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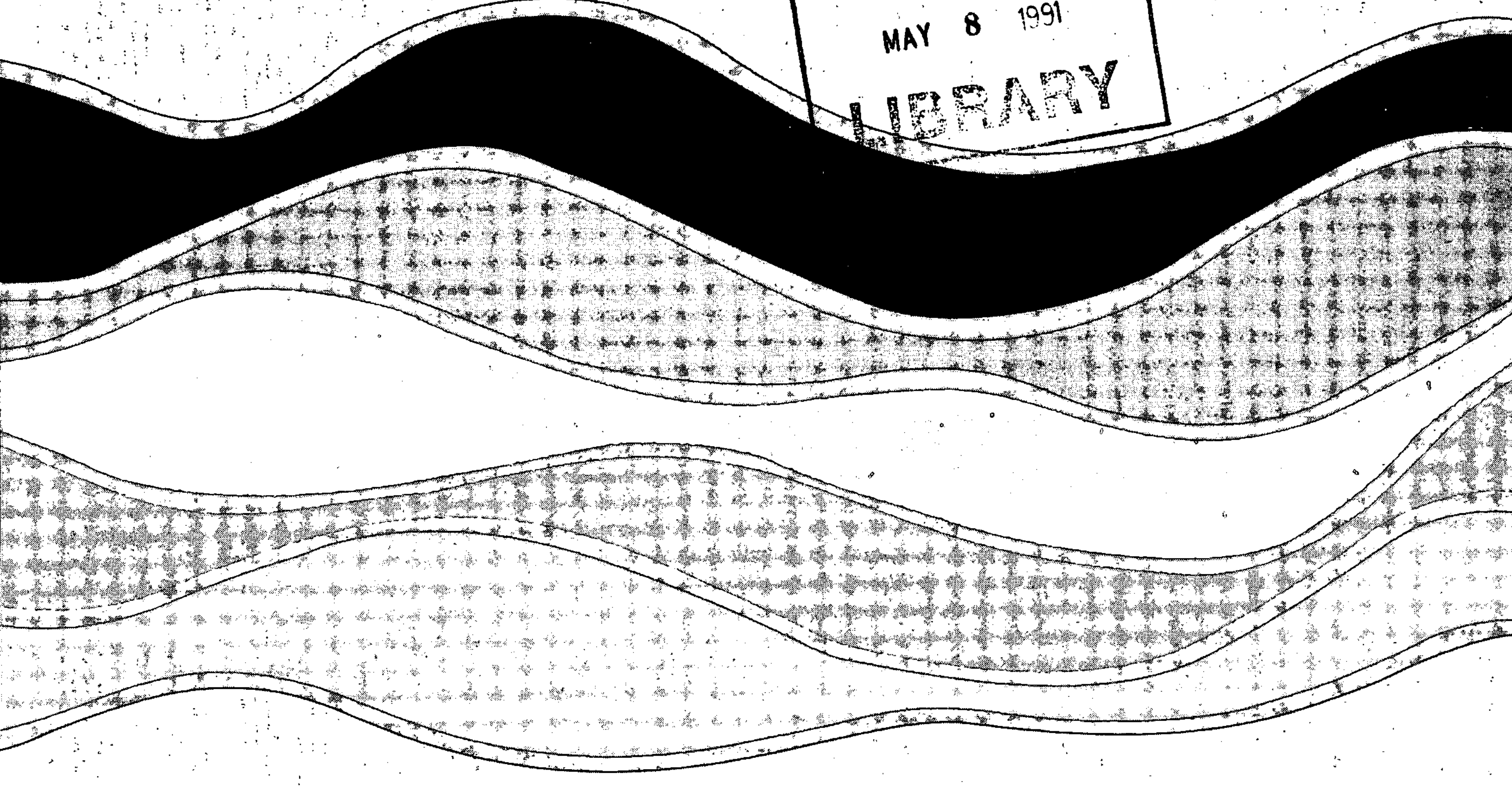

LOADINGS OF SELECTED CHEMICALS INTO ST. LAWRENCE RIVER SYSTEM FROM LAKE ONTARIO, 1986/87

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Management Perspective

Determination of the mass output through the St. Lawrence River outflow system is an important component in computing a mass balance of chemical parameters for Lake Ontario.. During 1986 and 1987 a network of self recording current meter moorings were deployed in the main channels of the St. Lawrence River system in Lake Ontario. On two occasions in 1987, detailed Lagrangian experiments were carried out using a cluster of satellite drifters. The data from the current meter network and Langrangian drifter experiments provided the horizontal and vertical distribution of currents that are adequate to compute the distribution of water transport through the St. Lawrence outflow. Combining the above transport calculations with the ongoing chemical monitoring data at the St. Lawrence inflow, loading estimates of selected chemicals have been calculated. These loading estimates are useful not only for modelling mass balance of chemicals in Lake Ontario but serve as input loading estimates to the St. Lawrence River system from Lake Ontario.

Perspective de gestion

La détermination du débit massique à la sortie dans le fleuve Saint-Laurent est un élément important du calcul d'un bilan massique de paramètres chimiques pour le lac Ontario. Au cous de 1986 et de 1987, un réseau de mouillages supportant des moulinets auto-enregistreurs a été mis en place dans les chenaux principaux du Saint-Laurent dans le lac Ontario. A deux occasions en 1987, des expériences détaillées basées sur la méthode de Lagrange ont été effectuées à l'aide d'un groupe de dériveurs suivis par satellite. Les données fournies par le réseau de moulinets et les données tirées des expériences réalisées au moyen de dériveurs ont permis de déterminer la distribution verticale et la distribution horizontale des courants qui permettent de calculer la distribution du transport dans l'eau à la sortie dans le Saint-Laurent. En combinant les calculs de transport susmentionnés aux données de surveillance continue des substances chimiques à l'entrée dans le Saint-Laurent, on a fait des estimations des charges de certaines substances chimiques. Ces estimations, en plus d'être utiles pour la modélisation du bilan massique des substances chimiques dans le lac Ontario, sont utilisées comme estimations des charges d'entrée dans le Saint-Laurent à partir du lac Ontario.

ABSTRACT

Determination of the mass output through the St. Lawrence River outflow system is an important component in computing mass balance of chemical loadings to Lake Ontario. The total flow rate in the St.Lawrence River System at the Wolfe Island area was calculated from detailed time series current meter measurements from a network of current meters and Lagrangian drifter experiments. This flow is roughly distributed in the ratio of 55% to 45% in the South and North channel, respectively. Loading estimates of selected chemicals have been made by combining the above transport calculations with the ongoing chemical monitoring data at the St. Lawrence outflow. A vertical gradient in the concentration of some organic and inorganic chemicals was observed. The measured concentration for some of the chemicals was higher during the summer months and also is higher in the South Channel than in the North Channel of the St.Lawrence River. These loading estimates are useful not only for modelling mass balance of chemicals in Lake Ontario but also for serving as input loadings to the St. Lawrence River system from Lake Ontario.

RÉSUMÉ

La détermination du débit massique à la sortie dans le Saint-Laurent est un élément important du calcul d'un bilan massique de charges chimiques pour le lac Ontario. Le débit total dans le fleuve Saint-Laurent dans la région de l'île Wolfe a été calculé à partir de mesures détaillées (séries chronologiques) effectuées au moyen d'un réseau de moulinets et d'expériences effectuées au moyen de dériveurs basées sur la méthode de Lagrange. Ce débit se répartit grossièrement suivant le rapport 55% à 45 % dans le chenal Sud et le chenal Nord respectivement. Des estimations de charges de certaines substances chimiques ont été faites en combinant les calculs de transport susmentionnés avec les données de surveillance continue des substances chimiques à la sortie dans le Saint-Laurent. Un gradient vertical de la concentration de certaines substances organiques et inorganiques été observé. La concentration mesurée de certaines des substances était plus élevée pendant les mois d'été; elle est aussi plus élevée dans le chenal Sud que dans le chenal Nord du Saint-Laurent. Ces estimations, en plus d'être utiles pour la modélisation du bilan massique des substances chimiques dans le lac Ontario, sont utilisées comme estimations des charges d'entrée dans le Saint-Laurent à partir du lac Ontario.

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Acknowledgements

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Satellite Drifters

h_{cd} = average depth of the drifter compartment

h_{av} = average depth of the current meter cross section

U_a = drifter velocity 'a' meters passed the current meter cross section

U_b = drifter velocity 'b' meters before current meter cross section

$U_a' = U_a \cos(\theta_c - \theta_a)$ = drifter velocity component perpendicular to the current meter cross section.

$U_b' = U_b \cos(\theta_c - \theta_b)$ = drifter velocity component perpedicular to the current meter cross section.

$U_c = U_b' + (U_a' - U_b') \frac{b}{a+b}$ = linearly interpolated velocity

U_c = drifter velocity at the current meter cross section

$U_{cc} = \frac{U_c}{1.2}$ = average velocity in the drifter compartment

$$U_{av} = U_{cc} \left(\frac{h_{av}}{h_c}\right)^{2/3} \frac{n_c}{n_{av}}$$

U_{av} = cross sectional average velocity based on Manning equation

$U_{aver} = \frac{\sum_{i=0}^{N} U_{av}}{N}$ = cross sectional average velocity based on all drifters

N = Number of drifters passed each channel

Q_{ND} = North channel flow rate based on drifter data

Q_{SD} = South channel flow rate based on drifter data

Q_{TD} = Total flow rate through both the channels

θ_a = drifter direction 'a' meters passed the current meter cross section

θ_b = drifter direction 'b' meters before the current meter cross section

θ_c = direction of the current meter cross section

$\theta_{cn} = 243^{o}$ (north channel)

$\theta_{cs} = 230^{o}$ (south channel)

List of Symbols

Current Meters

h_c = water depth at the current meter location

h_{avc} = average depth of the current meter compartment

h_{av} = average depth of the current meter cross section

k_s = equivalent roughness

U_{12} = Current meter (Neil Brown) velocity

U_{20}= current meter (Geodyne) velocity

U_s = water surface velocity

$U_{mn}'=U_{mn}\cos(\theta_{cn}-\theta_{mn})$ mn = 12 or 20

$U_{ms}'=U_{ms}\cos(\theta_{cs}-\theta_{mn})$ ms = 12 or 20

U_* = shear velocity

U_{ca} = average velocity at the current meter compartment

U_{av} = cross sectional average velocity based on Manning equation

U_c = current speed = $(U^2+V^2)^{0.5}$

U = west-east velocity component

V = north-south velocity component

Var. U = Variance of the U velocity component

Var. V = Variance of the V velocity component

T_c = Temperature at the current meter depth

Var. T_c = Variance of the Temperature

z = distance from the channel bottom

Q_{NC} = North channel flow rate

Q_{SC} = South channel flow rate

Q_{TC} = Total flow rate through both the channels

θ_{12} = current meter (Neil Brown) velocity vector direction

θ_{20} = current meter (Geodyne) velocity vector direction

θ_c = direction of the current meter cross section

θ_{cn} = 243 ^{o} (north channel)

θ_{cs} = 230 ^{o} (south channel)

1. Introduction

Knowledge of physical characteristics of the Kingston Basin and the St. Lawrence outflow area is very important from the point of view of determining the chemical loadings to the St. Lawrence River System. Towards this goal, during the years 1986/87 detailed physical limnological experiments were conducted to determine the flow distribution in the main channels of the St. Lawrence River outflow.

In 1987 for a period of four and a half months, June 2 to October 14, two pairs of self recording current meters were deployed at the mouth of the St. Lawrence River. Each pair of current meters consisted of one 'Neil Brown' current meter positioned 12 m below the water surface and one 'Geodyne' current meter positioned 20 m below the water surface. The first pair was located at the North channel and the other at the South channel of St. Lawrence River. Also clusters of drifting buoys were released in two cases for periods of two weeks. During the first release three of the seven drifters entered the north channel of St. Lawrence River. During the second release all four drifters of the second cluster entered the South channel of St. Lawrence River.

In order to estimate loadings of selected chemical entering the St. Lawrence River System, calculations of the flow distribution in the main channels of the St. Lawrence River system were performed with the available current meter and satellite drifter data. The current meter data were used to calculate the physical loadings for the period of the experiment and the results are compared with the loadings based on Cornwall station measurements.

The physical loadings based on Cornwall station flow measurements and the concentrations of selected chemicals based on the Wolfe Island station measurements are used to estimate the chemical loadings to the St. Lawrence River. These loadings are compared with the reported loadings from previous years. In addition to the above, chemical loadings based on the chemical measurements in the North and South channels, collected during a transect study in 1987 and on the flow distribution derived from the current meter and satellite drifters results are computed and compared with the previous ones. Finally, recommendations for further studies, in particular location of current meters, velocity profiles and release points of satellite drifters are proposed.

This report is one of three reports on this subject and deals directly with the chemical loadings from Lake Ontario to the St. Lawrence River. The second report that will follow will provide detailed information on chemical sampling and analysis of nutrients, major ions and organics with a comparison and discussion on the level of concentration and loadings of these chemicals during the last 10 years. The third report will deal with the climatological and dynamical characteristics of the Kingston Basin and the flow distribution in the main channels of the St. Lawrence Outflow Area.

2. Physical Experiments

Description of Current Meter and Satellite Drifter Data

Two pair of current meters were located at the north (Mooring No. 13) and south channel (Mooring No. 14) of the St. Lawrence River (see Fig. 1). Detailed information on the current meter moorings, i.e., mooring number, longitude, latitude, water depth, etc., can be found in Table 1. The Neil-Brown acoustic current meters used in this study provide two velocity components and temperature information.

During 1987 for a period of three weeks , August 25 to September 15, clusters of drifting buoys were released on two occasions (see Fig. 2). During the first experiment three of the seven drifters entered the north channel of the St. Lawrence River and the data from two of them (no. 5381 & 5388) were used for calculating the flow rate through the north channel. During the second experiment, all four drifters of the second cluster (no. 5380, 5385, 5387 & 5389) entered the South channel of the St. Lawrence River, providing very detailed data to calculate the flow rate through the South channel.

These drifting buoys are manufactured by Hermes Electronics and are shown in Fig. 3. The drifters are elliptically shaped buoys consisting of 0.6 m in diameter upper and lower fiberglass hulls. The lower hull contains a high frequency (401.65 MHz) transmitter and batteries while an antenna is extended into the upper hull. In order to provide payload shock protection and thermal stability for the radio transmitters, the buoy was filled with rigid foam. To ensure that current drag is the dominant force on the drifter, the buoys were tethered to "roller blind" drogues. The drogues consist of a 2.4 X 3.0 m reinforced polyethylene tarpaulin with a 3.0 m length of 15 mm diameter steel reinforcing bar attached to the bottom and a 3.0 m length 20 mm diameter aluminum conduit attached to the top.

Remote tracking of the drifter buoys is provided by the Argos satellite positioning system. The system consists of two polar orbiting Tiros-N satellites, a data processing centre, a computer system for accessing the data and the signal source, the drifting buoy (ARGOS User's Guide). The doppler shift in frequency between two consecutive signals is used to determine the buoy position relative to the satellite. The present data together with other data are transmitted to the NESS (National Environmental Satellite Service), a ground tracking station. The buoy signal is separated from other information and transmitted to the CNES (Centre National D'Etudes Spatiales) space center in Toulouse, France where it is processed. The satellite system can provide about 7 positions per day in the Great Lakes region with a position error less than 500 m (Pickett et al., 1983).

Data Reduction and Analysis

The current meter data were translated and written on a digital tape in a standard format including information such as station number, year, day, hour, latitude and longitude, velocity, temperature etc. A number of statistical and plotting programs were used for calculating the means and variances of velocity and temperature data from the current meters.

The monthly geographic positions of the drifter buoy was written to digital tapes. A program was used to write the data to a hard disk. The records were sorted according to buoy number, year, day, time, location, satellite, longitude, latitude. The drifter positions were interpolated to hourly averages using an interpolation procedure that insures a smooth transition from one segment of the track to the next (Akima, 1970). Local velocities were computed from the differences in the hourly coordinate values. The final data analysis was performed using NWRI's main-frame computer, Cyber 180/830.

