SW winds (7 knots) were not yet sufficient to completely rearrange the lake's surface currents for the day of observation, the 12th. This appears to contradict somewhat the earlier observation that the fact of major importance was the direction of the wind, rather than the speed. However, with the exception of July 12 and 27, the wind directions were persistent enough that such a conclusion could be drawn. In the light of these two "anomalous" runs, a better way of expressing the conclusion would be to state that the wind direction is the most important factor, provided the direction remained fairly steady for about 2 days before the day of observation and during the day of observation. The wind rearranges the surface currents of the lake, which then control the movement of the river's plume a short distance from the mouth of the river.

On the basis of the "anomalous" data of July 12 and 27, the response time of the nearshore currents would be about 1 to 2 days, which agrees with the results of an upwelling episode off Rochester studied by Sweers (1969).

Another small point of interest might be added here. Studies of sediment deposits by Dr. P.G. Sly at the CCIW (Sly, 1970, pers. com.) pointed to the probable existence of 3 "near-bottom rivers", narrow bands of bottom water with relatively rapid flow moving over the bar in westerly and northwesterly directions. One "river" ran along the shoreline roughly along the 12 - 14 foot isobath, and the other two through two troughs, the northerly one passing through the bar at about 43°17'N, 79°06'W, and the other one somewhat south of this. These results, however, await confirmation by direct measurements in the area.

6. INFRARED IMAGERY STUDIES

At various times during the 1968 and 1969 field seasons, an aircraft equipped with a modified Reconofax IV infrared line scanner (8 - 14 microns) was flown along parallel north to south tracks in the western end of the lake to collect infrared film strips which were then used to produce a composite, or mosaic picture of the relative surface temperature pattern of the very thin surface layer of the lake. (These mosaics were obtained and assembled by W. McColl of the Canada Centre For Inland Waters.) These mosaics were then studied with a view to determining the shape and direction of the Niagara River plume in each case.

A total of 7 mosaics made in 1968 and 7 in 1969, of varying quality and clarity of detail, were studied. The inferred movement of the plume, relative to the wind (see Section 5) was borne out in all cases where the plume was defined well enough for its axis and direction of movement to be determined. A detailed study of relevant wind records appears to indicate a response time of the plume of about one day, which is consistent with the conclusion reached in Section 5. The imagery also confirmed the sharper western edge of the plume when the plume moved eastward and northeastward.

Detailed examination of the imagery showed some other interesting phenomena which could not be detected by the coarser temperature and drogue measurements. The figures included in the following examination are not meant to be representative in showing the behaviour of the plume according to wind direction. Each figure will thus be discussed in order of occurrence.

Figure 10: Mosaic of August 15, 1968.

The winds for August 14 and 15 were from the SW. The plume appears to move north, straight out into the lake in a fanwise pattern, with a sharp leading edge on the west and north. The remains of the eastward flowing plume (mosaic of August 13, not shown) appears east of the river. This is the only case observed where the plume appeared to be moving directly off shore.

Figure 11: Mosaic of September 13, 1968.

Here the plume moves directly eastward along the southern shore, driven by winds from the NW on September 12 and 13. The western edge of the plume is very sharp, and eddies of about 13 km diameter appear in the plume as it moves eastward. The remains of the plume from September 10 and 11 (east and northeast winds) appear north of the plume.

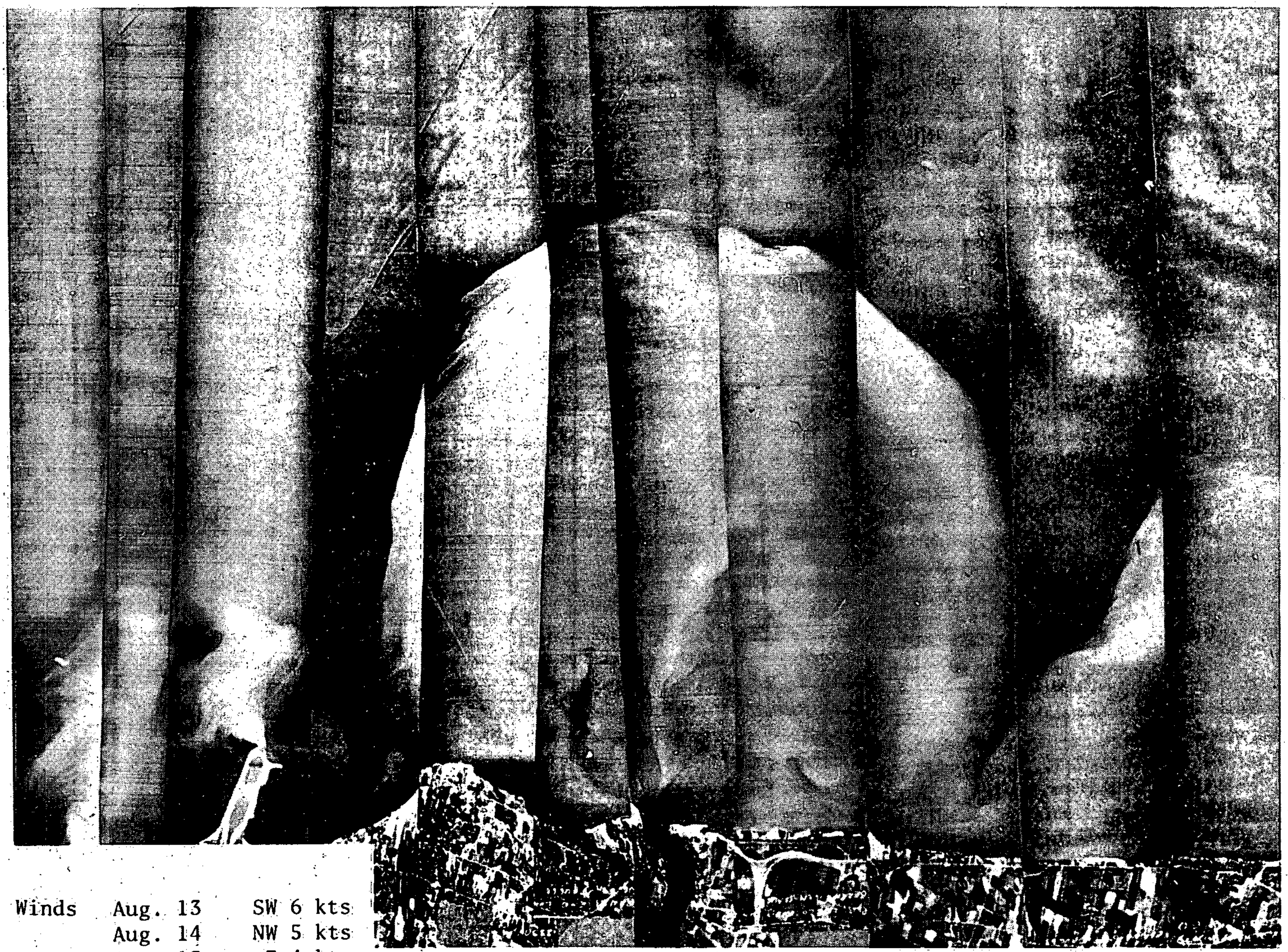
Figure 12: Mosaic of May 21, 1969.

This is the first in a series taken on May 21, 23, 26 and 27 (Figures 12 - 15). The winds were as follows: May 19, SE 11; May 20, SW 20; May <u>21</u>, N8; May 22, NE 7; May <u>23</u>, S2; May 24, SW 7; May 25, N16; May <u>26</u>, E8; May <u>27</u>, NE2; where the directions are given in terms of 8 compass points and speeds, in knots.

For Figure 12, the strong winds of May 20 from the southwest drive the plume characteristically northeastward near the mouth, with a sharp western edge where the plume is in contact with easterly lake currents on the surface. The plume then appeared to curve back southeastward, and flow eastward along the southern shore. Strong NE winds on the 18th would have driven the plume northwestward, the eddies and lighter area west and north of the definite plume of the 21st, are probably the remains of this plume.

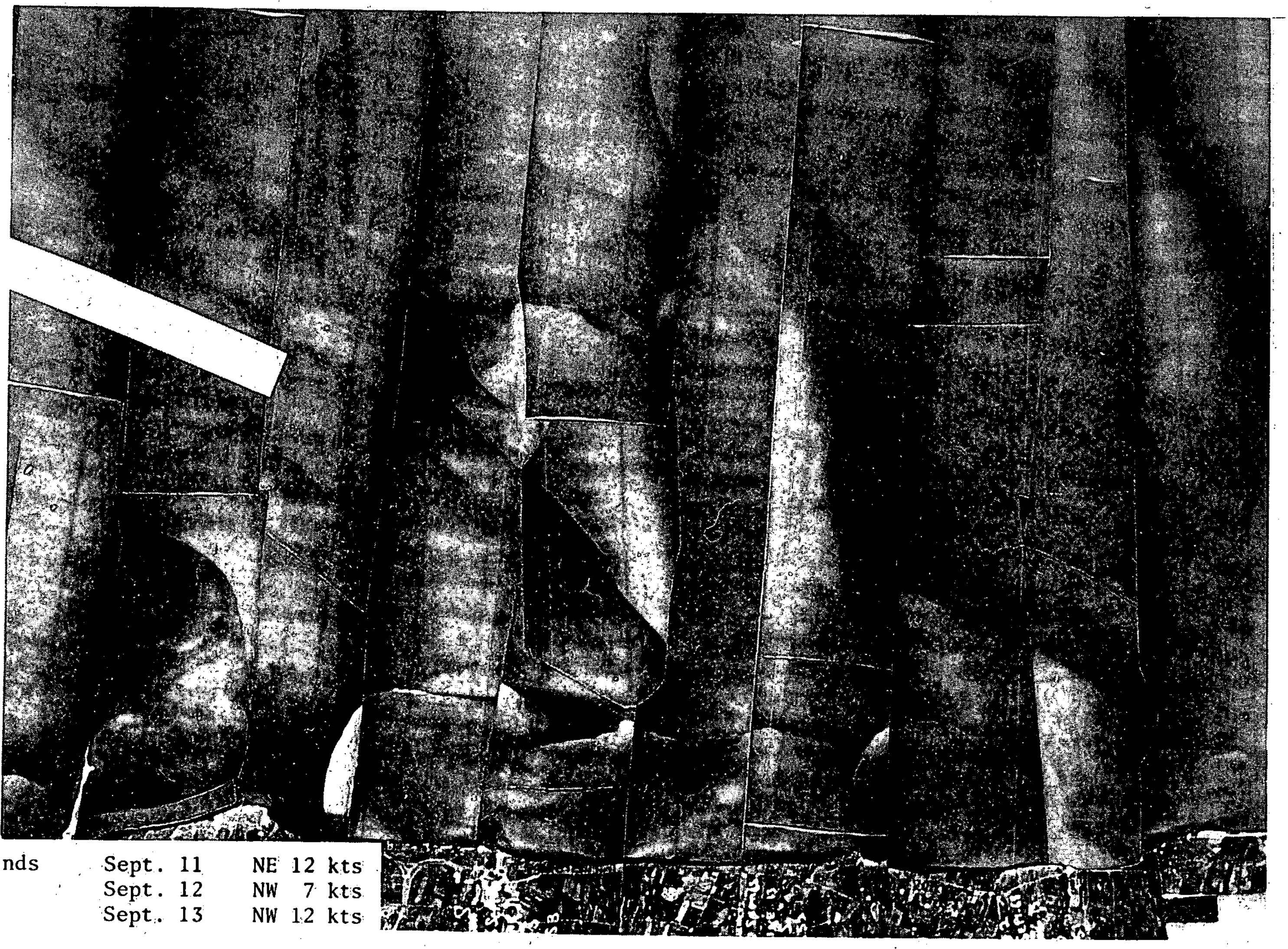
Figure 13: Mosaic of May 23, 1969.

Two days after Figure 12 was taken, the winds were from the north and northeast, driving the plume north and northwestward, as seen in the figure. The flow near the river's mouth is approximately northwestward, consistent with its expected behaviour. At the extreme northern tip, a large eddy appears to be detaching, with bandlike structure near the constriction. The past remains of the plume appear at both the west and east. Large scale eddying appears to be present throughout the plume, but primarily in its eastern part where the river's outflow moved in the past couple of days before swinging northward.