3. Physical Loadings

Discharge Measurements (Cornwall Station)

The St. Lawrence River flow rate is routinely measured at hourly intervals at the Moses-Saunders Power Plant control facilities at Cornwall, Ontario. These flow measurements, with a nine-day lag, to account for the travel time of the water mass from Kingston to Cornwall (Sylvestre, 1987), are used to estimate the inflow to the St. Lawrence River. The contribution of the tributaries along this section is approximately 1% of the total flow (Casey and Salbach, 1974).

The St. Lawrence River discharge during the years 1986 and 1987, based on daily estimates from Cornwall, is given in Fig. 4 (see also Table 1).

Flow Distribution / North and South Channels

The data from the two current meter moorings and six satellite drifters were provided information on the flow distribution in the south and north channels of the St. Lawrence River. The cross section areas through the current meters in south and north channels are given in Figs. 4 and 5 (depths are referenced to chart datum). Table 1 indicates the monthly averaged water levels from June to October. The water levels are above the chart datum during these months, with a average value of 0.61 m during the experimental period, June 2nd to October 14th (see also Table 2). These cross sections were divided into twenty compartments, in order to calculate the cross sectional average velocities from the available velocity data. Details on the average depths of the individual compartments and the total flow areas for the north and south channels can be found in Tables 3 and 4, respectively. Figures 5 and 6 indicate the current meter locations and the location of the drifters when they are crossing these cross sections. The detailed drifter paths approaching and passing the current meter cross sections are given in Figs. 7 and 8. The variation in flow area, is within 2%, 200 m before and after the section passing through the current meter in both channels. Three independent methods based on the above data were used in the present study based on the above data and are presented below:

Method 1: Current Meters (Eulerian Measurements)

The current meter velocities and directions (U_c', θ_c), averaged over the period of the experiment (four and a half months), can provide sufficient information for the estimation of the cross sectional average velocities in the north and south channels of the St. Lawrence River. The velocity components at 12 and 20 meters from the water surface perpendicular to the cross section, are calculated using the following equations:

$$U_{cn}(z)=U_{cn}'(z)\cos(\theta_n-\theta_{cn}) \qquad z = 2 \text{ or } 10 \qquad (1)$$
$$U_{cs}(z)=U_{cs}'(z)\cos(\theta_s-\theta_{cs}) \qquad z = 2 \text{ or } 10 \qquad (2)$$

where the z is the distance between the current meter and the channel bottom, the subscripts n and s denote north and south, θ_c denotes direction of the current meter cross section from the true north where $\theta_n = 243^{\circ}$ (north channel) and $\theta_s = 230^{\circ}$ (south channel), see Figs. 6 and 7. The cross section orientations were chosen to be as close as perpendicular to the shores and to the resultant current meter velocity vectors, i.e. minimizing the magnitude of the lateral mean velocity vector (see Table 4 for lateral velocity V_c).

The bottom material in the designated cross sections consisted of fine silt with irregular bottom topography. Since the flow is turbulent, a logarithmic velocity profile in the rough turbulent regime is a good approximation. The equation appropriate for this profile is given by Yalin, 1972:

$$\frac{U(z)}{U_*} = 2.5 \ln\left[30.1 \frac{z}{k_s} \right] \qquad (3)$$

where k_s is the equivalent roughness, U_* the shear velocity, h is the water depth at the current meter location and U(z) is the velocity at the current meter location. The surface velocity is given by the following equation:

$$\frac{U_s}{U_*} = 2.5 \ln\left[30.1 \frac{h}{k_s} \right] \qquad (4)$$

where h is the water depth at the current meter location (h = 22 m for the moorings in both the north and south channels) and z = h. The average velocity is given by the following equation:

$$\frac{U_{ca}}{U_*} = 2.5 \ln \left[11.0 \frac{h}{k_s} \right] \tag{5}$$

where U_{ca} is the average velocity at the current meter compartment and corresponds to the velocity at a depth z=0.36 h. Using Eq. (3) for two depths, z_1 and z_2, and the corresponding velocities, U_1 and U_2, respectively, one can eliminate the equivalent roughness, k_s

$$\frac{U(z_1)-U(z_2)}{U_*} = 2.5 \ln \left[\frac{z_1}{z_2} \right] \tag{6}$$

This equation is useful because it provides a means for calculating the shear velocity, U_*, if the velocities at two depths in a cross section are known.

An accurate estimate of the total discharge can be made by dividing the cross section into compartments and use the following equation (Shen & Ackermann, 1980):

$$Q_T = \sum_{i=1}^{N} U_{ci} \, \Delta A_i \tag{7}$$

where i = index for compartments, N = total number of compartments, U_{ci} = the average velocity in the ith compartment, ΔA_i = $h_{ci} \Delta x_i$ the area of the ith compartment, h_{ci} = average depth of the i compartment and Δx_i = the horizontal distance between adjoining compartments.

The average velocity in any compartment of the composite area is calculated by using the Manning equation (Ven Te Chow, 1959) assuming that the Manning equation is applied individually for each compartment.

$$U_{ci} = U_{ca} \left(\frac{h_{ci}}{h_{ca}} \right)^{2/3} \frac{n_{ca}}{n_{ci}} \tag{8}$$

where n_{ci} = the Manning's roughness coefficient for the ith compartment, h_{ca} = average depth of the current meter compartment and n_{ca} = the Manning's roughness coefficient of the current meter compartment. The above approach is widely used in the instances, when the velocity data is limited. The velocity distribution can be synthesized from the depth data via Eq. (7) assuming $n_{ca} = n_{av}$ (Krishnappan & Lau, 1982).

Based on the above considerations, the average velocities were calculated for both the north and south channels. The cross sectional areas were divided into twenty compartments with $\Delta x_i = \Delta x$ for $i=1,N$. The Manning's roughness coefficient is taken to be the same in all compartments. Detailed calculations can be found in Tables 3 and 4.

These average velocities of the current meter compartments provide a quick estimate of the flow distribution. Average current speeds for the experimental period and monthly mean currents together with temperature information are given in Table 5. Calculations were performed for the south and north channels separately.

South Channel

CM. No.	z	$U_{cs}'(z)$	θ_{cs}	h	h_{ca}	h_{av}
	m	cm/s	deg.	m	m	m
14	10	14.2	51.1	22	25.25	14.26
14	2	11.3	40.3	22	25.25	14.26

$U_{cs}(z)$	U_*	k_s	U_s	U_{ca}
cm/s	cm/s	cm	cm/s	cm/s
14.12	via Eq.(6)	via Eq.(3)	via Eq.(4)	via Eq.(5)
11.13	0.743	15.04	15.580	13.715

The flow rate based on the average velocity of the current meter compartment is

$Q_s\ (ca) = U_{ca}\ A_{cs} = 0.13715 \times 34{,}272.18 = 4{,}700.43\ m^3/s$

where A_{cs} is the flow area in the North Channel. The flow rate via Eqs. (7) and (8) with $n_{ca} = n_{av}$ is

$Q_s\ (av) = \ = 3{,}845.21\ m^3/s$

$U_{av} = Q_s\ (av) / A_{cs} = 11.22\ cm/s$

The ratio of mean velocity U_{av} to shear velocity U_* is equal to 15.10 which corresponds to a Manning's roughness coefficient $n_{av} = 0.0329$. According to Ven Te Chow this value of the Manning's roughness coefficient is for natural channels with somewhat irregular side slopes and fairly even, clean and regular bottom, description which fit to the channels of the St. Lawrence River.

North Channel

CM. No.	z	$U_{cn}'(z)$	θ_{cn}	h	h_{ca}	h_{av}
	m	cm/s	deg.	m	m	m
13	10	11.4	59.6	22	20.88	14.10
13	2	3.4	62.5	22	20.88	14.10

Application of the above values to (Eq. 6) yields $U_* = 1.988$ m/s which is obviously a high value. The reason for this is the inaccurate mean current provided by the current meter at 2 m from the bottom because the low currents were close to the instrument's threshold (was occasionally sticking due to low velocities present). Application of Eq. (3) for different values of k_s and based on either velocities is given in the following table

	U_{12} = 11.4 cm/s	U_{20} = 3.4 cm/s
k_s	U_*	U_*
cm	cm/s	cm/s
10	0.5693	0.212
15	0.5997	0.227
20	0.6232	0.238

The value of the equivalent roughness, k_s, for the north channel is 15.04 cm. Based on the same order velocities and cross section areas one can estimate that the value of the equivalent roughness for the south channel will be of the same order. Based on the above arguments, $k_s = 15$ cm and $U_* = 0.5997$ cm/s (based on the current meter 10 m from the bottom).

$U_{cn}(z)$	U_*	k_s	U_s	U_{ca}
cm/s	cm/s	cm	cm/s	cm/s
11.38	via Eq.(6)	via Eq.(3)	via Eq.(4)	via Eq.(5)
3.4	0.5997	15.0	12.58	11.07

The flow rate based on the average velocity of the current meter compartment is

Q_N (ca) = $U_{ca} A_{cn} = 0.1107 \times 37{,}848.93 = 4{,}189.88$ m^3/s

where A_{cn} is the flow area in the North Channel. The flow rate based on Eqs. (7) and (8) with $n_{ca} = n_{av}$ is

Q_N (av) = 3,485.00 m^3/s

$U_{av} = Q_N\,(av) / A_{cn} = 9.21$ m/s
where U_{av} is the cross sectional average velocity.
The ratio of mean velocity U_{av} to shear velocity U_* is equal to 15.36 which corresponds to a Manning's roughness coefficient $n_{av} = 0.0323$. This value is similar to the corresponding one for the south channel due to the similarities between the south and the north channels.

The flow rates through the south and north channels based on the two approaches, identified with (ca) and (av), together with the total flow rate $Q_T = Q_s + Q_N$ are given below and the distribution of these in the channels are calculated:

Q_N (ca)	Q_s (ca)	Q_T (ca)	$\frac{Q_s}{Q_s+Q_N}$ (ca)	$\frac{Q_N}{Q_s+Q_N}$(av)
m^3/s	m^3/s	m^3/s	% Flow Rate	% Flow Rate
4,189.88	4,700.43	8,890.31	0.529	0.471

Q_N (av)	Q_s (av)	Q_T (av)	$\frac{Q_s}{Q_s+Q_N}$ (av)	$\frac{Q_N}{Q_s+Q_N}$(av)
m^3/s	m^3/s	m^3/s	% Flow Rate	% Flow Rate
3,485.00	3,845.21	7,330.21	0.525	0.475
* 3,365.69	4,215.14	7,580.83	0.556	0.444

The depth at the current meter locations in both south and north channels were 22 m. If this depth used as h_{ca} in Eq.(8) for both the north and south channels the flow distribution would be different as indicated by (*) in the last row of the previous Table.

Method 2: Satellite Drifters (Lagrangian Measurements)

The drifter velocity vector at the current meter cross section can be calculated by linearly interpolating the velocities and directions of the drifter as it approaches (U_a, θ_a) and passes (U_b, θ_b) through the cross section. The velocities perpendicular to the cross section (U_a', U_b') are calculated using the following equations

$$U_a' = U_a \cos(\theta_c - \theta_a) \tag{9}$$

$$U_b' = U_b \cos(\theta_c - \theta_b) \tag{10}$$

and the velocity at the current meter cross section is calculated by

$$U_d = U_b' + (U_a' - U_b') \frac{b}{a+b} \tag{11}$$

The average velocity of the drifter compartment is approximately equal to the surface velocity divided by 1.20 (the factor 1.20 is somewhat smaller in the present case because the drifter is at 3.5 m below the water surface)

$$U_{ad} = \frac{U_d}{1.2} \tag{12}$$

The flow through the St. Lawrence River is unsteady and it is controlled on daily basis by the Power Station at Cornwall. The decreasing flow rate from June to October together with the daily flow variation is evident in the high values of velocity component variances shown in Table 5. On the other hand the currents are quite uniform in the vertical indicating that the water moves as a coherent mass. The drifter data are Lagrangian; therefore, they are inadequate to provide mean Eulerian velocities for longer periods of time (the drifter crossed the mouth of St. Lawrence River in less than a day). However, the data indicates the flow distribution between the south and north channels. Based on the above considerations, the results for the north and south channels in terms of average velocity and flow rate are given below.

North Channel

Drifter No.	U_a	θ_a	U_b	θ_b	U_a' via Eq.(9)	U_b' via Eq.(10)
	cm/s	deg.	cm/s	deg.	cm/s	cm/s
5381	16.07	240.27	17.61	243.82	16.05	17.57
5388	21.93	251.26	19.47	254.57	21.70	19.09

Drifter No.	$\frac{b}{a+b}$	U_d via Eq.(11)	h_c	h_{av}	U_{ad} via Eq.(12)	Q_N via Eq.(7) & Eq.(8)
		cm/s	m	m	cm/s	m^3/s
5381	0.6036	16.99	15.54	13.23	14.16	5,488
5388	0.6111	20.68	16.15	13.23	17.13	6,470

$$Q_N \text{ (dr)} = \frac{5488+6470}{2} = 5979 \text{ m}^3/\text{s}$$

South Channel

Drifter No.	U_a	θ_a	U_b	θ_b	U_a' via Eq.(9)	U_b' via Eq.(10)
	cm/s	deg.	cm/s	deg.	cm/s	cm/s
5380	24.07	235.45	18.04	229.14	23.98	18.04
5385	21.41	242.77	17.54	235.42	20.88	17.46
5387	30.24	243.04	19.57	228.38	29.46	19.56
5389	17.14	229.77	17.10	229.90	17.14	17.10

Drifter No.	$\frac{b}{a+b}$	U_d via Eq.(11)	h_c	h_{av}	U_{ad} via Eq.(12)	Q_s via Eq.(7) & Eq.(8)
		cm/s	m	m	cm/s	m^3/s
5380	0.6100	21.66	12.70	13.59	18.05	8,001.5
5385	0.7411	19.99	12.70	13.59	16.66	7,385
5387	0.6666	26.16	23.57	13.59	21.80	6,399
5389	0.2564	17.11	23.89	13.59	14.26	4,148

$$U_{av} \text{ (dr)} = \frac{8001.5+7385+6399+4148}{4} = 6{,}483.5 \text{ m}^3/\text{s}$$

The flow rates through the south and north channels based on the satellite-tracked drifter data, identified with (dr), together with the total flow rate Q_T are given below and the distribution of these in the channels are calculated:

Q_N (dr)	Q_s (dr)	Q_T (dr)	$\frac{Q_s}{Q_s+Q_N}$ (dr)	$\frac{Q_N}{Q_s+Q_N}$ (dr)
m^3/s	m^3/s	m^3/s	% Flow Rate	% Flow Rate
5,979	6,483.5	12,462.5	**0.520**	**0.480**

These results agree with the flow distribution calculations based on the current meter data. The above results were not corrected for the differences in the flow rate between Julian days 244 and 256 when the drifters were released, see Table 6. Close inspection of the current meter velocities during the period that the drifters were passing through the designated cross sections reveal a possible increase in surface velocity in the south channel by 20% and a possible decrease in surface velocity in the north channel by 10%. Using the maximum corrections, one can get a flow distribution of 40% to 60% in the north and south channels of the St. Lawrence River, respectively, which is in agreement with that reported by Casey & Salbach, 1974. Our calculations, however, based on the current meter data, favour a 45% and 55% flow distribution.

The independent calculations based on current meter and satellite drifters data yield nearly identical flow distribution, i.e., 55% flow in the south channel and 45% in the north channel. Satellite drifter data (being Lagrangian) cannot be used to calculate total flow because the flow is unsteady. The current meter data can be used for calculation of the total flow rate because it provides a continuous velocity record in an Eulerian frame of reference.

Method 3: Combined Current Meter and Drifter data

The logarithmic velocity profile in the rough turbulent regime used previously for the current meter analysis is a good approximation if the flow is isothermal (one-layer flow). From the beginning of July till the end of September due to existence of the thermocline, a two-layer flow was present in both the current meter moorings in the north and south channels (see Table 5 for temperatures). In this barotropic flow in a stratified fluid the momentum diffusion is minimized across the interface and as a result sharp velocity gradients develop there. The velocity in the upper layer is higher than that in the lower layer due to the greater friction at the bed than at the interface. In otherwords the water in the upper layer, will move with higher velocity than the one we would predict based on the logarithmic profile for an isothermal flow. This hypothesis can be tested by using the Lagrangian drifter velocity 3.5 m below the water surface in the upper layer. In particular, the hourly average velocities from the current meters and the hourly average velocity from the drifter when it is passing the designated cross section can provide the vertical average velocity structure. Fitting a logarithmic velocity profile through the average velocities obtained by the current meters we can calculate the average velocity at 3.5 m below the water surface and compare it with the one obtained by the drifter. In all the cases the drifter velocity was higher than the velocity calculated from the logarithmic profile approach.

The cross sectional average velocities can be calculated following the same procedure used in the current meter analysis using a correction factor to account for the two-layer flow (the velocity in the upper layer has higher value than the one is predicted by the logarithmic profile) as follows: (a) the drifter velocity U_d is evaluated following the same procedure used in the second method, (b) the average velocity 3.5 m below the water surface in the current meter compartment U_d' is evaluated by the drifter velocity via Eq. (8) applied between the current meter and drifter compartments, (c) the compartment average velocity is evaluated by means of the depth integrated velocity

$$U_{cd} = \frac{12}{22}(U_d' + U_{12}')/2 + \frac{10}{22}(U_{12}' + U_{20}')/2 \qquad (13)$$

where U_{12}' and U_{20}' are the hourly averaged velocities during the time of the satellite drifter passage and (d) the cross sectional average velocity is evaluated via Eq. (7). Similar expression to Eq. (13) was used for strings of three current meters for transport calculations by Simons, Murthy & Campbell, 1985. The Eq. (13) cannot applied directly to estimate flow rates because the drifters passed the north and south channels at different times and the flow is unsteady. If U_{ca} (cd) is the average velocity at the current meter compartment during the time of the drifter passage, a correction factor can be applied to the flow rate during this time as

$$C_d = U_{cd} \;/\; U_{ca}\,(cd) \qquad (14)$$

that indicates the error introduced when we are not taking into account the drifter data. The flow rate including the correction factors is given by

$$Q(cd) = \frac{1}{N_d}\sum_{i=1}^{N_d} Q_i(cd) = Q(av)\frac{1}{N_d}\sum_{i=1}^{N_d} C_{di}\frac{U_{ca}(cd)}{U_{ca}} = Q(av)\,\frac{1}{N_d}\sum_{i=1}^{N_d}\frac{U_{cd}}{U_{ca}} \qquad (15)$$

where N_d is the number of drifters. The above steps are applied in both channels

<u>North Channel</u> U_{ca}=11.07 m/s, Q(av)=3,402.54 m^3/s

Drifter No.	U_d via Eq.(11)	U_d' via Eq.(8)	U_{12}'	U_{20}'	U_{cd} via Eq.(13)	Q_i(cd) via Eq.(15)
	cm/s	cm/s	cm/s	cm/s	cm/s	
5381	16.99	20.88	13.54	1.09	12.21	3,752.94
5388	20.68	25.41	11.16	2.70	11.83	3,636.14

Q_N (cd) = (3,752.94 + 3,636.14) / 2 = 3,694.54 m^3/s

<u>South Channel</u> U_{ca}=13.715 m/s, Q(av)=4,215.14 m^3/s

Drifter No.	U_d via Eq.(11)	U_d' via Eq.(8)	U_{12}'	U_{20}'	U_{ca} via Eq.(5)	Q_i(cd) via Eq.(15)
	cm/s	cm/s	cm/s	cm/s	cm/s	
5380	21.66	33.70	13.21	7.64	16.86	5,181.72
5385	19.99	31.10	12.36	7.51	15.75	4,480.57
5387	26.16	27.18	13.21	7.64	15.15	4,656.17
5389	17.11	17.78	9.71	5.84	10.60	3,257.78

Q_s (cd) = (5,181.72+4,840.57+4,656.17+3,257.78)/2= 4,484.06 m^3/s

The flow rates through the south and north channels based on this approach, is given below and the flow distribution in the channels is calculated:

Q_N (cd)	Q_S (cd)	Q_T (cd)	$\frac{Q_s}{Q_s+Q_N}$ (cd)	$\frac{Q_N}{Q_s+Q_N}$ (cd)
m^3/s	m^3/s	m^3/s	% Flow Rate	% Flow Rate
3,694.54	4,484.06	8,178.60	0.548	0.452

The flow rates in the north channel based on the integrated velocity method are consistently higher than the ones obtained via the logarithmic profile in conjunction with the Manning's equation (standard deviation/mean = 5.55%). This is not so, in the south channel where one flow rate is much lower (standard deviation/mean=16.6%).

4. Flow Rate Comparisons

It is of interest to compare these results with the direct Cornwall flow rate measurements traditionally used to estimate chemical loadings. The St.

Lawrence River flow rate is routinely measured at hourly intervals at the Moses-Saunders Power Plant control facilities at Cornwall, Ontario. These flow measurements, with a 9-day lag, to account for the travel time of the water mass from Kingston to Cornwall (Sylvestre et al., 1987), are traditionally used to estimate the inflow to the St. Lawrence River. The contribution of the tributaries along this section is approximately 1% of the total flow (Casey and Salbach, 1974) The St. Lawrence River discharge during the years 1986 and 1987, based on daily estimates from Cornwall, is given in Fig. 8 .

The average flow rate during the present study, taking into account the contribution of the tributaries, from 2 June to 14 of October is 8,282.50 m^3/s.

#1 Compartment Average	#2 Cross-sectional Average	#3 Combined Method	#4 Power Dam
Q_T (ca)	Q_T (av)	Q_T (cd)	$Q_{Cornwall}$
m^3/s	m^3/s	m^3/s	m^3/s
8,890.31	7,580.83	8,178.60	8,282.50
1.07 Q_C	0.915 Q_C	0.987 Q_C	Q_C

The flow rate based on the average velocity of the current meter compartment overestimates the traditional estimate based on Cornwall's power station by 7.34%. The reason for this difference is that the depth of the current meter compartment is larger than the average depth of the cross sectional area. The flow rate based on Eq.(7) in conjunction with the Manning's equation underestimates the Cornwall's estimate by 8.0 %. The same error is obtained if one uses the time series of the current meter and calculate the flow rate by using the integrated velocity method based on the information from the two current meters. The flow rate based on the satellite drifters is equal to 12,462.50 m^3/s which overestimates the flow rate. The reason for this difference is that application of Eq. (12) to two-layer turbulent flow such the present one is leading to higher estimates of mean current, because the magnitude of the current in the upper layer is higher than the one predicted by using the logarithmic velocity profile approach. In addition the satellite drifters pass through the south and north channels at different times, therefore they cannot be compared directly. The flow rate based on the depth integrated velocity method by combining the current meter and drifter data underestimates the Cornwall's estimate only by 1.3%. The latter difference is eliminated if the contribution of the tributaries between Wolfe Island and Cornwall is subtracted from the flow rate based on Power Plant control facilities at Cornwall. It is important to indicate that a larger number of drifters is likely to alter the flow rate within the flow rate estimates from the previous methods.

5. Chemical Experiments

Since 1977, Water Quality Branch - Ontario Region (WQB-OR) has operated a sampling station on the north shore of the south channel of the St. Lawrence River (latitude 44° 12' 24" N longitude 76° 14' 18" W) at Banford Point, Wolfe Island. At this location the south channel is approximately 2.5 km wide with a mean depth of 18.5 m (see Fig. 1).

During the study period water samples were routinely collected for five parameter groups: physicals (conductivity, pH), nutrients, major ions, trace metals and organochlorine compounds. The sampling program is consistent with that previously described by Sylvestre (1987) with the exception of organochlorine samples. To decrease the detection limit to the parts per trillion range, the protocol was changed to incorporate a Goulden Large Extractor (GLSE). This permitted an increase in sample volume from the previous historical 1 L to 38 L in April 1986 and a further increase to 44 L in August 1987. The GLSE is a liquid-liquid extractor using dichloromethane as the extraction solvent. Further details of the apparatus and its operation are found in Goulden and Anthony (1985). The extracts were collected into precleaned bottles closed with teflon lined caps and kept refrigerated until analysis. The analysis of the samples was performed according to the analytical methods summarized in the Analytical Methods Manual Update (Environment Canada, 1983).

The MLE censors data at the Method Detection Limit (MDL) and requires at least 3 values to be greater than or equal to the MDL. Mean concentrations and loadings could not be calculated for several compounds as the reported data did not meet the criteria.

Parameters reported as the sum of two or more compounds were calculated by summing the reported values prior to MLE analysis and using the highest MDL in the group for the MLE analysis.

In 1987 the Wolfe Island Station (WIS) sampling program was augmented by a transect study to compare water quality in the north and south channels. Samples were collected for major ions, nutrients and physicals at four stations in each channels (Figs. 9 and 10) at 1 m depths using a March 5C-MD pump and teflon lined stainless steel tubing. At the deepest station (one per transect, N-1 and S-3) large volume samples (38L or 44L) were collected for OCs at 1 metre depth. The samples were collected, preserved and analyzed following the same procedures used for the Wolfe Island samples.

6. LOADINGS TO THE ST. LAWRENCE RIVER FROM LAKE ONTARIO

The flow rates derived from the time series current meter and satellite drifter data and the direct measurements at Cornwall corrected for the 9-day time lag between WIS and Cornwall are used to estimate the loadings of selected chemicals in St. Lawrence River from Lake Ontario. Since the contribution of the tributaries along the station WIS and Cornwall is only 1 percent of the total flow (Casey and Salbach, 1974), it is reasonable to estimate the inflow rate to the St. Lawrence River at WIS based on the 9-day time lag to account for the travel time of the water mass in this section (Sylvestre, 1987). Imposing the 9-day time lag, the monthly moving average calculations of the total flow through the St. Lawrence River system based on hourly flow rate data collected at Cornwall were made for 1986 and 1987 (see Fig. 2).

The method of maximum likelihood estimation (MLE) was used to calculate the mean concentration and loadings, as well as confidence limits, of selected chemicals (El-Shaarawi, 1989). The calculation requires the transformation of the observations to satisfy the assumptions of normality. A modification to the method of maximum likelihood has been made to account for non-convergence (El-Shaarawi and Dolen, 1989).

The mean concentrations (mg/L) and loadings (tonnes per year) for nutrients and major ions at the WIS are presented below and compared with data from previous years and are presented in Table 7.

The data base NAQUADAT that contains the historical data from the Great Lakes stations was used for moving averages and regression slopes calculations. Regression analysis for moving averages for the nutrients and major ions for the 11 year period, 1977-1987, are shown in Figs. 5 to 9. The regression slopes of the moving averages reveal a decline of 0.16 µg/L/a for total phosphorus (TP), an increase of 9.6 µg/L/a for total Kjeldahl nitrogen (TKN), an increase of 10.7 µg/L/a for nitrate+nitrite, a 6.2 µg/L/a for sulphate (SO_4) and a decline of 0.44 mg/l/a for chloride (CL).

The observed increase in loadings for TP, SO_4 & Cl in 1986, are suspected to be a function of high water levels resulting increased flow rates through the Cornwall control structure.

The data for the 1987 season for which there was corresponding samples collected at the transect stations and WIS are summarized in Figs. 12 to 16. The transect data, unless otherwise noted are averages of each of the four stations in each transect. The 1 m loading estimate is the summation of the average values multiplied by the proportional mean monthly flow for each transect. Comparing the transect (1 m depth) and WIS (14 m depth) data the following observations can be made for the months in which sampling occurred:

(a) The concentrations of TP (Fig. 12), indicate the presence of a vertical gradient during the summer months when stratification occurs. The reduction of TP in the epilimnion is most apparent in July. The concentration of TP is slightly higher in the north channel than the south channel.

(b) The concentrations of nitrate-nitrite (Fig. 13), are similar in both the south and north channels. A slight difference depthwise is observed with the 14-m concentration higher. The difference is more pronounced during the stratification period.

(c) The concentrations of TKN, SO_4 and Cl (Figs. 14, 15 & 16), are similar in both the south and north channels and the WIS.

Organochlorine Compounds

Mean concentrations (ng/L) as calculated using the MLE of the organochlorine pesticides, PCBs and chlorobenzenes measured at the WIS (14 m below the water surface) in 1986 and 1987, are shown below with the method detection limits (MDL):

	MDL ng/L	1986	MDL ng/L	1987
Organochlorine pesticides and PCB's (ng/L)				
aBHC	.4	3.10 (1.11)	.12	1.77 (0.54)
LINDANE	.4	0.69 (0.24)	.04	0.40 (0.14)
tBHC (aBHC+LINDANE)	.4	3.80 (1.31)	.12	2.17 (0.67)
tDDT (ppTDE+opDDT+ppDDT)	.4	0.00 *		0.00 *
DIELDRIN	.4	0.38 (0.04)	.10	0.25 (0.07)
PCB	9.0	2.50 (1.57)		0.00 *
Chlorobenzenes (ng/L)				
tDCB (13DCB+12DCB+14DCB)	0.4	4.70 (7.93)		0.56 (0.30)
PeCB	0.4	0.00 *		0.00 *

* concentrations were observed but a mean could not be calculated

( ) standard deviation. The concentrations for most of the above organics were higher in 1986 than 1987.

Mean concentrations (ng/L) of the organochlorine pesticides, PCBs and chlorobenzenes measured at the North and South transects (1 m below the water surface) based on 8 months of data (April to December 1987), are shown below:

	Detection Limit	South Transect 179S (S3) 1987	Nort Transect 192N (N1)
Organochlorine pesticides and PCB's (ng/L)			
aBHC	0.12	3.70 (2.63)	2.76 (1.24)
LINDANE	0.04	0.75 (0.35)	0.56 (0.13)
tBHC (aBHC+LINDANE)	0.12	4.45 (2.94)	3.33 (1.35)
tDDT (ppTDE+opDDT+ppDDT)	0.32	0.00	0.00
DIELDRIN	0.10	0.25 (0.12)	0.23 (0.12)
PCB	1.2	1.32 (0.98)	1.34 (0.39)
Chlorobenzenes (ng/L)			
tDCB (13DCB+12DCB+14DCB)	0.45	0.75 (0.30)	0.63 (0.26)
PeCB	0.05	0.00	0.00

( ) standard deviation

Figures 17 - 22 show the measured concentrations calculate monthly loadings of organochlorine pesticides, PCBs and chlorobenzenes for 1987.

(a) The concentrations of PCBs (Fig. 17), indicate the existence of a vertical gradient during the summer months when stratification occurs. Concentrations at 1 m depth are higher than those at 14 m. Possible reasons for this difference are (a) thermal gradient reduces mixing (b) constant loadings to a restricted volume as a result of stratification and (c) affinity to biotic component associated with the epilimnion.

(b) The concentrations of a-BHC + lindane (Fig. 18), are generally higher during the summer months and slightly higher in the south channel than the north channel .

(c) The concentrations of dieldrin (Fig. 19) are similar in south channel and the WIS (except for October) and are slightly higher than in the north (only until July).

(d) There are no conclusions to be made on the concentrations of the chlorobenzenes at this point due to the variability of the analytical procedure used and the suspected volatilization of the components.

Loadings

Loadings (kg per year) of organochlorine pesticides, PCBs and chlorobenzenes measured at the north and south transects (1 m below the water surface) based on the 45% to 55% flow distribution between the north and south channel and on total flow (based on Cornwall station measurements adjusted by 9 days lag time), are shown below. It should be noted that loading estimates are based on 8 months of data using the mean annual flow. The fourth column presents the loadings in kg per year based on the same physical loading (Cornwall flows) but the chemical data is based on WIS measurements (14 m below the water surface).