Winds	Aug. 13	SW 6 kts
	Aug. 14	NW 5 kts
	Aug. 15	E 4 kts

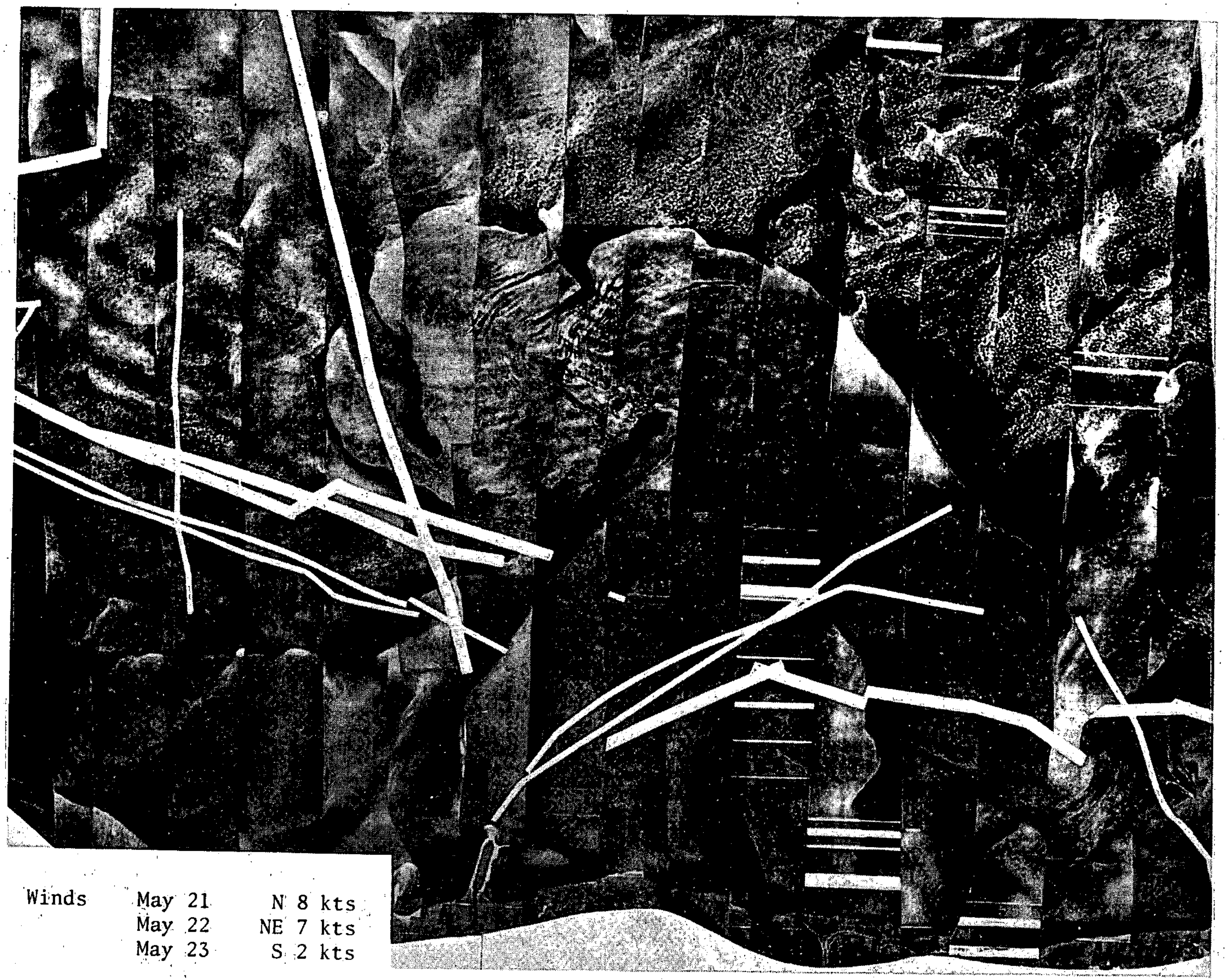
Figure 10. Infrared mosaic, August 15, 1968.



Winds
Sept. 11 NE 12 kts
Sept. 12 NW 7 kts
Sept. 13 NW 12 kts

Figure 11. Infrared mosaic, September 13, 1968.

Figure 12. Infrared mosaic, May 21, 1969.



Winds		
	May 21	N 8 kts
	May 22	NE 7 kts
	May 23	S 2 kts

Figure 13. Infrared mosaic, May 23, 1969.

It should also be noted that the extreme northern tip of the plume extends about one-half way across the lake.

Figure 14: Mosaic of May 26, 1969.

The winds for this day were from the east, for the 25th from the north, and for the 24th from the southwest. The warm plume in the immediate area of the river's mouth flows northwestward, but the plume itself then curves toward the northeast and southward, producing a large eddy of about 20 km diameter. The western edge of the plume is again sharpened by the eastward flowing lake current and the remains of the plume from the days before (especially May 23) show up as lighter areas around the plume.

Figure 15: Mosaic of May 27, 1969.

A day later, the winds are weak, and from the northeast. The plume near the river's mouth moves almost directly north after moving northwestward; the rest of the plume is ill-defined and confused with a large amount of eddying and the remains of former plumes.

Figure 16: Mosaic of July 14, 1969.

On July 11 and 12, the wind was from the southwest; on the 13th, it swung to the northwest, and returned to the southwest on the day of observation (July 14). Near the river's mouth, the plume moved directly out into the lake, and then curved northeastward further out, under control of the winds of the 13th.

Figure 17: Mosaic of July 15, 1969.

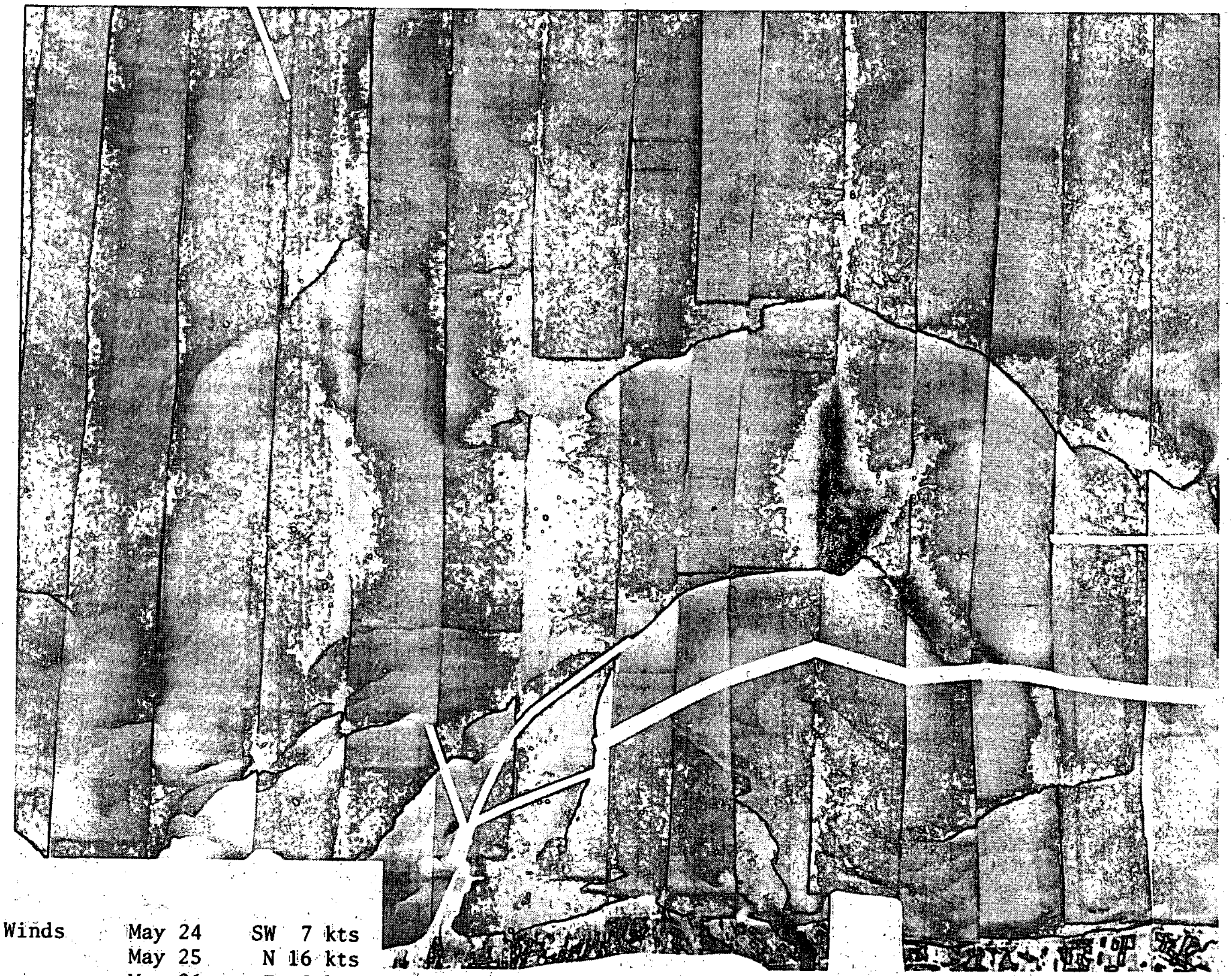
On July 15, winds were from the west following southwest winds on the day before the mosaic was taken. These have again imposed movement toward the northeast. A larger eddy appears to be present just east of the river's mouth, possibly being part of the remains of the relatively higher northwesterly winds on the 13th. On both the 14th and 15th, the plume is relatively poorly defined due to a lack of temperature definition.

Figure 18: Mosaic of September 3, 1969.

The winds for September 2 and 3 were strong from the northeast; on the 1st they were weaker and from the northwest. The plume moves as expected, toward the northwest, and has in this case, a sharper edge on its eastern edge produced by the lake currents moving westward. The remains of the plume moving northeastward and eastward on the 1st, appear to the north and east of the plume.

West of the plume and the two piers of the Welland Canal entrance, there are a series of 4 - 5 eddies in a northward line, having probably been produced by shear instability; this may have been produced by the general shift of the water mass of the plume toward the west, with northward flow along the shear zone.

These examples show many features which direct measurements were not able to show because the area covered by the direct measurements was, by necessity, small. But a very striking aspect of the plume's behaviour should be emphasized here, that of the large areal extent of the plume when it moves out over the lake (Figure 14) as well as its "hugging" the shoreline (Figure 12) along the U.S. shore, east of the river, when steady winds from the northwest occur. The former condition implies a fairly large direct transboundary movement of the river's waters, without too much dilution;



Winds	May 24	SW 7 kts
	May 25	N 16 kts
	May 26	E 8 kts

Figure 14. Infrared mosaic, May 26, 1969.

Winds			
	May 25	N	16 kts
	May 26	E	8 kts
	May 27	NE	2 kts

Figure 15. Infrared mosaic, May 27, 1969.

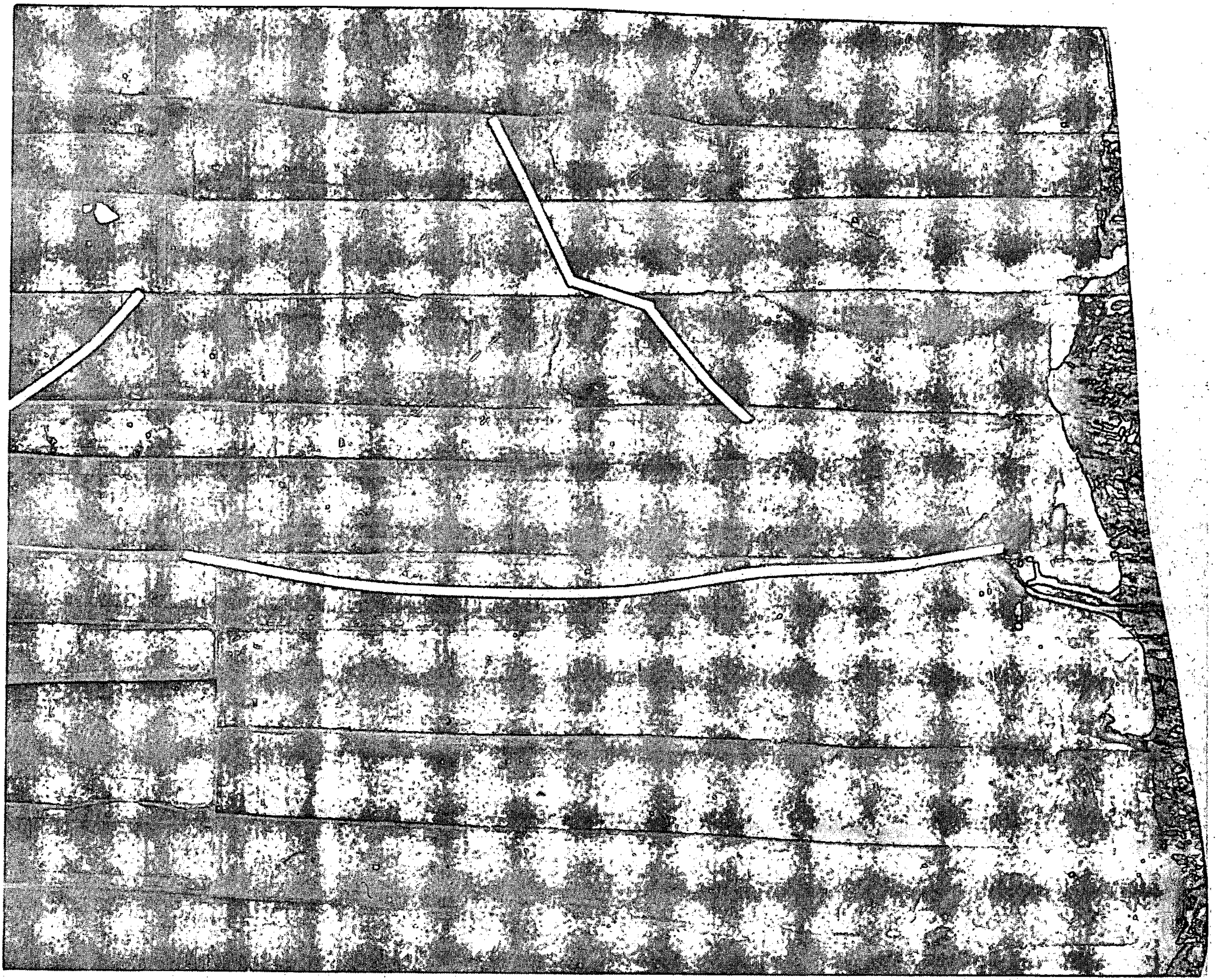


Figure 16. Infrared mosaic, July 14, 1969.