	South Transect (based on 55%)	**North Transect** (based on 45%)			
	179S (S3) **(1 m depth)**	**192N (N1)** **(1 m depth)**	**(S3 + N1)**	**WIS** **(14 m)**	**Average**
Parameters	**1987**	**1987**	**1987**	**1987**	
a-BHC	517.9	316.5	834.5	452.2	643.3
LINDANE	105.4	64.6	170.0	101.8	135.9
tBHC	623.4	381.4	1,004.9	554.1	779.5
PCBs	184.5	153.6	338.1	63.4	200.8
tDCB	104.5	72.2	176.7	143.9	160.3
DIELDRIN	35.2	26.6	61.7	63.4	62.6

** The estimates for the WIS are based on seven month samples (the station was down during the month of June)

The organics loading data summarized in Figs. 17 to 22 indicate the following:

(a) there is a definite depthwise gradient in the concentration at the sites sampled.

(b) the concentration for most of the organic chemicals is higher at 1 m below the water surface than 14 m below surface (WIS) with exception the tDDT, PeCB and dieldrin.

(c) the total loadings of the organic chemicals based on the measurements from transect samples have some values twice as high as those based on the traditional WIS measurements and

(d) the concentrations of some of the chemicals are higher in the south channel than in the north channel of St. Lawrence River. This difference is further increased in the loadings estimate due to the difference in flow distribution.

Strachan and Edwards (1984), and Sylvestre (1987) reported estimates of chlorinated pesticides and PCB loadings from Lake Ontario. These estimates are compared with estimates calculated in this study (kg/year) in the table below:

Parameters	**Water**[1]	**1982/84**[2]	**1986(WIS)**	**1987(WIS)**
DIELDRIN	100	100	108	63.43
tBHC	2300	1650	1075	554.07
PCB's	1000	100	709	63.44
tDCB	---	---	1331	175.27

[1] Data from Strachan and Edwards, (1984).

[2] Sylvestre, (1987).

The above results imply:

(a) The insecticides, dieldrin and tDDT, reveal a trend towards lower concentrations. This was expected because use of these chemicals was banned in 1969 (Harris and Miles, 1975). The high persistence of dieldrin is evident for it is still detected 15 years after being banned.

(b) tBHC also reveals a trend towards lower concentrations. The concentrations are still relatively high compared to other components due to ubiquitous distribution.

(c) PCB loadings were high during 1986 possibly due to high water levels. The loadings were significantly lower during 1987 but were still higher than the ones measured during 1982/84. This is possibly due to lower extraction limits resulting from larger sample volumes used during 1986/87.

(d) Loading estimates for chlorobenzenes are not available prior 1986. The estimate for tDCBs is high but this is thought to be an artifact of sampling and analytical procedures rather than an actual ambient concentrations.

7. Conclusions

The logarithmic velocity profile and the depth integrated velocity methods were used with Manning's equation to analyze current meter and satellite drifter data for estimating cross sectional average velocities. The depth integrated velocity method is proven to be more accurate in the two layer channel flow structure. Based on the above methods, the flow in the St. Lawrence River was found to be distributed 45% to 55% in the north and south channel, respectively.

Comparison between the total flow rate through the St. Lawrence River System based on the present study and on the traditional estimate of the Power Plant control facilities at Cornwall were found to be in very good agreement. Therefore, the flow rates based on a 9 day lag of Cornwall's measurements provide a reliable estimate for calculating chemical loadings. In addition, the present study shows that reliable flow rate results can be obtained in complex flows, such as the one in the St. Lawrence outflow area, with limited field data.

During the summer months the thermal structure of Lake Ontario extends into the St.Lawrence River at least as far as the Wolfe Island Station. A seasonal vertical gradient or depthwise dependence in the concentration of organic and inorganic chemicals was found between 1 m and 14 m depth.

The concentration of most chemicals is higher in the south channel than the north channel of St. Lawrence River. The total chemical loading estimates based on the transect measurements (at 1 m depth) are higher than the traditional estimates using the WIS (14 m depth).

It should be noted that the increase in the total loadings estimates for some chemicals from years prior to 1986 may not be due to increased inputs but possibly a function of lower detection limits due to increased sample volumes and new extraction technology.

8. Recommendations

(1) The current meters in the St. Lawrence River at Wolfe Island should be located at the cross sections where the chemical data is obtained. For example, for the period May to the end of October, at station 192N-N1 in the north channel, four current meters should be installed (two in deep water at N1 and one in shallow water at each of N3 and N4). Monthly samples of chemical data should be collected at locations N1, N2, N3 and N4 in station 192N (At N1 & N2 locations at three depths: 1 m, mid-depth and bottom-2m; at N3 & N4 locations at 1 m and bottom-2m). At the station 179S-S3 in the south channel, four current meters should be installed at two locations at two depths between S1-S2 locations and at the S3 location. Monthly samples for chemical analysis at locations S1, S2, S3 & S4 should be collected at three depths (1 m, mid-depth and bottom-2m).
During the same period weekly vertical temperature profiles should be taken at stations 192N-N1 and 179S-S3.

(2) Sampling for organic analysis should be continued in both south and north channel cross-sections 179S and 192N, respectively, but at

different depths in order to further investigate the depthwise dependance. Sampling for organics should be expanded to investigate the dependance of parameter concentrations with thermal structure of the water column.

(3) In order to obtain more detailed and accurate physical loading estimates a number of conventional and satellite drifters should be released simultaneously in the north and south channels at varying distances from the shore. In addition, a number of vertical velocity profiles at varying distances from the shore should be measured at 0.2 h and 0.8 h, where h is the local water depth, in order to provide adequate information for the proper calculation of the cross sectional average velocity.

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TABLE 1

MONTHLY MEAN FLOW RATES (m^3/s)
WOLFE ISLAND AREA, LAKE ONTARIO

MONTH	1986	1987
JANUARY	7,513.09	7,353.51
FEBRUARY	8,315.50	7,607.51
MARCH	8,548.45	8,161.09
APRIL	9,332.84	8,866.93
MAY	9,235.45	9,312.29
JUNE	9,306.71	8,878.77
JULY	9,338.22	8,656.19
AUGUST	9,397.39	8,088.23
SEPTEMBER	9,008.34	7,785.77
OCTOBER	9,403.28	7,725.26
NOVEMBER	9,559.13	7,032.77
DECEMBER	9,445.08	7,407.48

The experiments lasted 4.5 months. The average flow rate for these months is Flow Rate[(June+July+August+September+October/2)/4.5)] = 8,282.50 m^3/s

$$\mathbf{Q_{Cornwall} = 8,282.50\ m^3/s}$$

TABLE 2

Water Levels

Chart Datum is 74.005 (Kingston- Portsmouth)

	Water Level	Above the chart datum (m)
June	74.845	0.840
July	74.753	0.748
August	74.569	0.564
September	74.438	0.433
October	74.352	0.347

Average Water Level above Chart Datum = 0.61 m

TABLE 3

North Channel

Depth (m)	Seg. Area (m^2)	Av. Depth (m) h_{ci} (+0.61 m)	$(\frac{h_{ci}}{h_{ca}})^{2/3}$	$U_{ca}(\frac{h_{ci}}{h_{ca}})^{2/3}$ ($h_{ci}\Delta x$)
1- 0				
2- 4.57	306.51	2.90	0.2678	11.40
3- 10.37	1,002.03	8.08	0.5309	63.01
4- 11.59	1,472.86	11.59	0.6753	114.96
5- 13.57	1,687.48	13.19	0.7361	142.60
6- 14.63	1,891.37	14.71	0.7916	171.03
7- 15.24	2,003.38	15.54	0.8211	187.48
8- 15.85	2,085.21	16.15	0.8425	199.91
9- 16.77	2,187.82	16.92	0.8690	215.96
10- 17.38	2,290.44	17.68	0.8950	232.42
11- 17.68	2,351.47	18.14	0.9103	242.54
12- 18.90	2,453.42	18.90	0.9356	259.73
13- 20.73	2,657.98	20.42	0.9852	295.49
14- 19.82	2,719.69	**20.88**	1.0000	306.69
15- 18.60	2,576.83	19.82	0.9657	281.13
16- 17.07	2,392.39	18.44	0.9205	249.32
17- 16.16	2,228.74	17.22	0.8793	222.40
18- 11.89	1,881.31	14.63	0.7887	169.48
19- 5.79	1,185.80	9.45	0.5893	81.79
20- 3.35	613.02	5.18	0.3947	30.03
21- 0	224.68	2.28	0.2287	7.66

h_{ca} = 20.88 m

$$Q_N = \sum_{i=1}^{N} U_{ci}\,\Delta A_i = 3{,}485\ m^3/s$$

Flow Area Orientation = 153°

Segment Length $(\Delta x)_N$ = 134.14 m

The width of the flow area at the water surface = 20 X 134.14 = 2,682.8 m

Flow Area A_{cn} = (36,212.43 + 2,682.8 X 0.61) = 37,848.93 m^2

Average Flow Depth = 14.108 m

TABLE 4

South Channel

Depth (m)	Seg. Area (m^2)	Av. Depth (m) h_{ci} (+0.61 m)	$(\frac{h_{ci}}{h_{ca}})^{2/3}$	$U_{ca}(\frac{h_{ci}}{h_{ca}})^{2/3}$ ($h_{ci}\Delta x$)
1- 0				
2- 1.52	110.39	1.53	0.1543	3.89
3- 5.49	422.88	4.13	0.2991	20.35
4- 7.32	767.39	7.00	0.4251	49.03
5- 7.62	901.26	8.11	0.4690	62.67
6- 8.63	956.15	8.57	0.4865	68.70
7- 9.45	1,066.55	9.49	0.5208	81.44
8- 10.37	1,195.64	10.56	0.5592	97.31
9- 11.59	1,324.74	11.63	0.5964	114.30
10- 11.59	1,398.33	12.24	0.6171	124.47
11- 12.50	1,453.23	12.70	0.6324	132.35
12- 19.82	1,949.70	16.84	0.7633	211.81
13- 25.92	2,759.27	23.57	0.9551	370.96
14- 20.43	2,796.06	23.89	0.9638	379.42
15- 33.54	3,255.74	27.70	1.0637	485.53
16- 29.57	3,807.11	32.29	1.1782	626.91
17- 19.51	2,960.75	**25.25**	1.0000	416.08
18- 19.21	2,335.78	20.05	0.8575	283.31
19- 14.33	2,023.30	17.44	0.7814	224.56
20- 3.66	1,085.25	9.64	0.5263	83.60
21- 0	220.79	2.45	0.2111	8.52

$h_{ca} = 25.25$ m

$$Q_S = \sum_{i=1}^{N} U_{ci}\,\Delta A_i = 3{,}845.21 \text{ m}^3 / \text{s}$$

Flow Area Orientation = 140^0

Segment Length $(\Delta x)_S$= 120.15 m

The width of the flow area at the water surface = 20 X 120.15 = 2,413.0 m

Flow Area A_{CS} = (32,800.25 + 2,413.0 X 0.61) = 34,272.18 m^2

Average Flow Depth = 14.26 m

TABLE 5

Current Meter Moorings

(2nd of June - 14th of October)

CM No.	z (m)	U_c' (cm/s)	V_c' (cm/s)	Var.U_c (cm/s)^2	Var.V_c' (cm/s)^2
13	10	11.4	0.68	21.00	6.74
13	2	3.4	0.03	14.07	2.22
14	10	14.2	-0.27	23.38	5.99
14	2	11.3	1.97	34.13	8.17

		June		July		August		September	
Mooring No.	h_c	U_c'	θ_c	U_c'	θ_c	U_c'	θ_c	U_c'	θ_c
13	12	12.95	57.5	11.12	55.2	13.40	61.7	11.58	60.0
13	20	1.05	64.5	2.69	70.7	3.57	67.2	4.63	65.2
14	12	14.99	50.2	12.91	49.5	14.31	53.0	14.53	51.2
14	20	12.57	38.5	11.95	36.7	12.11	45.2	9.70	46.0

Mooring No.	h_c	Temperature (T_c) in degrees Celsius			
13	12	16.20	21.30	21.00	18.10
13	20	13.30	16.50	17.60	17.80
14	12	16.90	21.70	19.80	18.20
14	20	15.50	20.90	15.30	18.10
surface temperature		21.20	22.00	22.00	18.10

Table 6

Satellite Drifter Experiments

North Channel

No.	Julian Day	Time	Speed	Direction	
5381	244	0030	18.41	247.71	
		0040	**17.61**	**243.82**	**b***
		0050	**16.07**	**240.57**	**a***
		0060	13.75	236.59	
5388	244	1000	10.11	259.35	
		1100	**19.47**	**254.57**	**b***
		1200	**21.93**	**251.26**	**a***
		1300	19.67	244.28	
		1400	16.60	231.96	

South Channel

No.	Julian Day	Time	Speed	Direction	
5380	256	2200	14.27	218.43	
	257	**0000**	**18.04**	**229.14**	**b***
		0100	**24.09**	**235.45**	**a***
5385	256	2200	14.75	227.03	
		2300	**17.54**	**235.42**	**b***
	257	**0000**	**21.41**	**242.77**	**a***
		0100	25.64	247.72	
5387	256	2300	13.10	201.20	
	257	**0000**	**19.57**	**228.38**	**b***
		0100	**30.24**	**243.04**	**a***
5389	256	2100	17.31	229.21	
		2200	**17.10**	**229.90**	**b***
		2300	**17.14**	**229.77**	**a***
	257	0000	19.43	229.80	

b* - approaching the designated cross section
a* - passing the designated cross section

Current Meter Velocities during the Passage of Drifters from the Designated Current Meter Cross Sections

No.	Julian Day	Time	U_{12}	Dir.	U_{20}	Dir.
13	244	0300	11.80	59.0	3.32	260.00
		0400	**11.77**	**52.0**	**4.06**	**181.00**
		0500	**15.62**	**57.0**	**2.44**	**160.00**
		0600	16.60	64.0	1.67	240.00
13	244	1000	14.27	64.0	3.72	25.00
		1100	**12.94**	**61.0**	**2.86**	**50.00**
		1200	**9.69**	**49.0**	**2.66**	**57.00**
		1300	12.39	53.0	3.50	31.00
13	256	2100	8.49	51.0	2.30	64.00
		2200	**8.32**	**54.0**	**1.35**	**32.00**
		2300	**10.36**	**59.0**	**2.02**	**32.00**
	257	**0000**	**13.27**	**64.0**	**3.83**	**60.00**
		0100	**11.89**	**59.0**	**3.73**	**90.00**
14	256	2100	8.86	62.0	4.30	46.00
		2200	**8.83**	**59.0**	**4.97**	**47.00**
		2300	**10.40**	**61.0**	**6.73**	**50.00**
	257	**0000**	**14.13**	**57.0**	**8.30**	**48.00**
		0100	**12.60**	**60.0**	**7.10**	**40.00**
14	244	0300	16.82	42.0	13.86	54.00
		0400	**16.82**	**44.0**	**11.93**	**56.00**
		0500	**16.50**	**44.0**	**12.05**	**57.00**
		0600	17.60	42.0	14.14	49.00
14	244	1000	16.56	42.0	13.38	50.00
		1100	**16.20**	**40.0**	**11.40**	**32.00**
		1200	**16.28**	**42.0**	**11.72**	**33.00**
		1300	13.15	37.0	10.58	13.00

Table 7

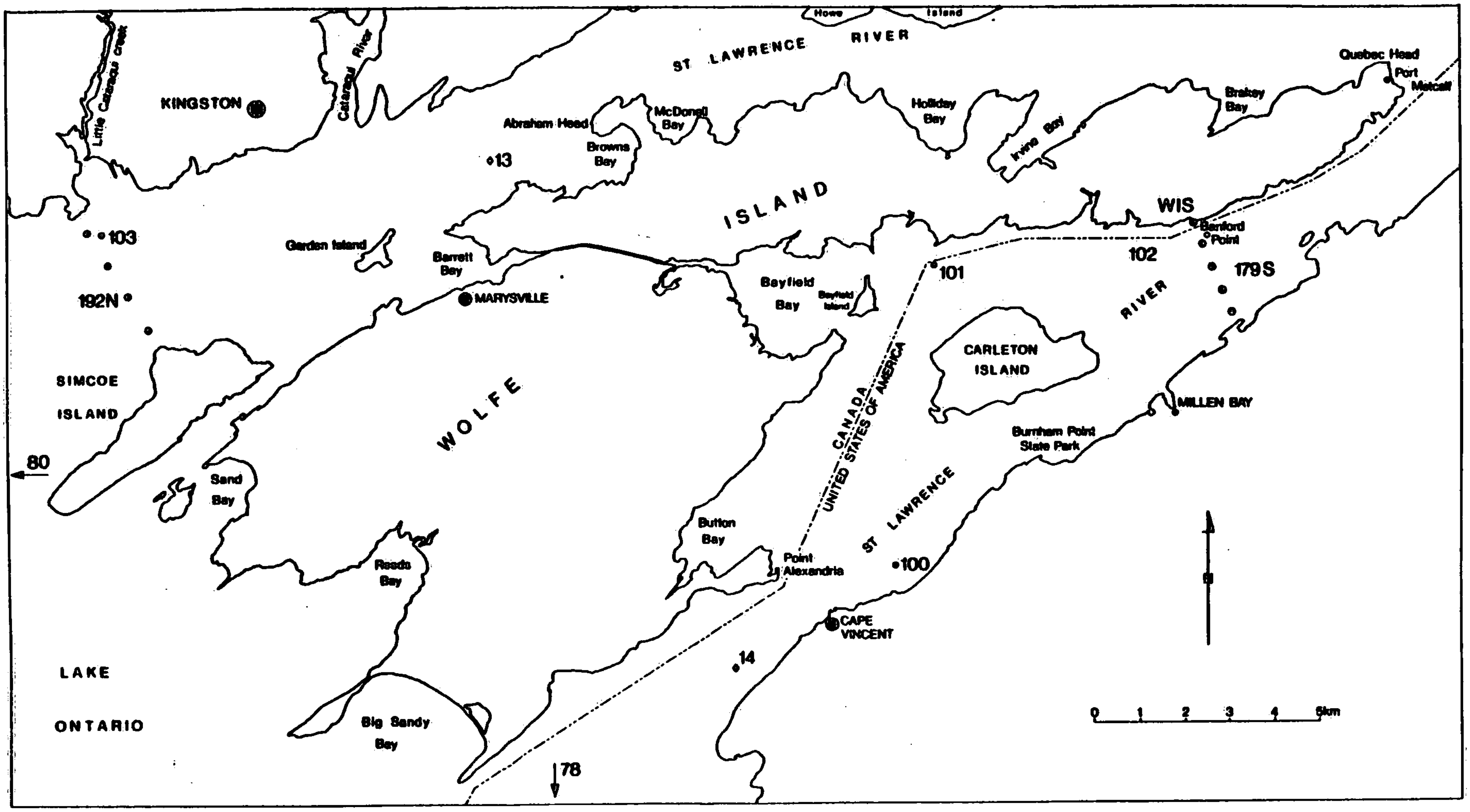
Mean Concentrations (mg/L)

	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
TP	0.0163 (0.0052)	0.0162 (0.0077)	0.0128 (0.0057)	0.0141 (0.0072)	0.0112 (0.0046)	0.0130 (0.0058)	0.0126 (0.0060)	0.0114 (0.0026)	0.0116 (0.0041)	0.0126 (0.0079)	0.0141 (0.0069)
NO_3-NO_2	0.225 0.087	0.221 (0.095)	0.215 (0.100)	0.217 (0.086)	0.230 (0.093)	0.243 (0.095)	0.233 (0.104)	0.238 (0.082)	0.265 (0.082)	0.349 (0.073)	0.360 (0.291)
TKN	0.234 (0.0510)	0.191 (0.061)	0.203 (0.063)	0.226 (0.038)	0.237 (0.080)	0.233 (0.045)	0.231 (0.048)	0.241 (0.047)	0.205 (0.027)	0.208 (0.032)	0.211 (0.045)
SO_4	26.9 (1.0)	26.7 (1.1)	26.7 (1.2)	26.6 (0.7)	26.2 (2.1)	27.3 (1.0)	28.1 (0.4)	27.3 (0.8)	26.4 (1.1)	26.0 (1.5)	26.1 (1.4)
Cl	27.5 (0.9)	27.4 (0.9)	27.2 (0.7)	26.8 (0.6)	26.1 (0.7)	25.9 (0.7)	25.6 (0.7)	25.1 (0.7)	24.5 (0.8)	23.6 (0.9)	23.3 (0.8)

Yearly Loadings (Metric Tonnes x 10^3)

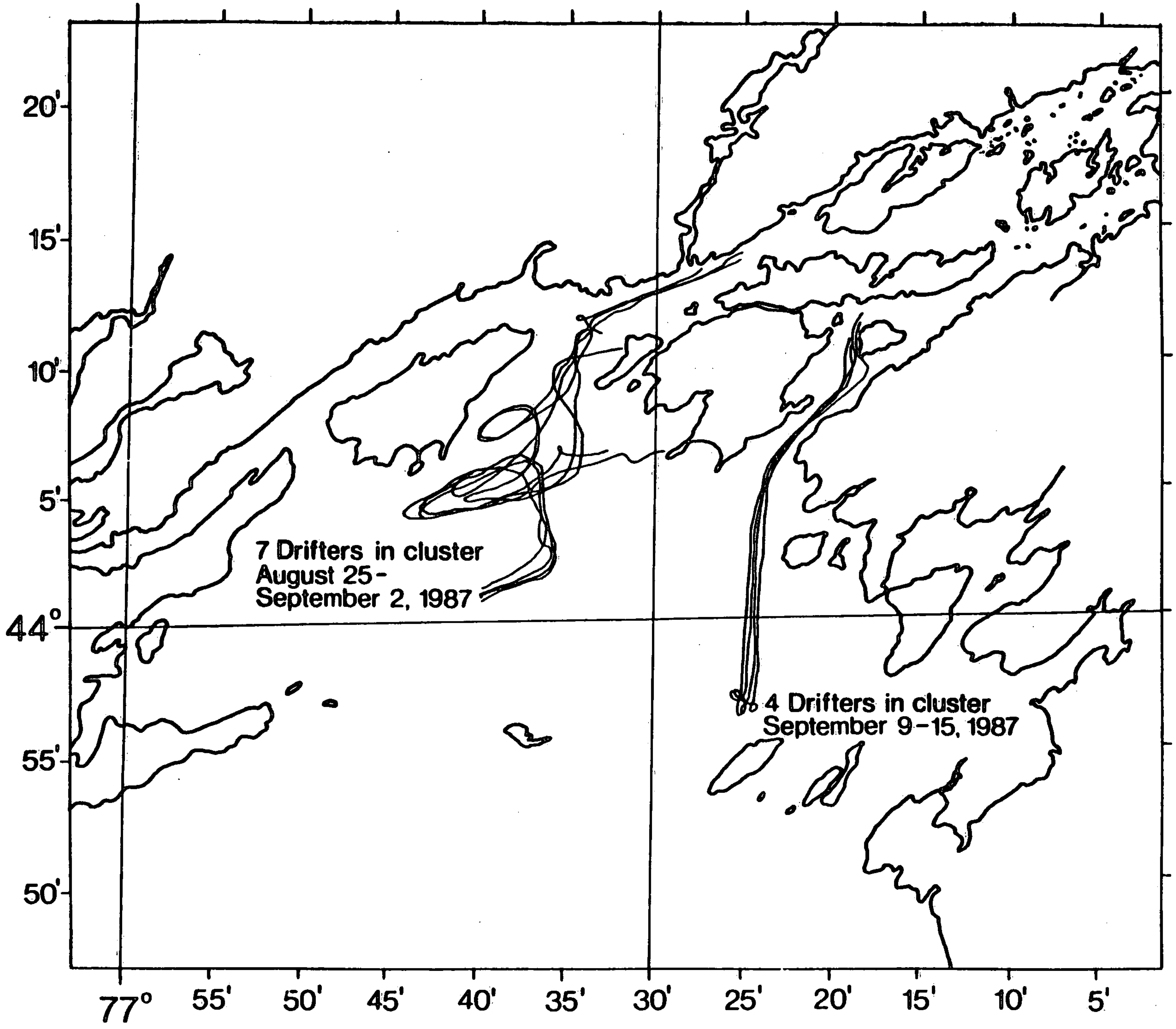
	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
TP	3.88 (1.39)	3.98 (1.93)	3.17 (1.43)	3.48 (1.86)	2.74 (1.19)	3.12 (1.45)	3.05 (1.50)	2.87 (0.75)	2.96 (1.12)	3.54 (2.31)	3.49 (1.78)
NO_3-NO_2	52.64 (20.59)	54.78 (24.95)	52.87 (24.30)	52.64 (20.26)	55.47 (22.52)	55.96 (23.29)	55.90 (25.20)	59.61 (20.54)	66.98 (20.58)	96.56 (20.70)	89.64 86.04
TKN	55.52 (13.65)	47.86 (18.14)	51.28 (17.57)	55.86 (11.47)	57.79 (21.99)	55.96 (11.17)	55.61 (12.69)	61.21 (14.75)	52.14 (8.98)	57.25 (10.52)	52.29 (12.43)
SO_4	6,377 (539)	6,620 (635)	6,626 (539)	6,552 (604)	6,393 (933)	6,595 (549)	6,767 (502)	6,877 (624)	6,695 (581)	7,420 (672)	6,300 (1,007)
Cl	6,552 (649)	6,803 (499)	6,760 (500)	6,600 (580)	6,378 (562)	6,248 (459)	6,171 (467)	6,329 (595)	6,222 (470)	6,743 (403)	5,627 (804)

( ) standard deviation



SAMPLING STATION LOCATIONS (WIS - DESIGNATES WOLFE ISLAND STATION)

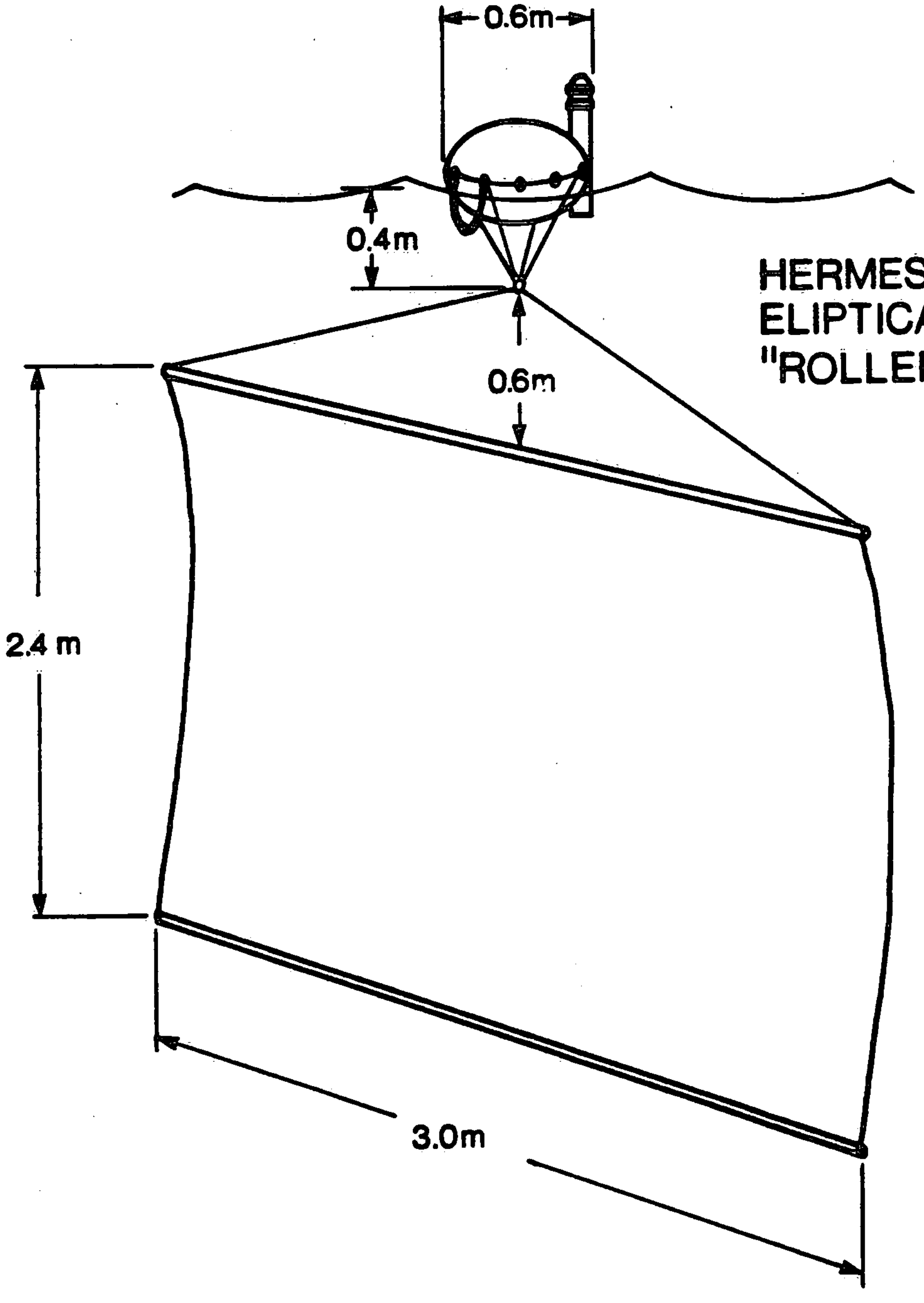
Figure 1



20'
15'
10'
5'
44°
55'
50'
77°
55'
50'
45'
40'
35'
30'
25'
20'
15'
10'
5'
7 Drifters in cluster
August 25-
September 2, 1987
4 Drifters in cluster
September 9-15, 1987