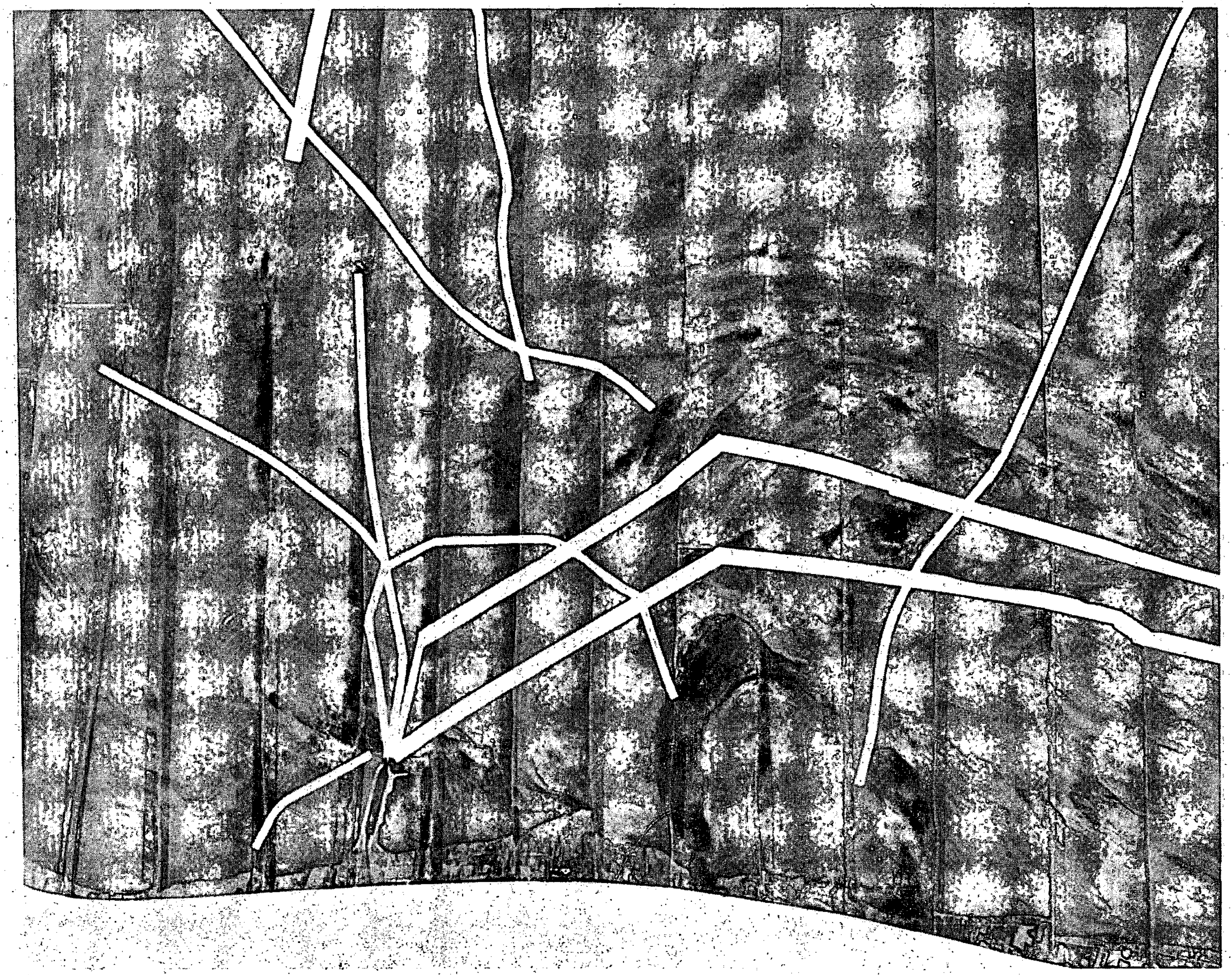
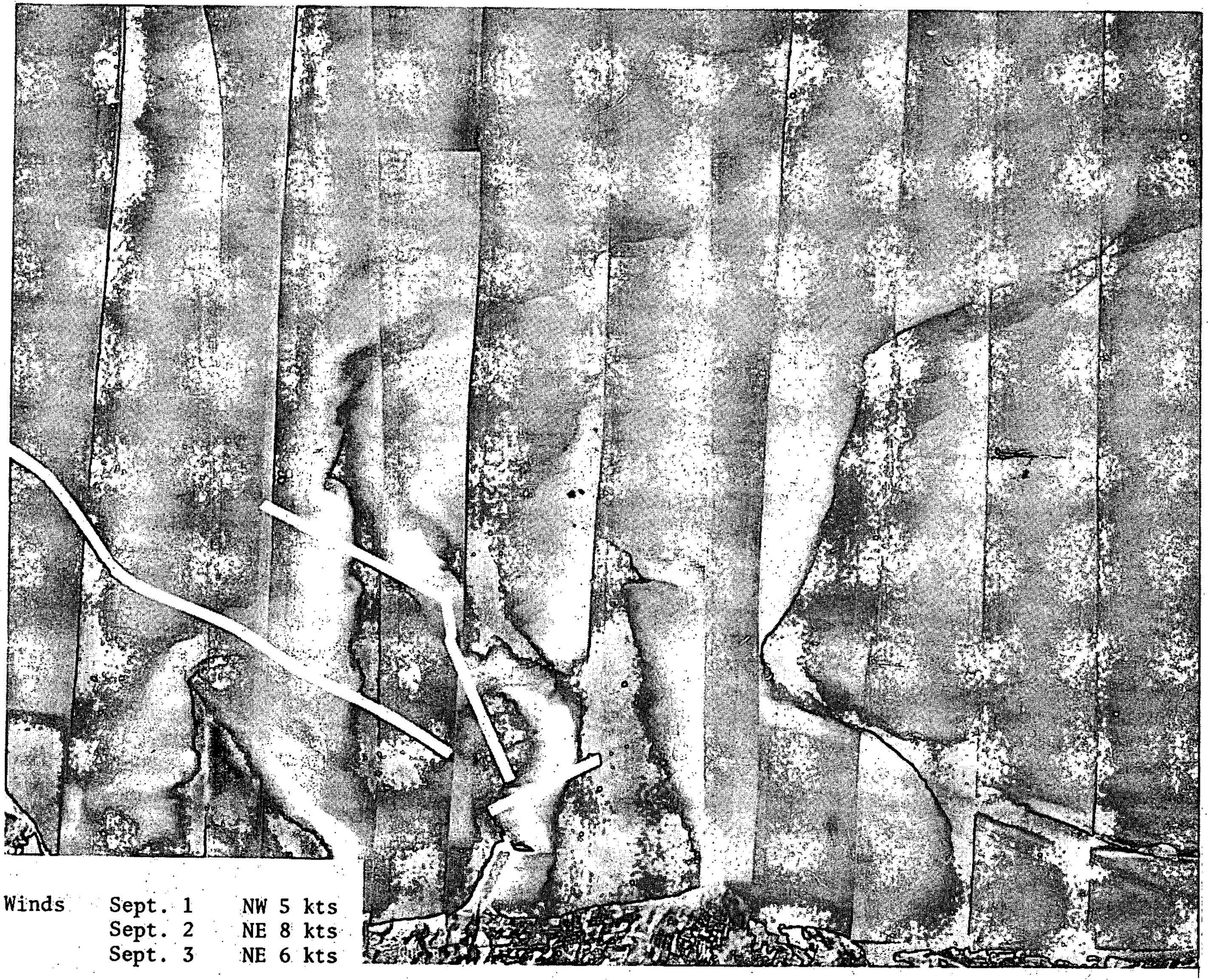


Figure 17. Infrared mosaic, July 15, 1969.



Winds		
	Sept. 1	NW 5 kts
	Sept. 2	NE 8 kts
	Sept. 3	NE 6 kts

Figure 18. Infrared mosaic, September 3, 1969.

the latter implies that most of the river's waters flow into U.S. territorial waters, and not only that, but also directly along the shore without very much dilution.

7. CONCLUSIONS

Detailed studies consisting of temperature surveys, current measurements by drogues, and infrared imagery measurements were carried out in the Niagara River bar area. This information was obtained for the purpose of giving a descriptive evaluation of the extent and dynamics of the Niagara River plume, and to aid in the later interpretation of current meter records collected in the area at the same time.

Temperature measurements showed close to isothermal conditions in the bar area in early spring. As the summer progressed, a thermocline developed outside the bar, but generally isothermal conditions existed inside the bar area. The plume under these conditions tended to flow out over the lake's surface, and appeared to entrain colder and deeper water from further out in the lake.

The motion of the plume was controlled by the surface currents of the lake in the vicinity of the river's mouth. These currents were driven primarily by the wind of the day before observations were made, and to a lesser degree by winds two days before. Response time of the plume to changes in wind direction was about 1 to 2 days after the change. With winds persisting from the north and northeast for these two days, the plume moved northwestward and westward, with winds persisting from the east to southwest, the plume moved northeastward. With winds persisting from the west, the plume moved eastward, and with winds persisting from the northwest, the plume moved eastward and southeastward, flowing closely against the U.S. shore. This behaviour was confirmed both by drogue measurements and infrared imagery.

The edge of the plume on the side away from the direction the plume moved, was usually fairly sharp and well-defined; the other edge was more diffuse and often had large eddies. These details were obtained mostly from the infrared mosaics.

Detailed analyses of current meter records obtained in this area are planned for the immediate future.

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Casey, D.J. 1967. A report on chemical, biological and physical findings in Lake Ontario. U.S. Dept. Interior, Federal Water Pollution Control Administration, Great Lakes Region, Rochester Program Office. Preliminary Report, Dec. 6, 1967, 56 pp., 59 figs. (unpublished report).

International Joint Commission. 1969. Pollution of Lake Erie, Lake Ontario and the international section of the St. Lawrence River. Volume 1 - Summary. International Lake Erie Water Pollution Board and the International Lake Ontario - St. Lawrence River Water Pollution Board. 150 pp.

Part 11 - The Mixing of the Niagara River Plume in Lake Ontario

C.R. MURTHY

1. EXPERIMENTAL METHODS

Fluorescent Dye Tracing Techniques

Tagging the lake water with fluorescent dyes or radioactive tracers has been widely used in dispersion studies in natural bodies of water. Radioactive tracing in freshwater bodies such as the lakes is bound to cause considerable public reaction, even if the program is carefully and safely conducted. On the other hand, fluorescent tracing techniques have proven to be nearly ideal and are field tested in a variety of situations, such as circulation, dispersion and mixing studies in large and small water bodies, hydraulic and hydrologic studies and rate of flow measurements in streams to mention only a few. Even to use fluorescent tracing techniques prior approval from regulatory agencies may be necessary, particularly if the experiments are conducted in the vicinity of water intakes. For our experiments at the Niagara River mouth, permission to use fluorescent tracing technique was given by the Ontario Water Resources Commission and the U.S. Federal Water Quality Administration. Fluorescent dye is released instantaneously or continuously at surface and subsurface depths. If the specific gravity of the dye is adjusted to unity, then there could be little doubt that the dispersion of the dye cloud (or plume) is due to lake currents and turbulence. The dye plume (or cloud) is followed by measuring dye concentrations using the optical technique of fluorometry.

Water soluble fluorescent rhodamine B dye in 40 per cent acetic acid-methanol solution was released continuously at a constant rate from a raft anchored near the river mouth. The dye plume formed in the wake of this continuous point source was used as the experimental target. Dye concentrations across the plume were determined using sensitive fluorometers mounted in an instrument boat at various distances from the source and at different depths below the surface. Continuous sampling was done using a boom fitted to one side of the instrument boat. The continuous samples were then processed by fluorometers whose outputs were recorded continuously on strip chart recorders and thus provided instantaneous cross plume concentration profiles. On a few occasions, aerial photography of the dye plume was undertaken to support dye diffusion data. Time sequence air-photos were taken in order to obtain the overall behaviour of the dye plume.

The map of the Niagara River mouth, Lake Ontario, with a schematic representation of dye plume formation is shown in Figure 19.

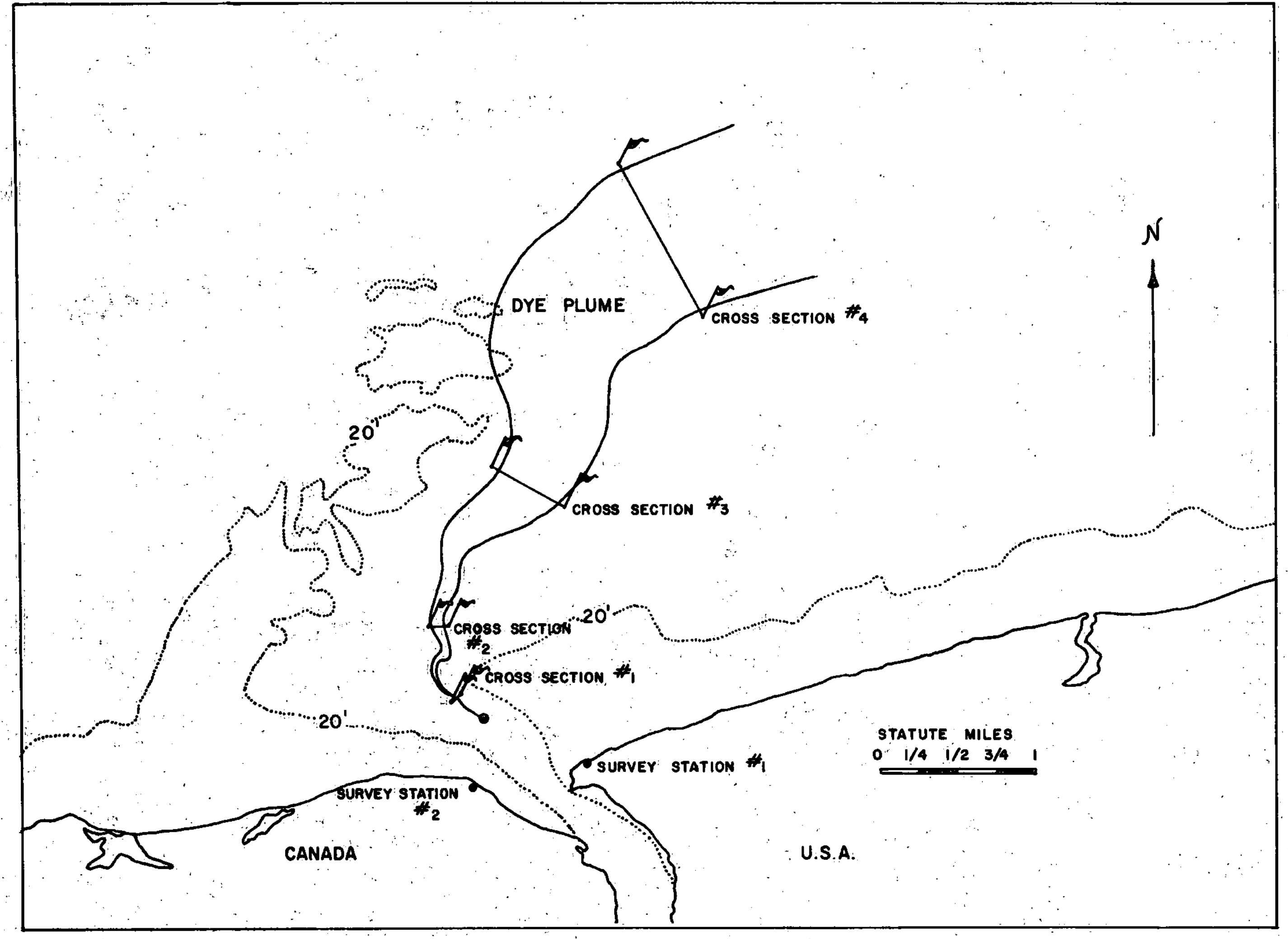


Figure 19. Niagara River Mouth, Lake Ontario.

Experimental Equipment

A 20 ft. x 8 ft. raft with ten 45 gallon drums to provide the necessary flotation was used as a platform for the dye source system. The dye source itself consisted of two 45 gallon drums mounted upright in the centre of the platform and a constant rate Watson Marlow (Model MHRK) squeezer type flow inducer powered by two 12 volt lead storage batteries of 150 amp. hour capacity. A 1/4" I.D. tygon tubing used for the pump, gave 3 gallons per hour dye discharge. An aluminum framework rigidly fastened to the centre of the raft and extending about 6 ft. clear of the side was used to release the dye to eliminate any possible disturbance from the raft itself. The dye discharge tube was mounted vertically at the end of this framework and its depth below the surface could be easily adjusted. In anticipation of problems arising from strong currents at the river mouth, specially constructed heavy anchors were provided for anchoring the raft. A navigation light was also fitted as the dye raft was left at the river mouth throughout the season. A schematic diagram of the dye injection raft and anchor assembly is shown in Figure 20. The on-deck arrangement of the dye injection system is shown schematically in Figure 21.

A 35-foot all steel launch (CSL SWIFT) was used to monitor the dye plumes downstream from the source. This launch was very stable and convenient for sampling. It had a spacious enough cabin to mount all the scientific instruments and enough working space for four men involved in the sampling work. The deck area was sufficient to store all the hardware necessary for the conduct of the experiments. The instruments were arranged on a "unit" system. This unit was formed with a fluorometer, a single channel strip chart recorder and a pump. The on-deck arrangement of the instruments is shown schematically in Figure 22. This arrangement was preferred as malfunction of one of the components in a system will not disrupt the sampling in other systems.

The sampling equipment consisted of a Watson Marlow (Model HR) flow inducer on deck which samples through a 5/8" polyethylene hose attached to a Vee-fin depressor suspended by steel cable from a small pulley block and handwinch arrangement. A 3" tubular aluminum boom clamped rigidly across the rails of the instrument boat was used to mount the sampling unit. The handwinch enabled the sampling depth to be adjusted and also to retrieve the sampling unit when not in use. The sampling boom extended about 2 ft. clear of the side of the boat so as to eliminate bow wave effects. The sample was continuously pumped through Turner fluorometers (Model 111). Maximum flow (approximately 120 gal/hr) was maintained to get good response characteristics. Fluorometer outputs were recorded on strip chart recorders where notes concerning time, scale changes, chart speed and other data required to process the charts were jotted. A portable generator was used to supply power for the instruments. Sampling was done from the cabin of the instrument boat as close cooperation was necessary between the personnel in charge of sampling and the wheelman.

A two seater, single engine Piper Colt aircraft, leased commercially and suitably modified to mount the camera and associated equipment, was used for aerial photographic work. A Williamson F-52 aircraft camera with 9" x 7" negative size was used to photograph the dye plumes. The camera could be operated either electrically or manually. A drive motor powered by a 24 volt aircraft storage battery was used to operate the camera electrically. A Williamson intervallometer (3-60 secs) was used to select time sequence for a given percentage overlap between two successive frames.

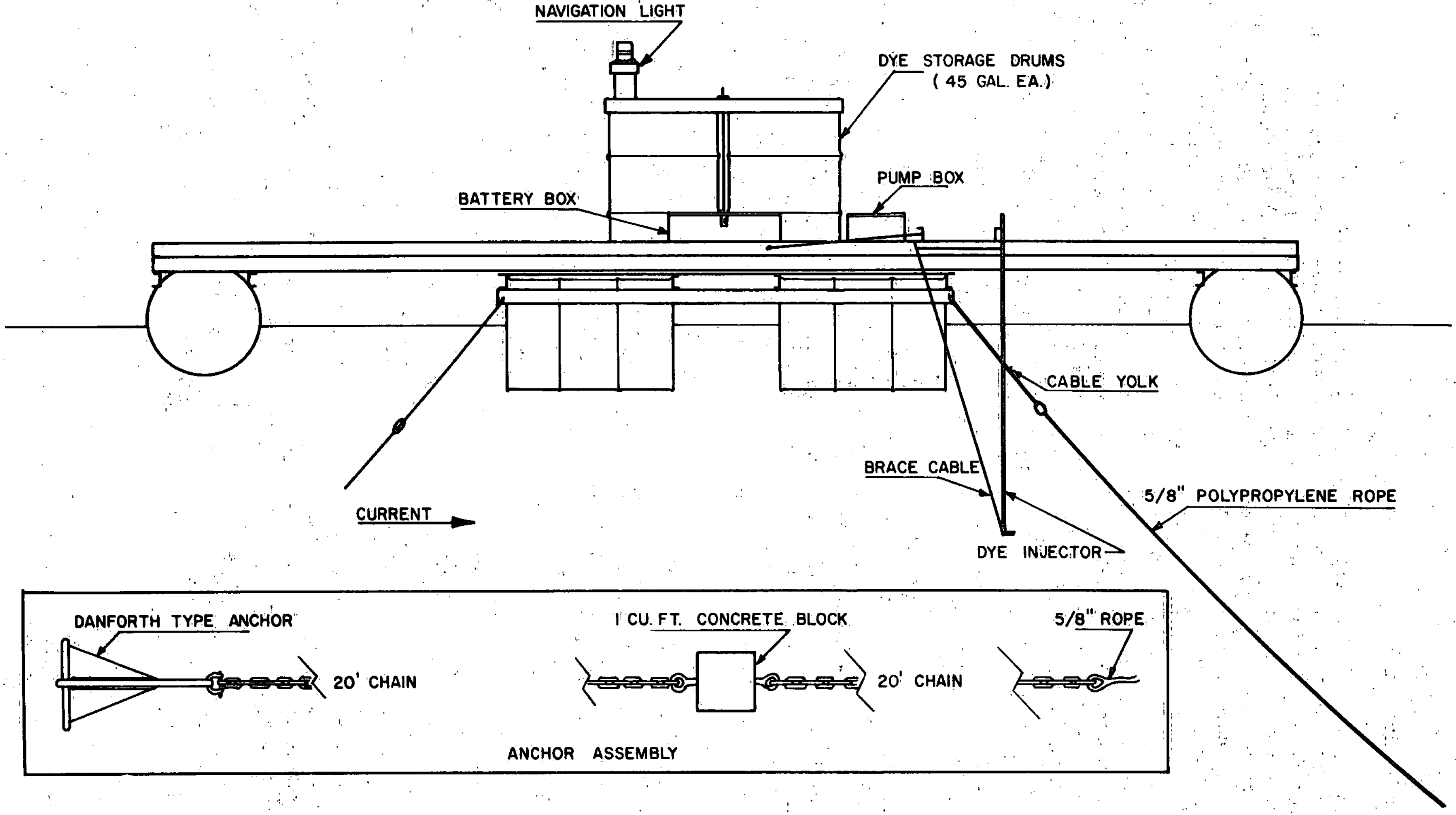


Figure 20. Dye injection raft.

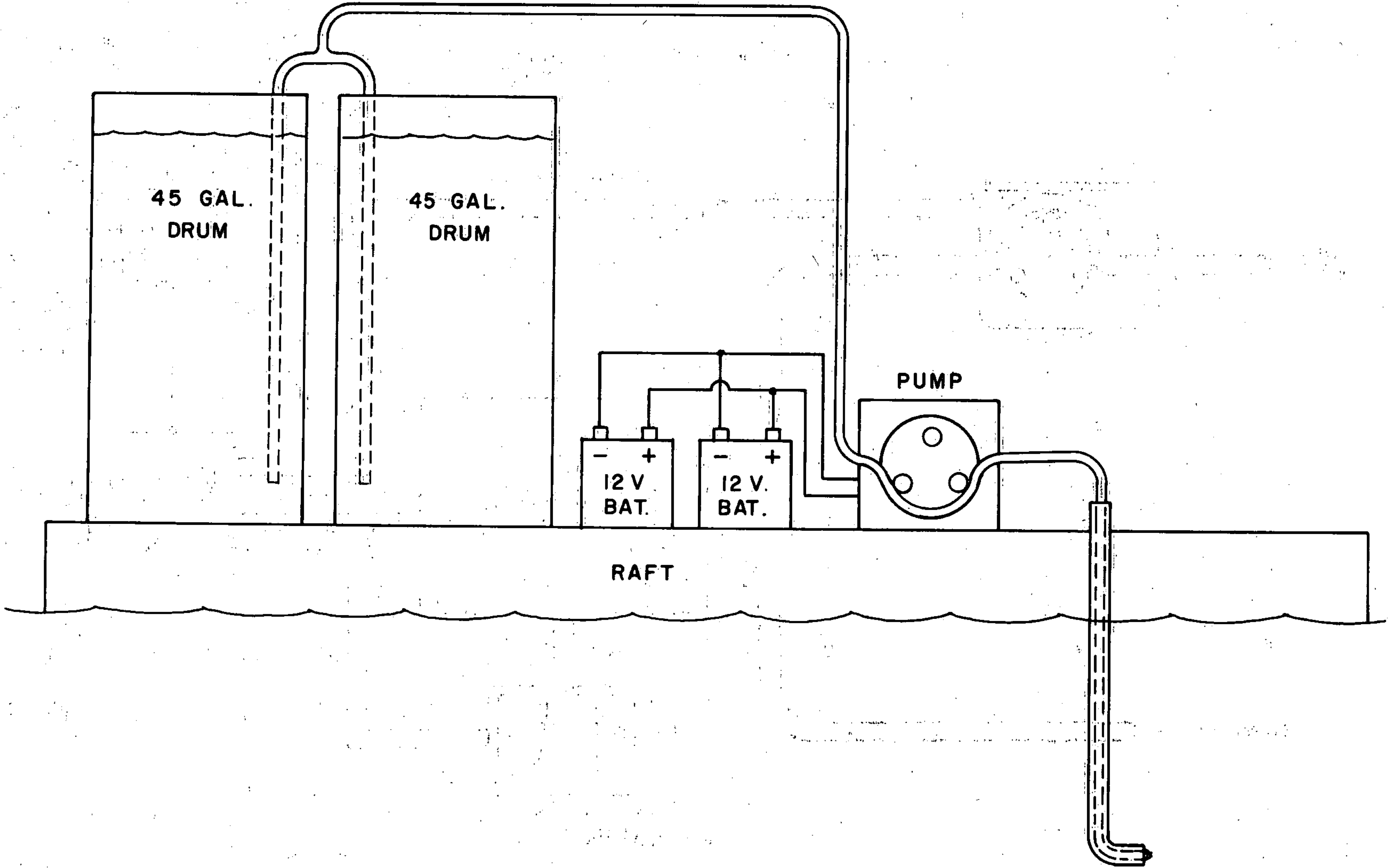


Figure 21. Dye injection system (schematic).