Figure 2

SATELLITE-TRACKED DRIFTERS



HERMES ELECTRONICS
ELIPTICAL BUOY WITH
"ROLLER BLIND" DROGUE

Figure 3

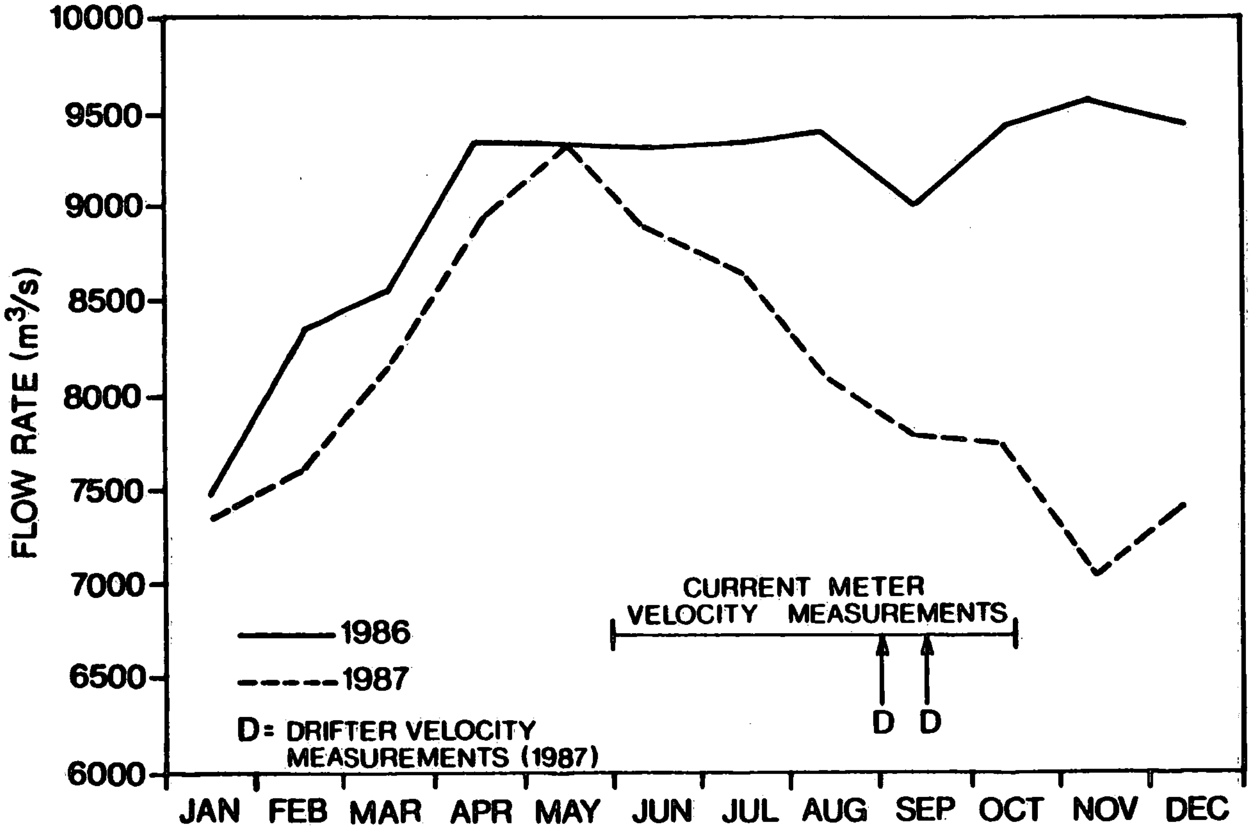
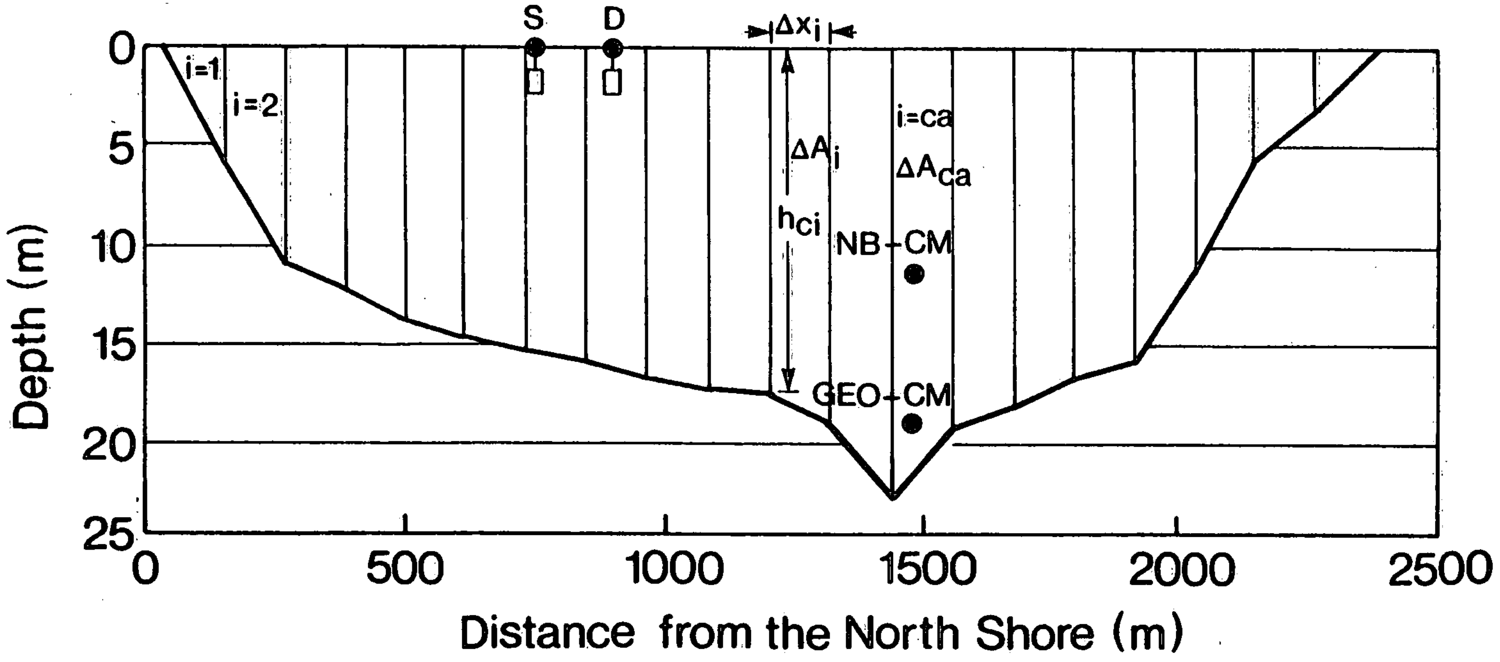

10000
9500
9000
8500
8000
7500
7000
6500
6000
FLOW RATE (m^3/s)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
1986
1987
D= DRIFTER VELOCITY MEASUREMENTS (1987)
CURRENT METER VELOCITY MEASUREMENTS
D
D

Figure 4

LAKE ONTARIO

NORTH CHANNEL (WOLF I. AREA)



CROSS SECTION (243°)
THROUGH CURRENT METER MOORING No 13

SD SATELLITE DRIFTER

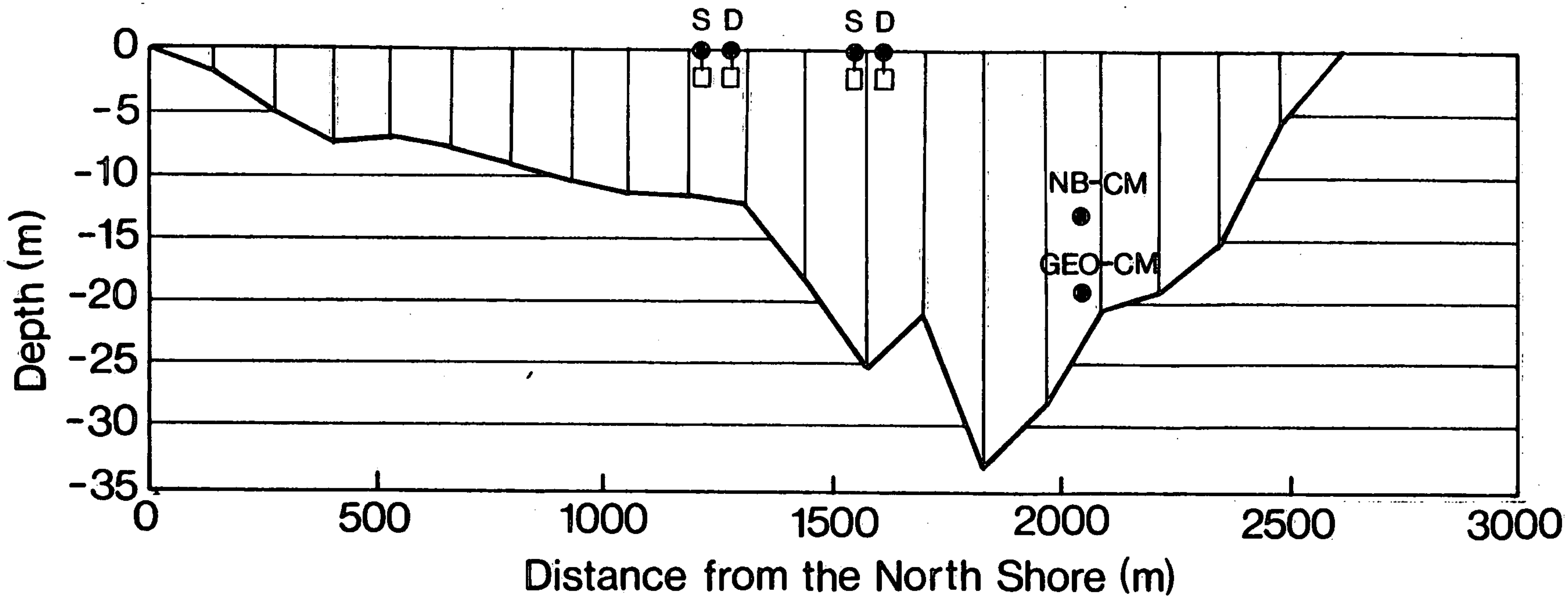
NB-CM NEIL BROWN CURRENT METER

GEO-CM GEODYNE CURRENT METER

Figure 5

LAKE ONTARIO

SOUTH CHANNEL (WOLFE I. AREA)



CROSS SECTION (230°)
THROUGH CURRENT METER MOORING No 14

SD SATELLITE DRIFTER
NB-CM NEIL BROWN CURRENT METER
GEO-CM GEODYNE CURRENT METER

Figure 6

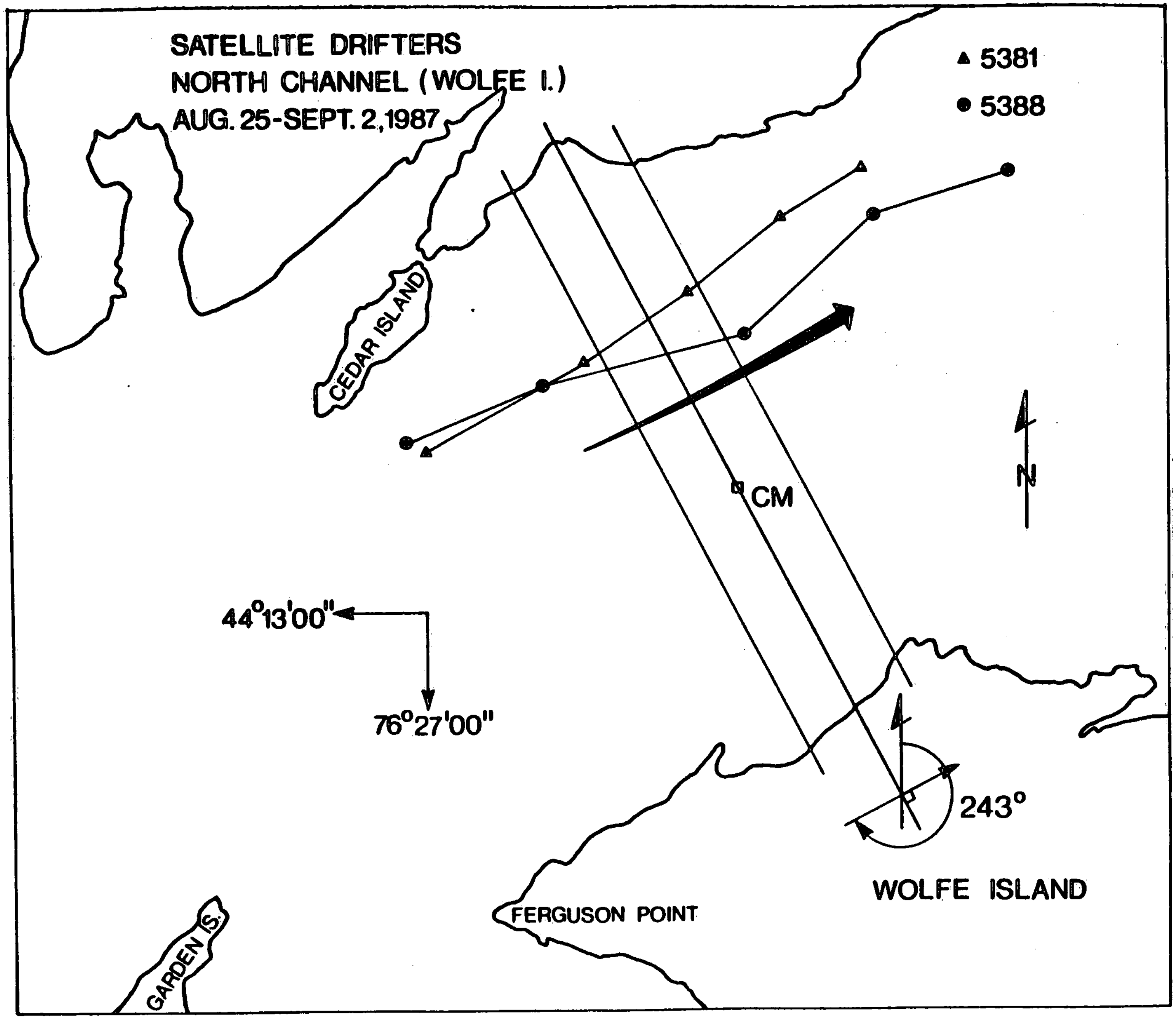

SATELLITE DRIFTERS
NORTH CHANNEL (WOLFE I.)
AUG. 25-SEPT. 2, 1987
▲ 5381
● 5388
CEDAR ISLAND
CM
N
44°13'00"
76°27'00"
243°
WOLFE ISLAND
FERGUSON POINT
GARDEN IS.

Figure 7

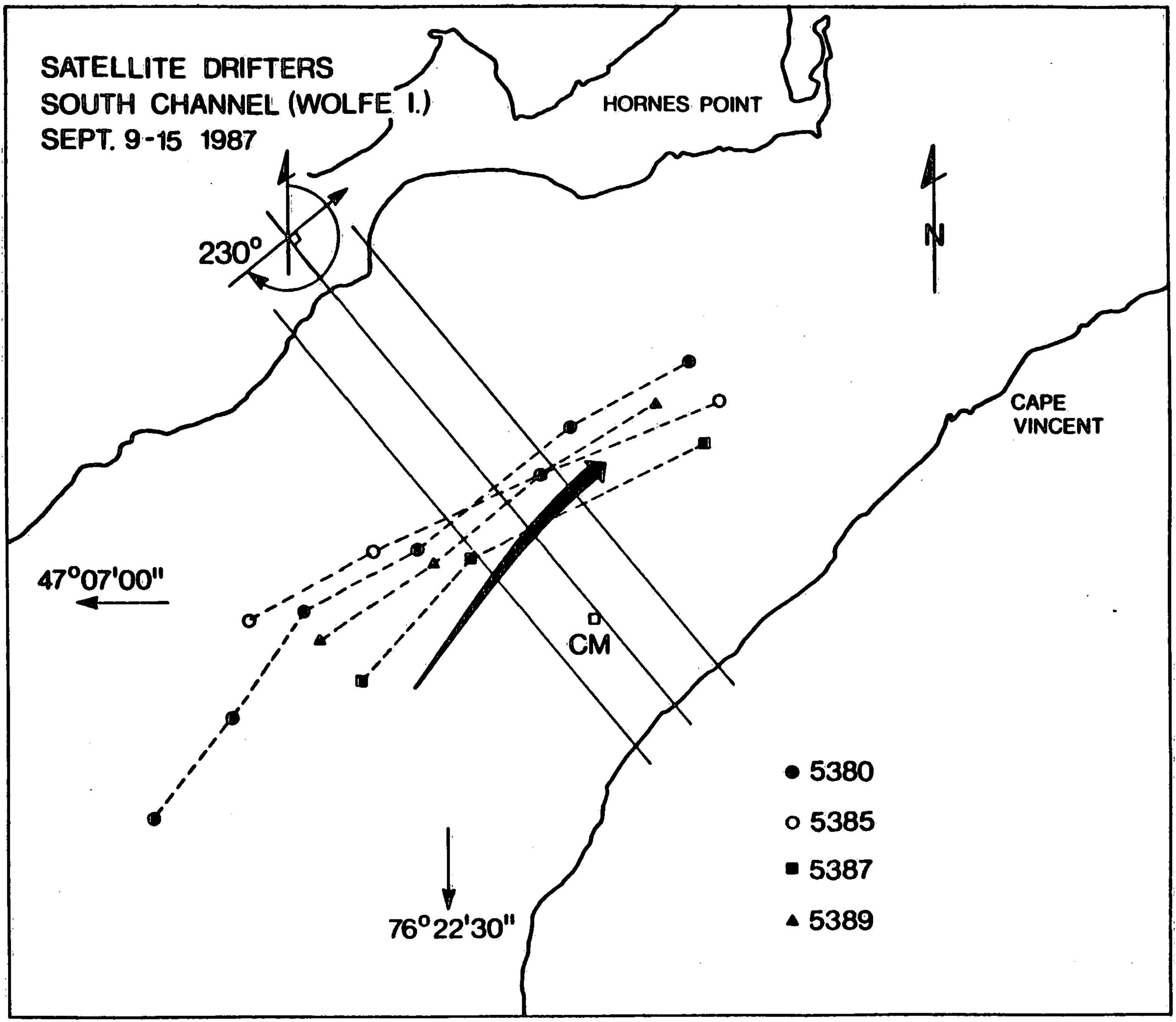
SATELLITE DRIFTERS
SOUTH CHANNEL (WOLFE I.)
SEPT. 9-15 1987
HORNES POINT
N
230°
CAPE VINCENT
47°07'00"
CM
76°22'30"
● 5380
○ 5385
■ 5387
▲ 5389