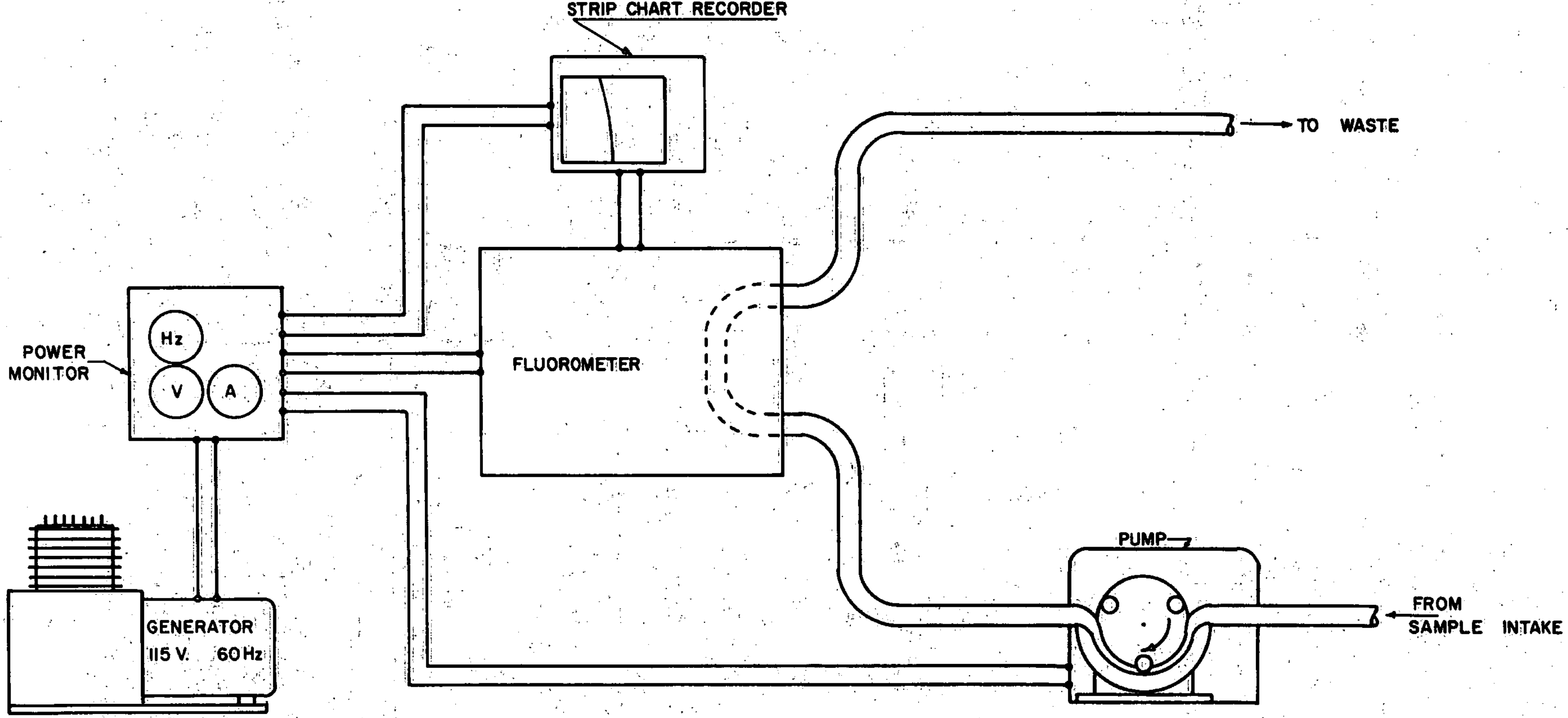


Figure 22. Sample analysis system.

Three types of films were used:

(1) black and white super XX aerographic daylight

(2) infrared EKT 8443 (false colour - dye plume appears yellow in the positive)

(3) EKT Aero 8442 (true colour - dye plume appears vivid red in the positive).

The films were supplied in rolls of 100 exposures and were processed by the Rockcliffe Airphoto Production Unit of the Department of Energy, Mines and Resources, Ottawa. Best results were obtained from EKT Aero 8442.

Experimental Procedure and Data Collection

Experiments were conducted on a day-to-day basis, depending on weather conditions. The decision to conduct an experiment was normally made early in the morning so that the different groups involved in the conduct of the experiments would have sufficient time to coordinate their efforts before the start of the experiment. Three different groups were involved to fulfil the three different tasks: a) fluorometric sampling of dye plume, b) drogue tracking, temperature survey and shore based survey of marker flags used for dye plume sampling and c) aerial photography. A crew of 10, divided into three groups, was required to carry out the experiments. Radio contact was maintained between the different groups and the shore based transit stations. The dye was released about half to three quarters of an hour before the start of the experiment to allow the dye plume to develop.

The fast river current developed the plume much more rapidly than in a typical lake with slow currents. Close to the source, the dye plume was narrow and always unidirectional as might be anticipated. However, away from the source, the plume was well spread out and the direction was clearly dependent upon the prevailing wind direction. One striking aspect of all the dye plumes observed was the erratic lateral meandering bearing no relation to typical lake conditions. Figure 23 is an airphoto of the dye plume taken at an altitude of 5,000 feet corresponding to a scale of 1" = 130 m on 9" x 7" negative. A mosaic of the dye plumes prepared from the time sequence airphotos of the same series is shown in Figure 24. While lateral meandering of the dye plume was quite pronounced, it was minimal on other occasions (see Fig. 25).

The first cross-section was chosen as close to the dye source as possible (about 250 - 300 m usually). Two anchored marker flags were dropped across the dye plume such that the line joining them is almost perpendicular to the plume. The dye plume was sampled a number of times using the marker flags as reference markers. Upon completion of one cross-section, the instrument boat was moved further downstream from the dye source and the process repeated. Under fair weather conditions up to four regularly spaced cross-sections were sampled in each experiment. On each cross-section, about 15-20 crossings of the plume were made. A log book was also maintained to record all relevant information necessary for data analysis, such as time taken for each crossing, sample depth, sensitivity range and filter combinations of each fluorometer, recorder change, chart speed and any other remarks about the dye plume behaviour and equipment operation.

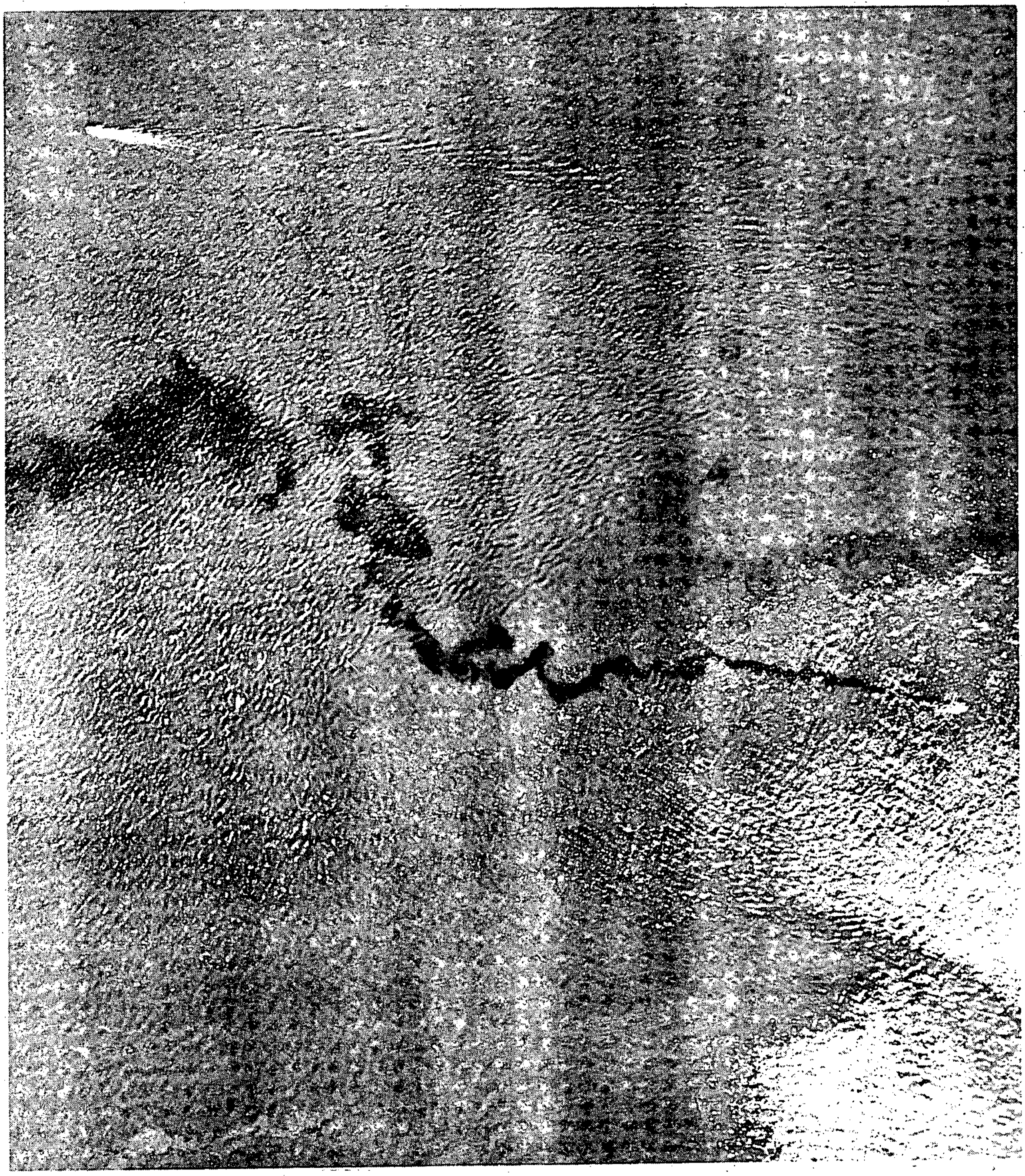


Figure 23. Aerial photograph of instantaneous dye plume from an altitude of 5,000 feet.

RUN NO.	PLUME	TIME
4	– – – –	1:30
5	———	1:38
7	-------	1:55

ALTITUDE - 5000 FT.
WIND DIRECTION - NE
WINDSPEED - 04 KT.

SCALE : 1 IN. (ON 9"x9" NEGATIVE) = 417 FT.

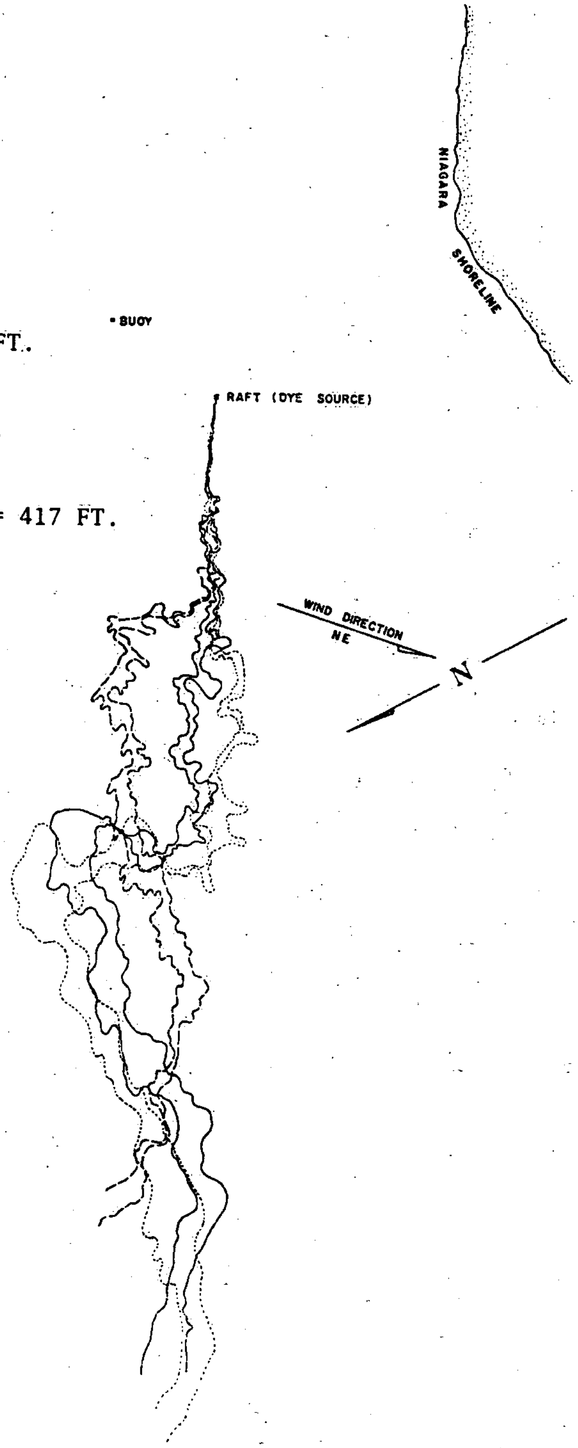
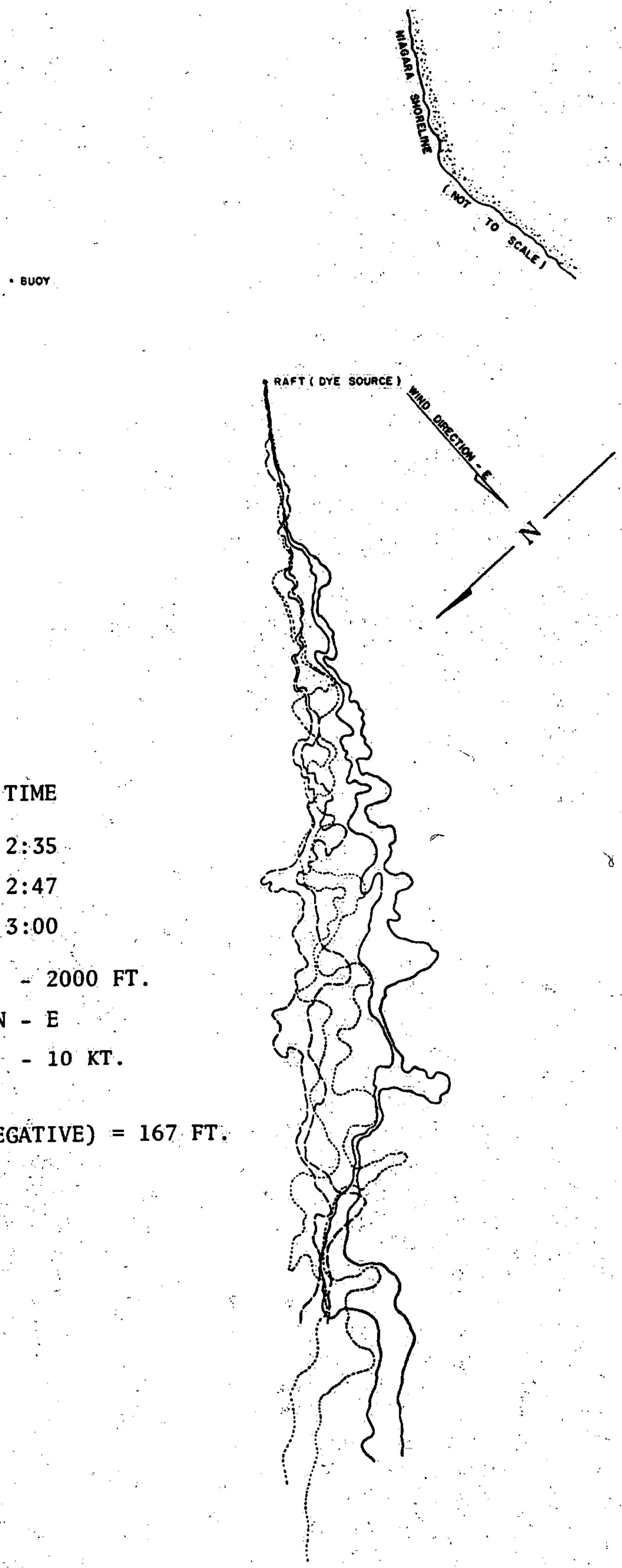