Figure 8

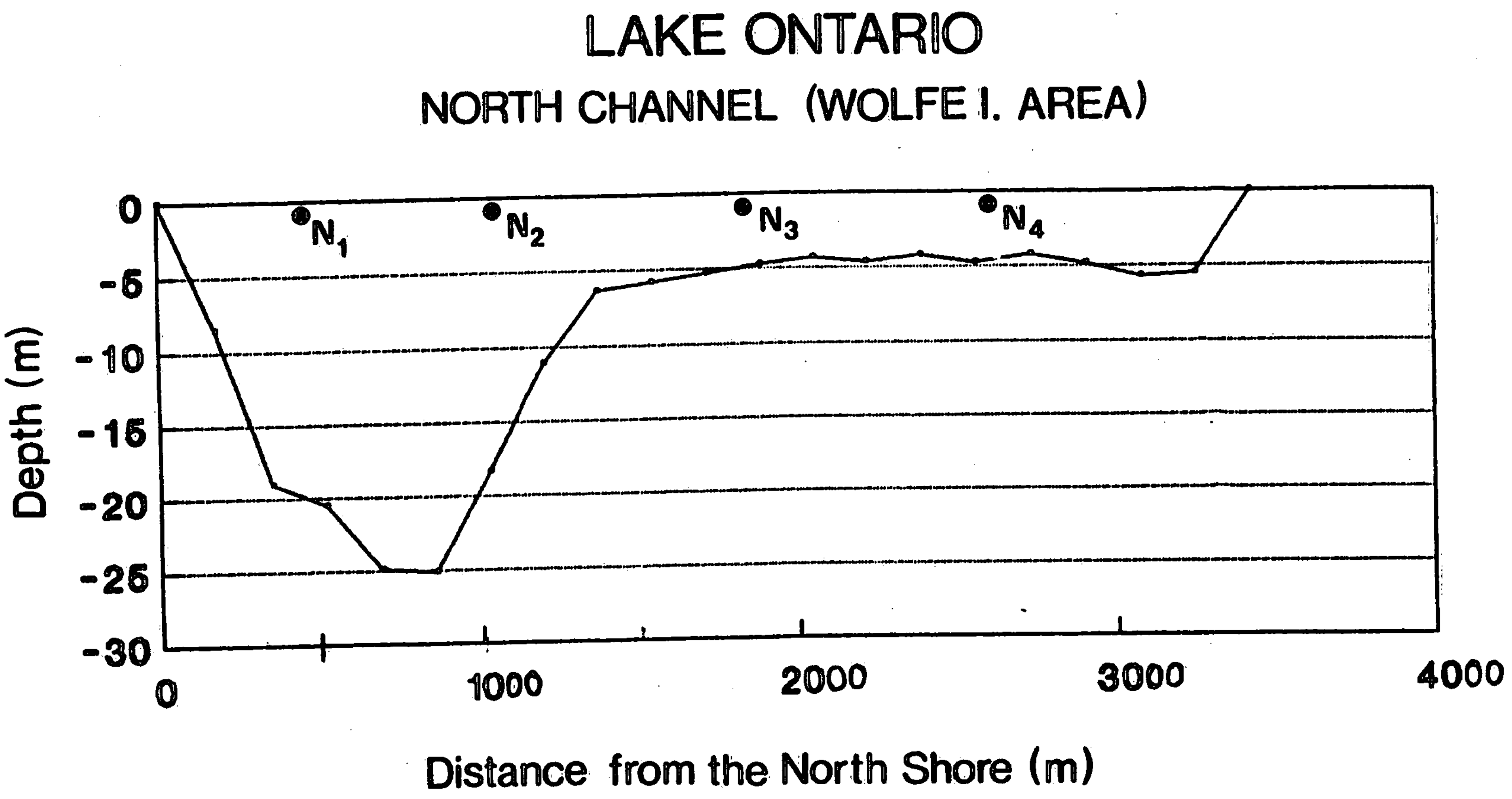

LAKE ONTARIO
NORTH CHANNEL (WOLFE I. AREA)
Depth (m)
0
-5
-10
-15
-20
-25
-30
N_1
N_2
N_3
N_4
0
1000
2000
3000
4000
Distance from the North Shore (m)

Figure 9

LAKE ONTARIO

SOUTH CHANNEL (WOLFE I. AREA)

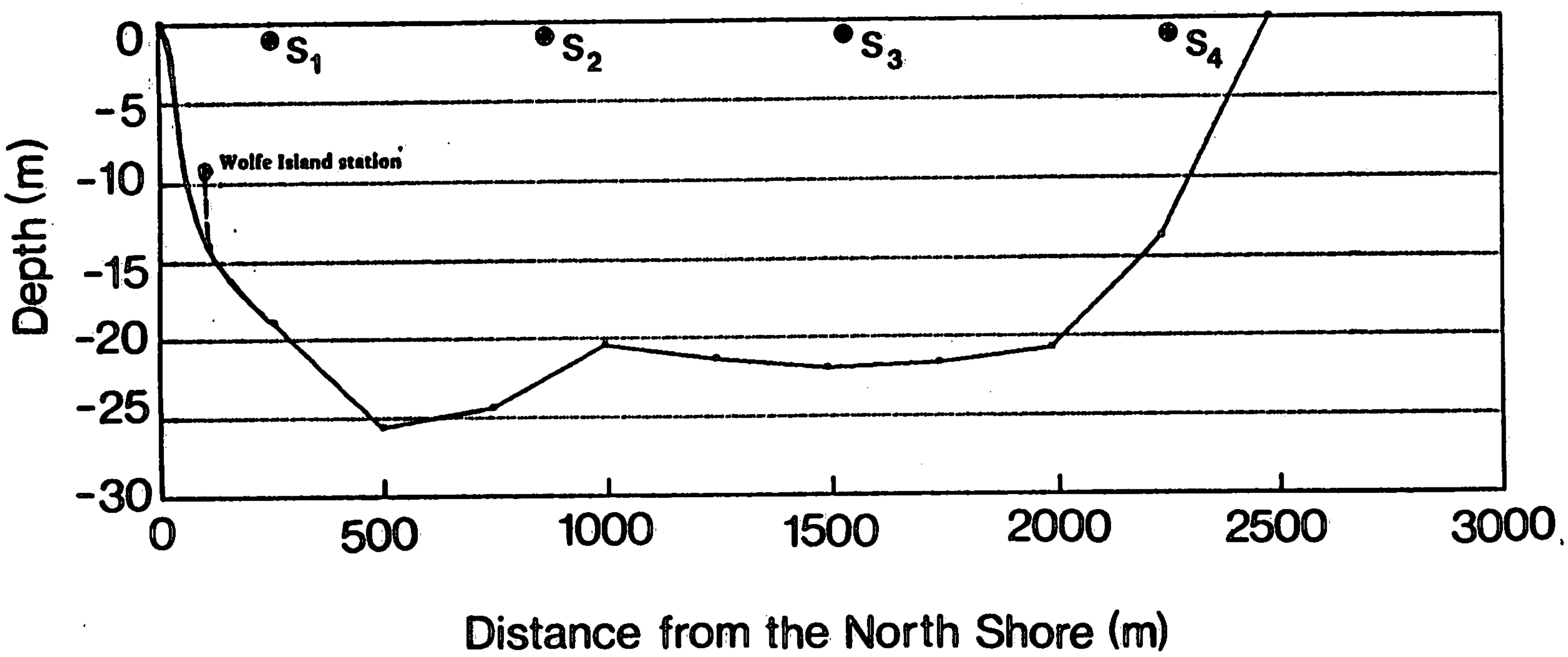


Figure 10

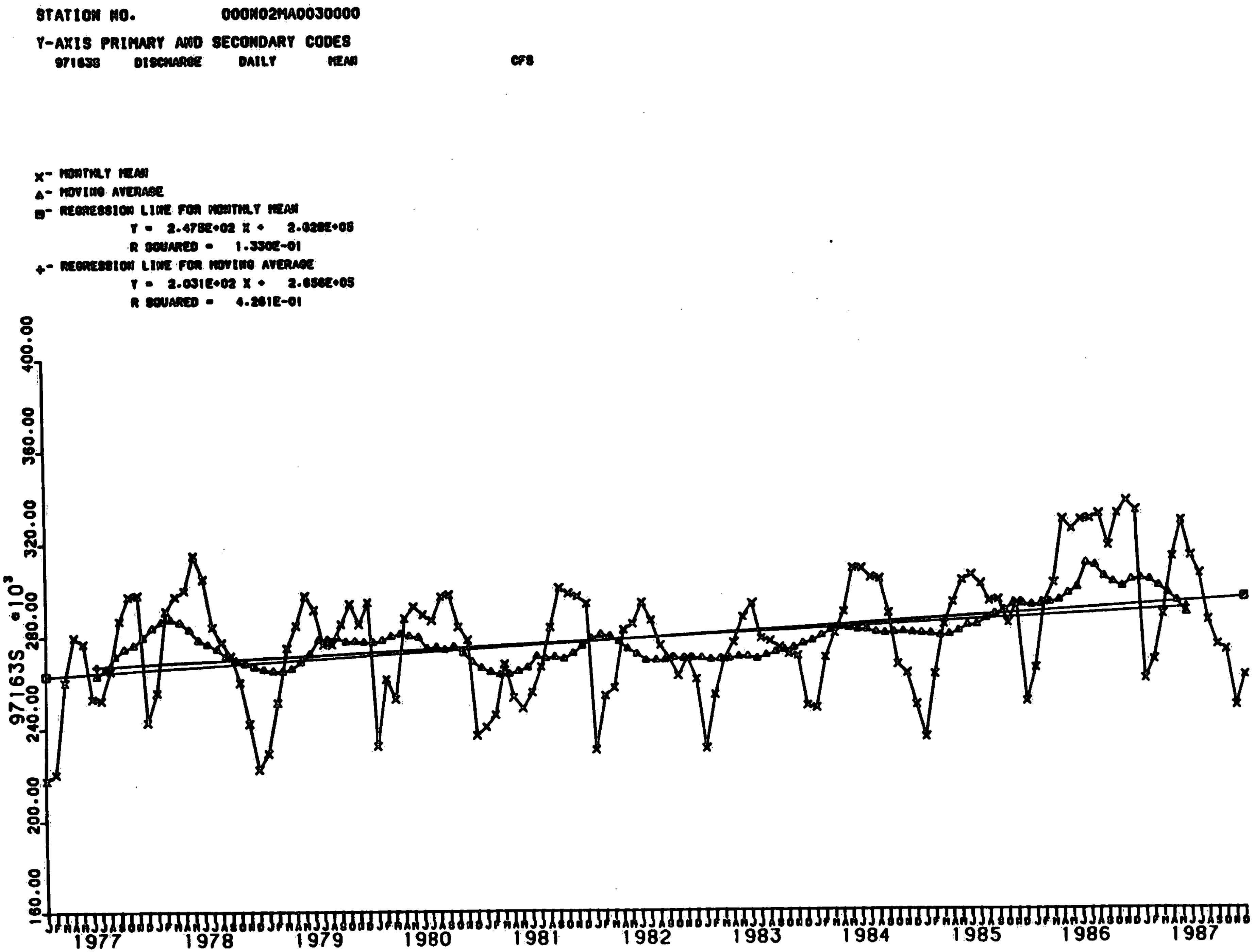
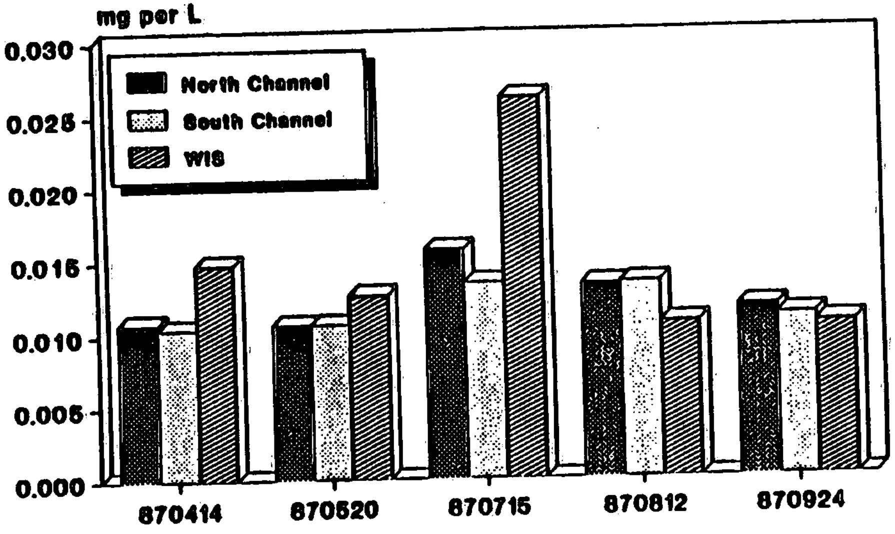

STATION NO. 000N02MA0030000
Y-AXIS PRIMARY AND SECONDARY CODES
97163S DISCHARGE DAILY MEAN CFS
X- MONTHLY MEAN
△- MOVING AVERAGE
⊡- REGRESSION LINE FOR MONTHLY MEAN
Y = 2.479E+02 X + 2.028E+05
R SQUARED = 1.330E-01
+- REGRESSION LINE FOR MOVING AVERAGE
Y = 2.031E+02 X + 2.656E+05
R SQUARED = 4.281E-01
97163S *10³
400.00
360.00
320.00
280.00
240.00
200.00
160.00
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987

Figure 11

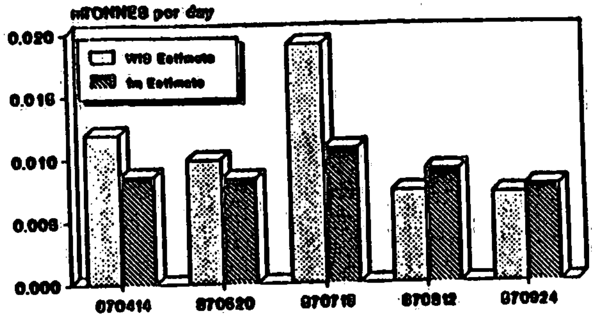
Figure 12

Measured Concentrations for Total Phosphorus.



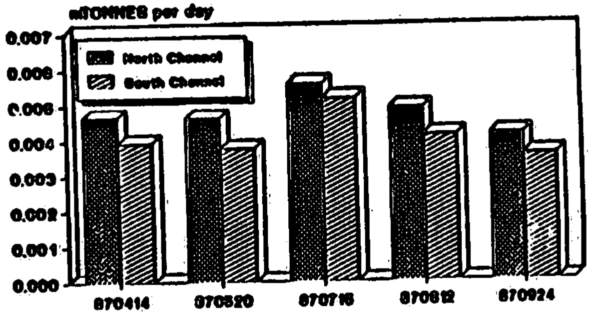
(a)

Instantaneous Loading Estimates for Total Phosphorus to the St. Lawrence River.