Figure 24. Dye plumes at different times, August 28, 1968. (Flight No. RC 1)



RUN NO.	PLUME	TIME
2	— — — —	2:35
4	-------	2:47
5	————	3:00

ALTITUDE - 2000 FT.
WIND DIRECTION - E
WINDSPEED - 10 KT.

SCALE : 1 IN. (ON 9"x9" NEGATIVE) = 167 FT.

Figure 25. Dye plumes at different times, September 9, 1968.
(Flight No. RC 3)

Due to pronounced lateral meandering of the dye plume, sampling was frustrating as the plume would swing away from the marker flags. However, this problem was taken care of by dropping an additional marker flag in line with the two marker flags already laid across the plume. From such a sampling procedure, cross-plume spatial instantaneous concentration profiles were collected at two sampling depths, 0.5 m and 1.5 m, and at fixed cross-sections of the diffusing dye plume.

While dye plume sampling was in progress, a second launch was busy tracking drogues, making temperature measurements and assisting in the surveying of the marker flags laid along the plume. Pre-established transit stations (see Fig. 19) on either side of the river mouth were used to track drogues successively at intervals of 10-15 minutes and also for surveying the marker flags.

Aerial photography was carried out according to a set plan, because ground to air radio contact was not possible. The dye plume was photographed sequentially every 20 minutes. About 8-10 frames were required to cover the entire length of the plume with 30-40 percent overlap. With 100 frames available per roll, it was possible to take about 8-10 sequences of the dye plume during each experiment. Additional data were noted by the photographer such as date, time, altitude, frame number, etc., required to process the dye photos.

During August and September 1968, six experiments were conducted, and in each experiment, 8-10 hours of data were collected.

Treatment of Data

Figure 26 shows typical cross-plume instantaneous concentration profiles measured at a fixed sample depth and a fixed cross-section of a diffusing dye plume. The observed profiles are markedly irregular and different, because the total amount of dye varied from one run to the next. In order to calculate the statistical parameters of interest from the measured concentration profiles, the method suggested by Csanady (1966) was employed. By overlapping the observed instantaneous concentration profiles such that their centres of gravity coincide, it was possible to look at relative lateral diffusion at a fixed depth and at a fixed distance from the source. The position of the centre of gravity y_c, of an individual profile C(y), measured from one of the marker flags is given by

$$y_c = \sum_i y_i C_i(y_i) / \sum_i C_i(y_i) \qquad \ldots\ldots(1)$$

where $C_i(y_i)$ is the concentration at location y_i, measured from the marker flag.

The mean profile $\overline{C}(y)$, constructed by overlapping the individual profiles such that their centres of gravity coincide, is given by

$$\overline{C}(y) = \frac{1}{n} \sum_j C_j(y) \qquad \ldots\ldots(2)$$

Here $C_j(y)$ is the concentration in the j-th run at location y, measured from the centre of gravity and n is the total number of runs.

A description of the dispersal process is customarily given in terms of the growth of the dye plumes observed. The parameter characterizing the growth of a dye plume is the variance (or its square root, the standard deviation) of the distribution of mean concentration. By definition the variance of the mean profile $\overline{C}(y)$ is given by

$$S_y{}^2=\int_{-\infty}^{\infty} y^2\ \overline{C}(y)\ dy/\int_{-\infty}^{\infty} \overline{C}(y)\ \ dy \qquad .....(3)$$

To process the data in the computer, it is necessary to digitize the analog fluorometer traces. Digital readings were read to the nearest 0.1 inch (corresponding time scale of the recorder is 1.5 secs) from the fluorometer traces. The profiles of each cross-section were digitized always from the same side of the plume although the profiles were obtained by criss-crossing the dye plume from both directions. The digital readings were then punched on IBM cards. Control cards for proper identification and additional data with regard to instrument settings, neutral density filters, etc., accompanied each data group to facilitate complete analysis by the computer. A computer program was written to compute the mean concentration profile and other statistical parameters of interest from digitized data. The time scale of the recorder chart was converted to distance scale by using the known boat speed and the chart speed. The boat speed was determined by establishing the distance between the marker flags (from shore-based survey), and the average time taken for the boat to criss-cross the flags a number of times.

2. RESULTS AND CONCLUSIONS

Typical mean concentration profiles constructed from instantaneous profiles ranging from as few as 6 to a maximum of 25 are shown in Figures 26-31. The variance (or its square root, standard deviation) of the mean concentration distribution is a good measure of the spread of the contaminant in a turbulent flow field. From the point of view of elucidating the mixing characteristics of the river plume as it merges with the main body of the lake, the peak concentration (max. mean conc., $\overline{C}(o)$) is yet another useful parameter. Figures 32 and 33 show plots of the lateral standard deviation S_y and the corresponding peak concentration $\overline{C}(o)$ of the mean concentration distributions with distance X, from the source. From these two diffusion characteristics, it is easy to infer two very broad based conclusions with respect to the mixing of the river plume with the main body of the lake:

(1) Fairly close to the source, a zone of vigorous river-type mixing is evidenced by the corresponding rapid fall-off in concentration with distance from the mouth presumably due to large scale (energy containing) convective eddies in the stream.

(2) Followed by this intensive mixing close to the mouth, it appears that the dye plumes spread fairly rapidly with very little decrease of concentration. This is clearly a case of buoyant surface spread of the warmer (therefore less dense) river water to spread horizontally over the underlying colder (denser) lake water and more or less inhibiting the turbulent exchange in the vertical direction. Such a mechanism is entirely possible in view of the thermal structure ("diffusion floor") during the period diffusion experiments were carried out (See Section 4 in Part 1).

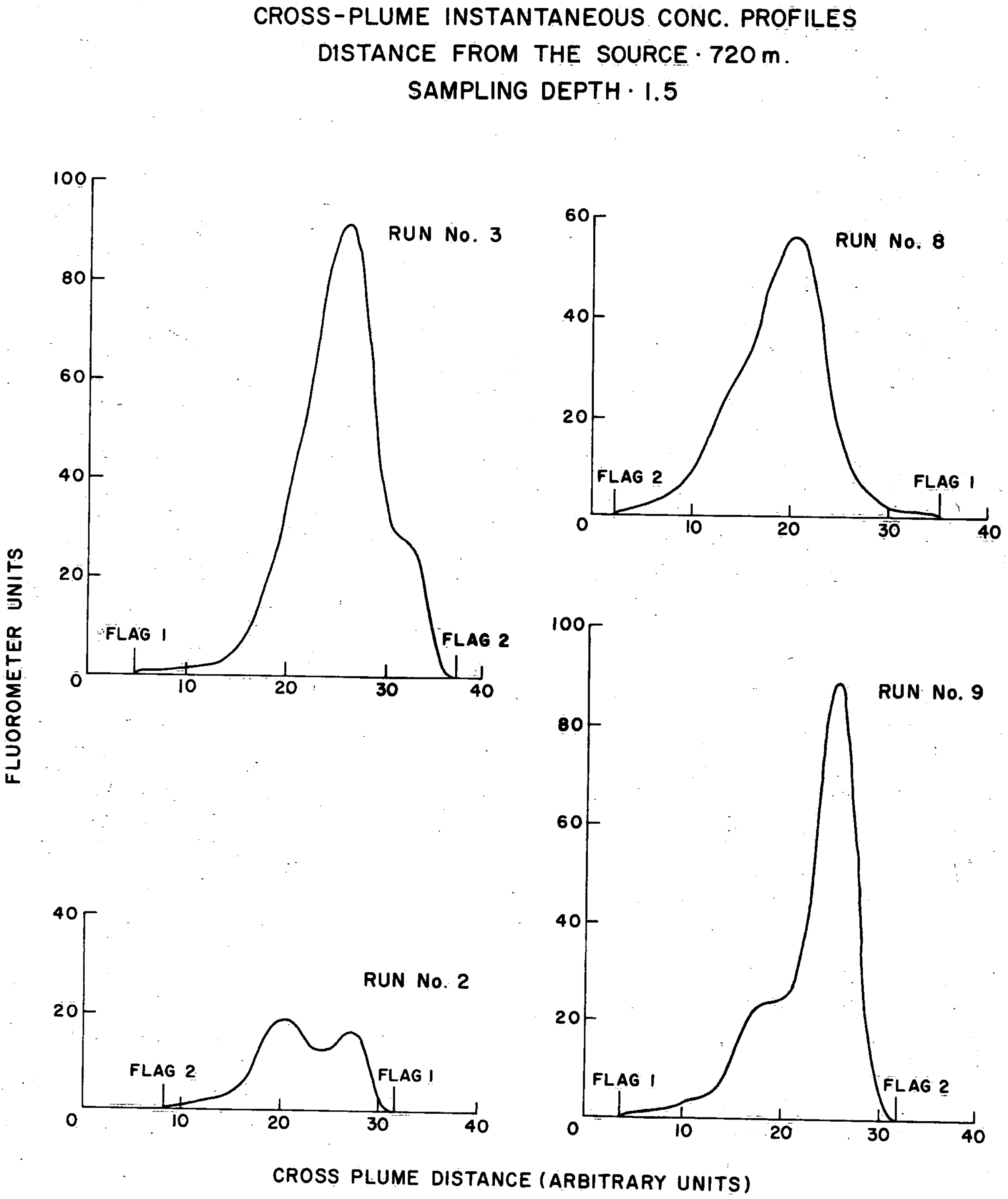


Figure 26. Diffusion experiment, September 14, 1968.

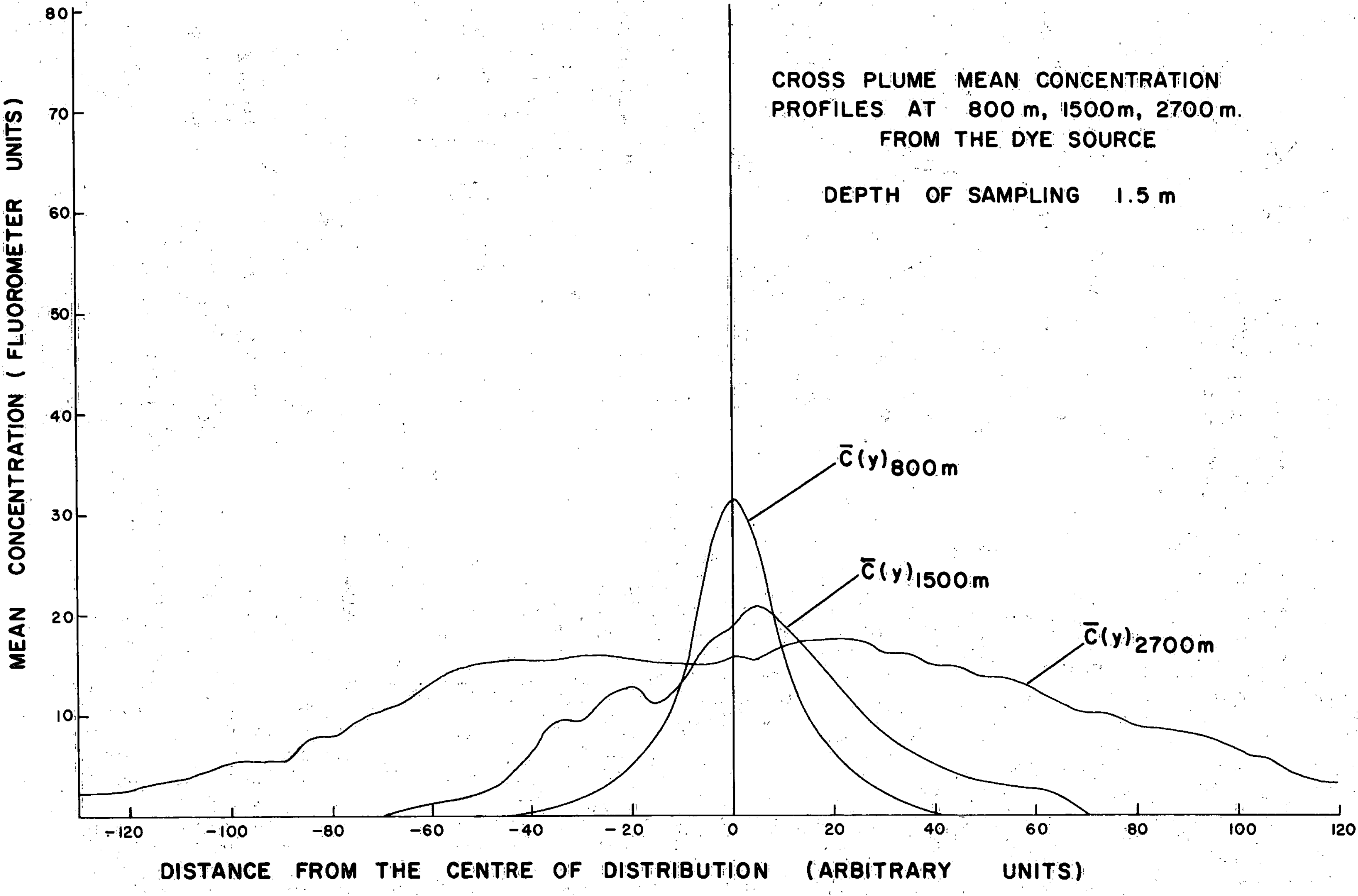


Figure 27. Diffusion experiment, August 13, 1968.

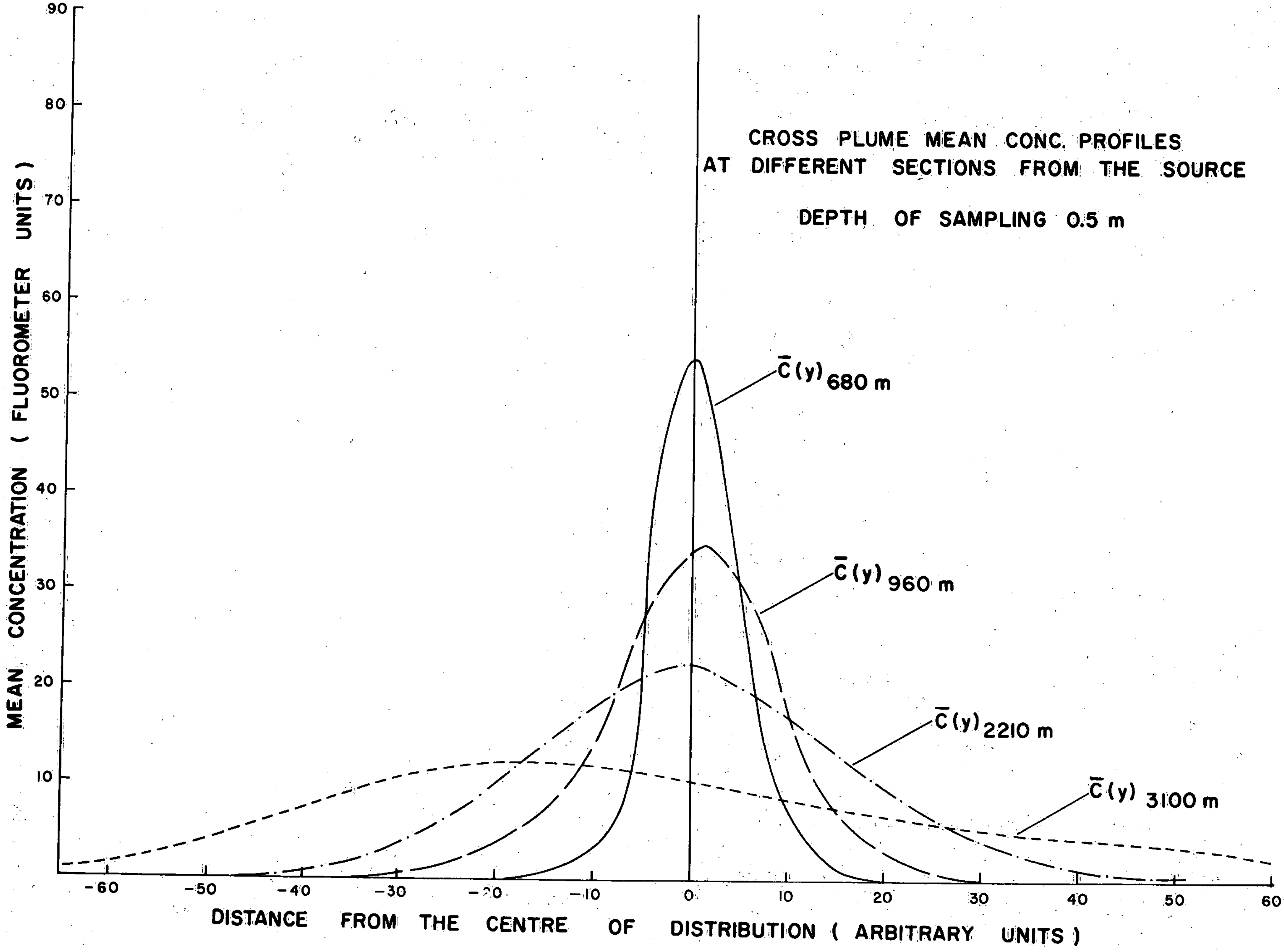


Figure 28. Diffusion experiment, August 24, 1968.

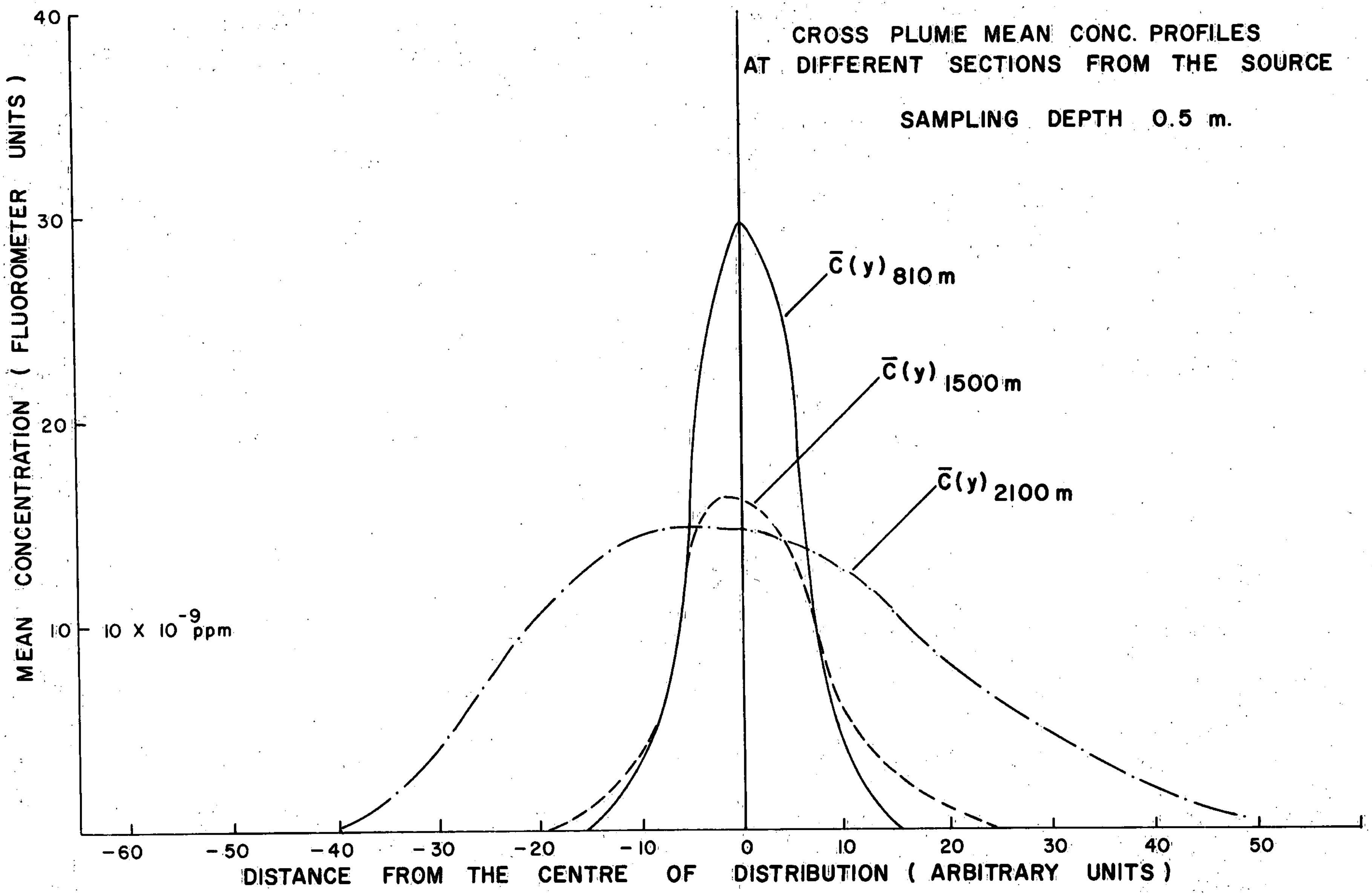


Figure 29. Diffusion experiment, September 9, 1968

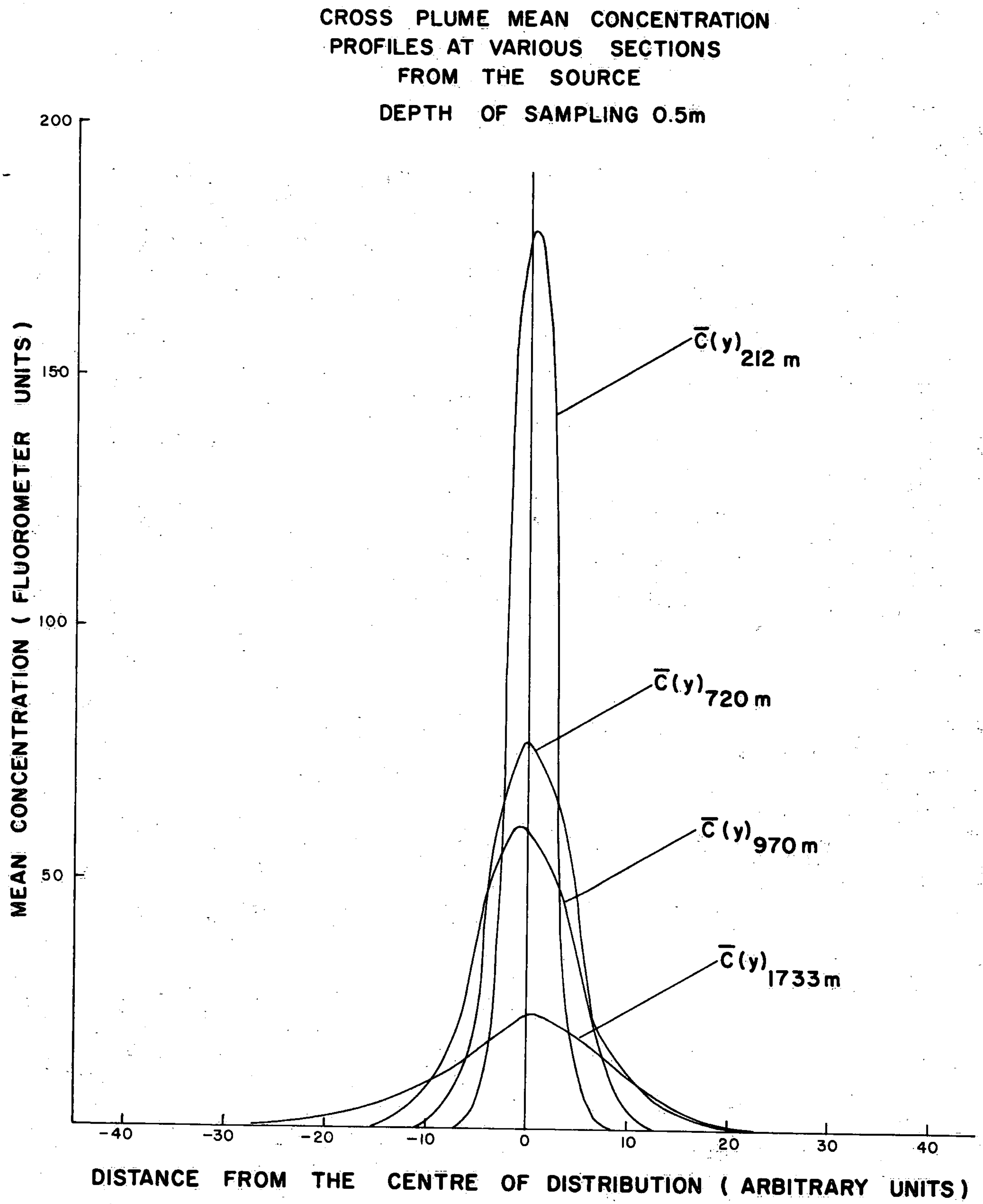


Figure 30. Diffusion experiment, September 14, 1968

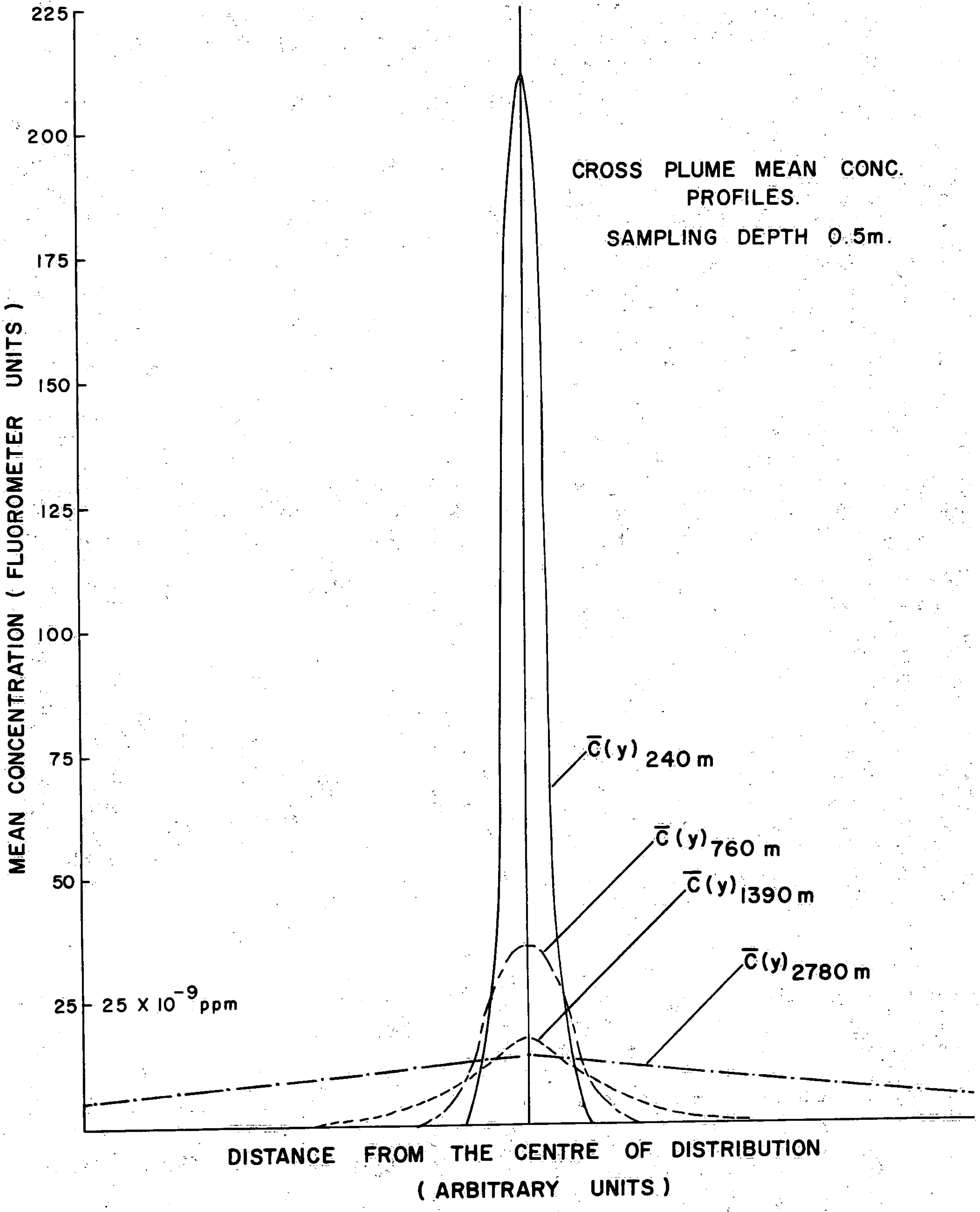


Figure 31. Diffusion experiment, September 20, 1968.

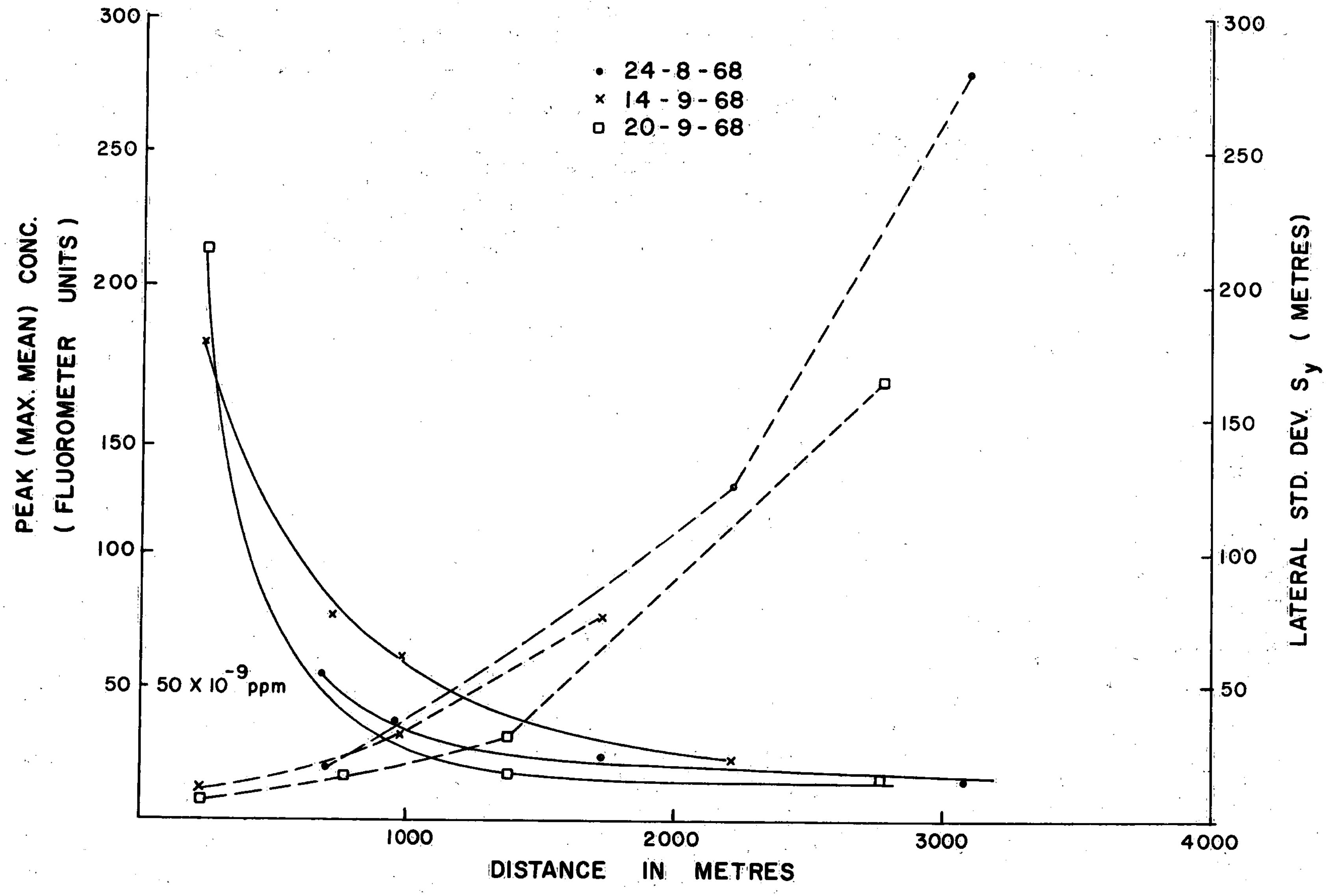


Figure 32. Diffusion characteristics (sampling depth 0.5 m.)

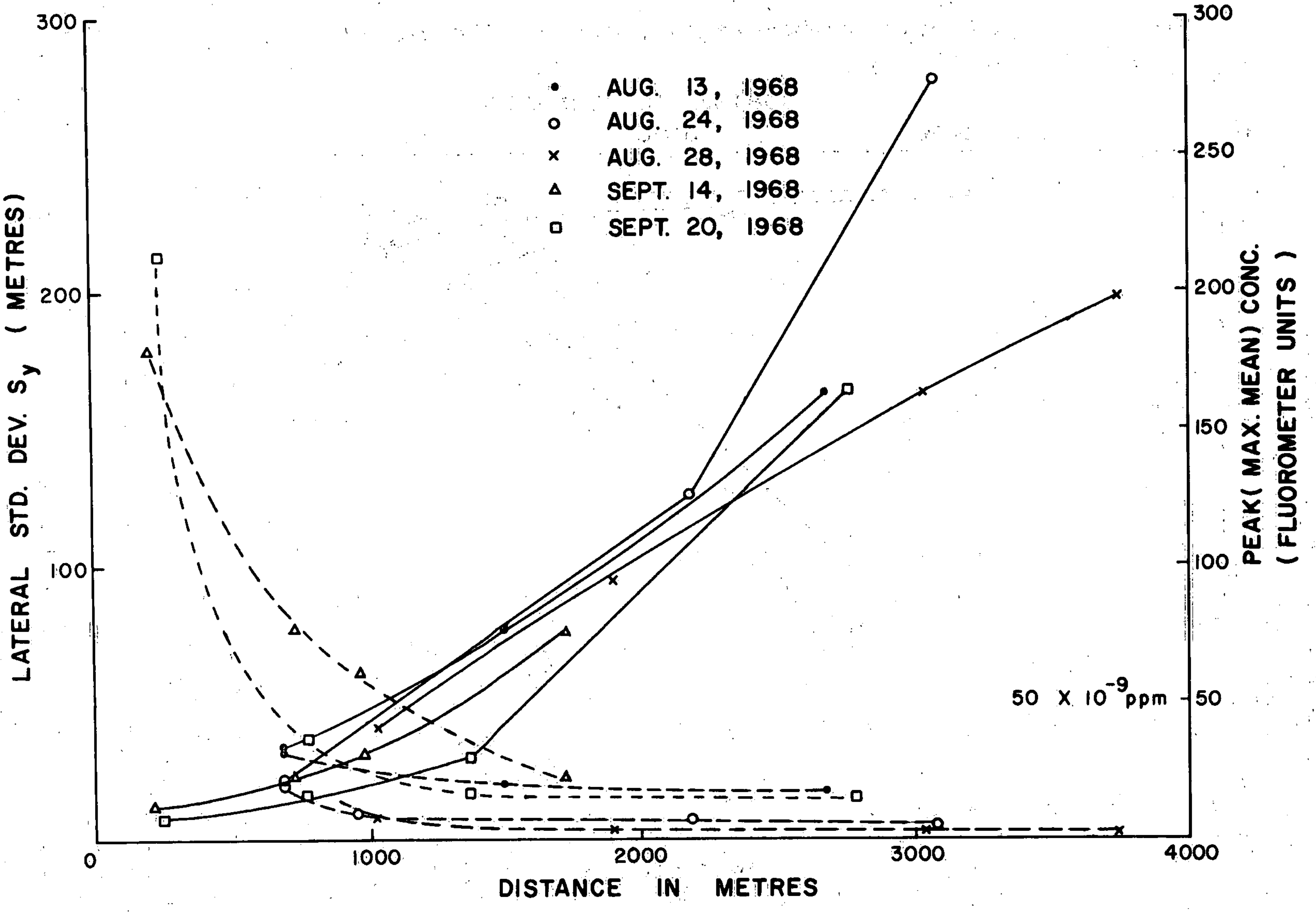


Figure 33. Diffusion characteristics (sampling depth 1.5 m.)

Although these conclusions have been arrived at based on point source dye plumes, the observed circulation and thermal features of the river plume from extensive drogue data and IR imagery does confirm the above findings. Sweers (1969) has arrived at similar conclusions based on temperature data of monitor cruises of Lake Ontario during the 1966 and 1967 field seasons.

No attempt was made to calculate eddy diffusion coefficients since diffusion parameters, evaluated from point source pilot dye plumes, are clearly not representative of the entire river plume diffusing in the main body of the lake, that is, the initial size of the river plume being a significant factor to influence the dispersal process. Further, the mean river current, another diffusion parameter, is highly variable with respect to distance from the river mouth; the river flow decelerates quite rapidly as it merges with the lake (See Section 5 in Part 1).

3. REFERENCES

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No. 37 Glacier Inventory of Canada - Axel Heiberg Island, Northwest Territories. C.S.L. Ommanney. 1969.

The first in a series of reports containing data collected for an inventory of perennial ice and snow masses on land surfaces in Canada.

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