(b)

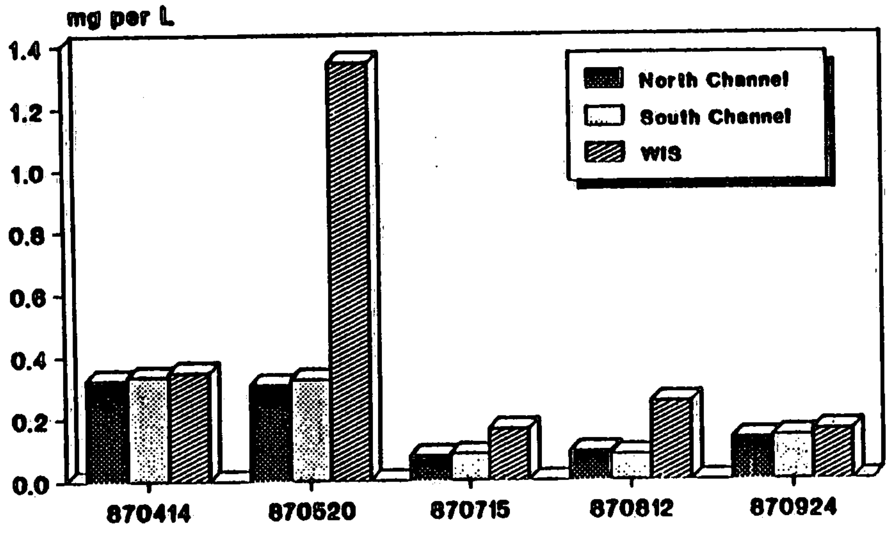
Instantaneous Surface Loading Estimates for Total Phosphorus to the St. Lawrence River.



(c)

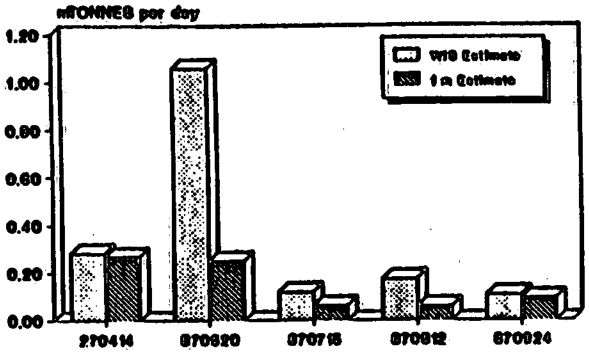
Figure 13

Measured Concentrations of Nitrate + Nitrite.



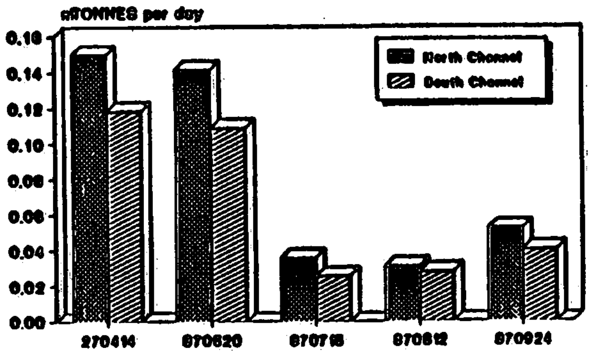
(a)

Instantaneous Loadings Estimates for NO2+NO3 to the St. Lawrence River.



(c)

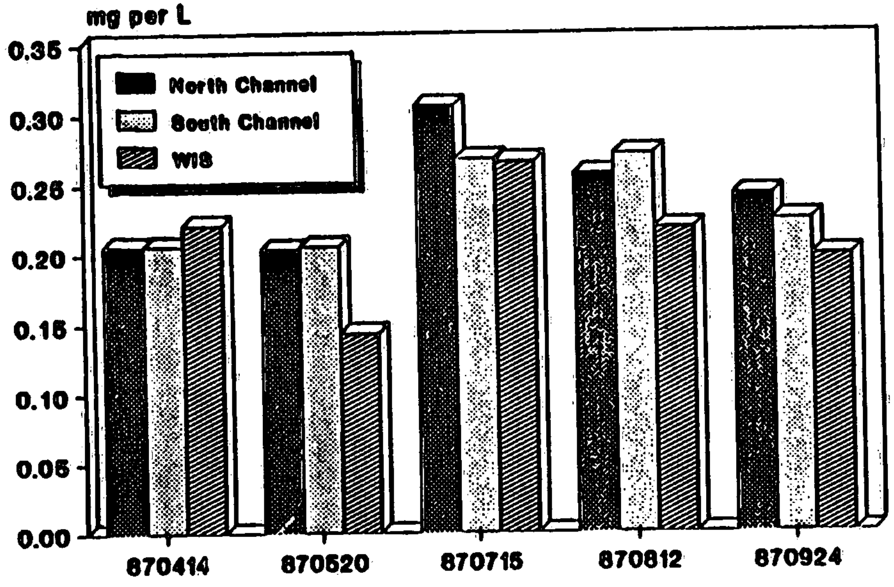
Instantaneous Surfaces Loading Estimates for NO2+NO3 to the St. Lawrence River.



(c)

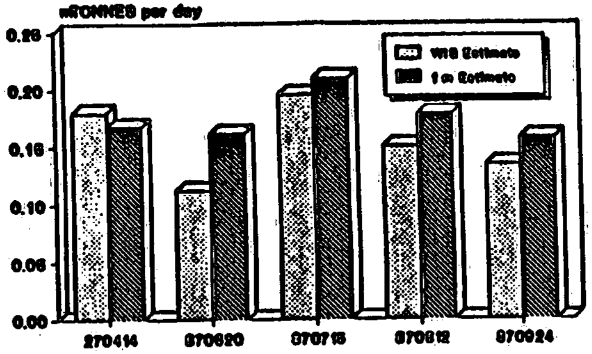
Figure 14

Measured Concentrations of TKN.



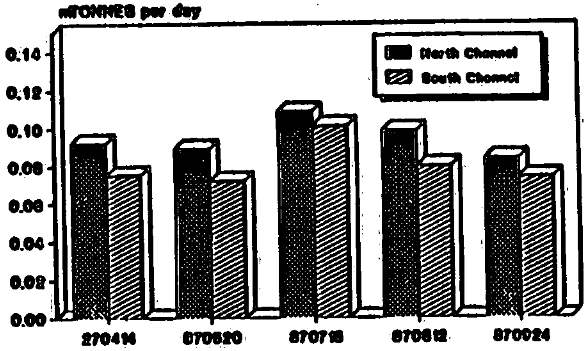
(a)

Instantaneous Loading Estimates for TKN to the St. Lawrence River.



(b)

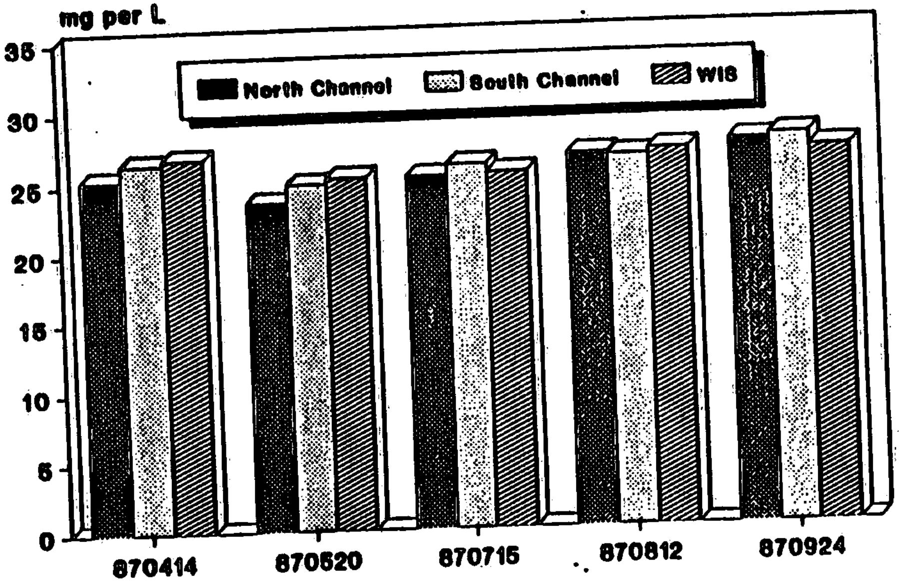
Instantaneous Surface Loading Estimates for TKN to the St. Lawrence River.



(c)

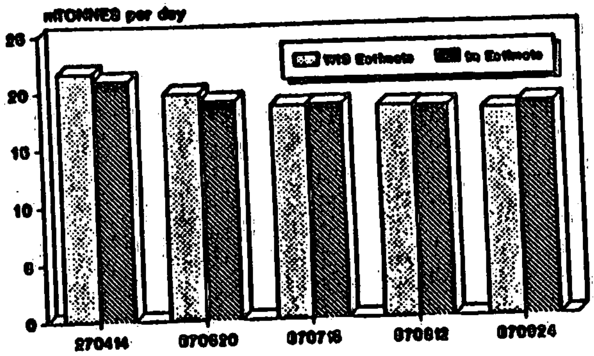
Figure 15

Measured Concentrations of Sulphate.



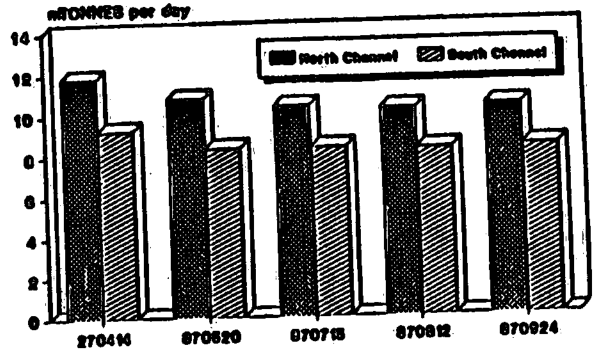
(a)

Instantaneous Loading Estimates for Sulphate to the St. Lawrence River.



(b)

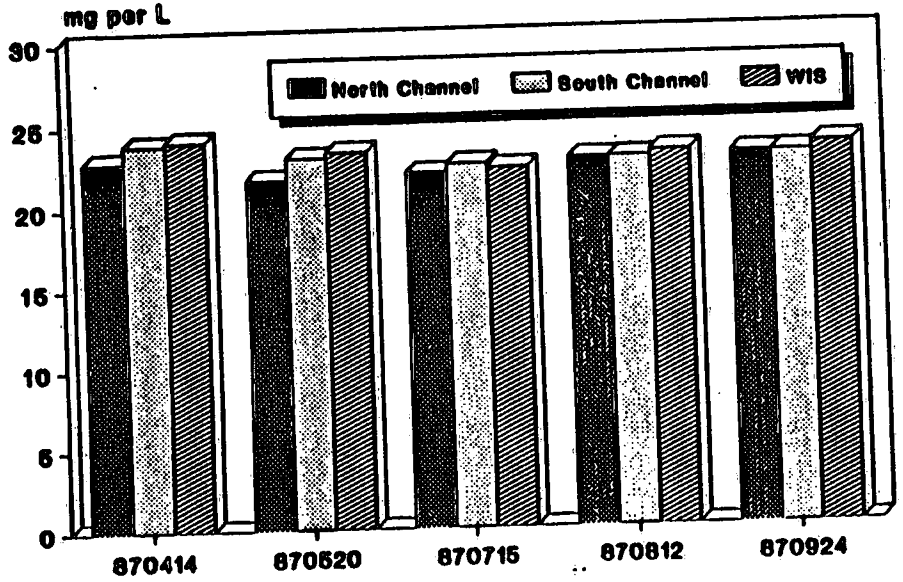
Instantaneous Surface Loading Estimates for Sulphate to the St. Lawrence River.



(c)

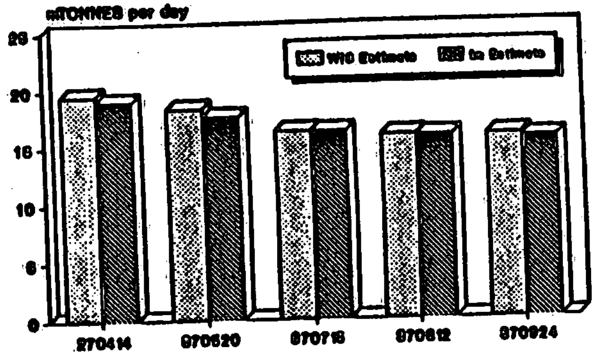
Figure 16

Measured Concentrations of Chloride



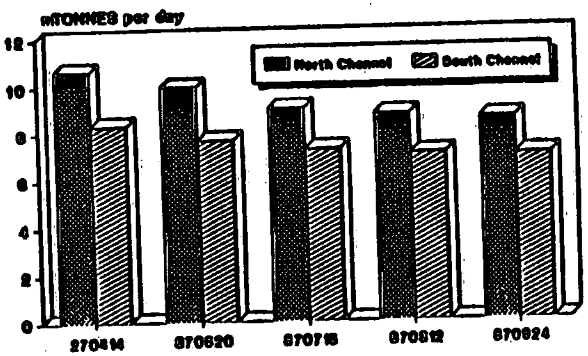
(a)

Instantaneous Loading Estimates for Chloride to the St. Lawrence River.



(b)

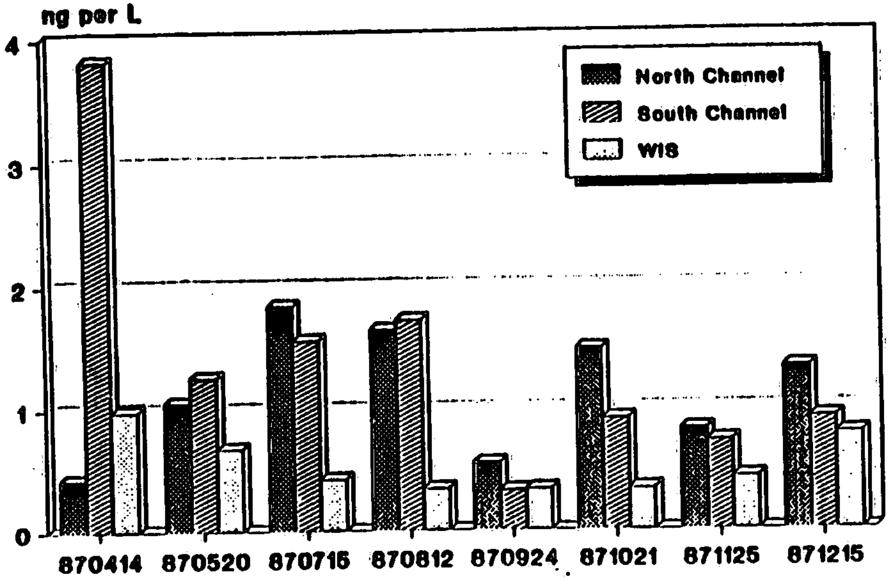
Instantaneous Surface Loading Estimates for Chloride to the St. Lawrence River.



(c)

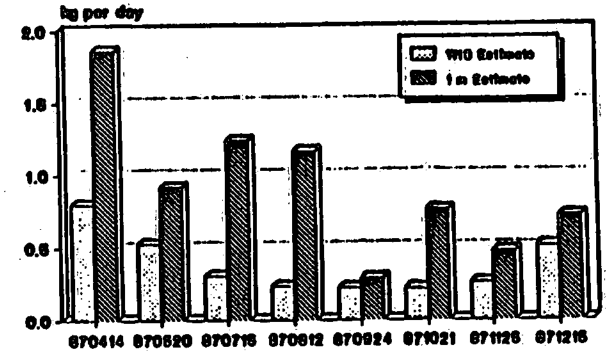
Figure 17

Measured Concentrations of PCBs.



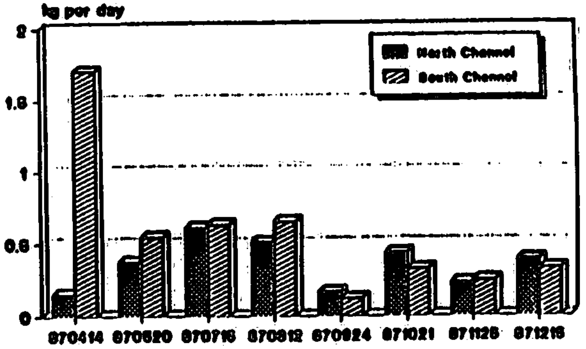
(a)

Instantaneous Loading Estimates for PCBs to the St. Lawrence River.



(b)

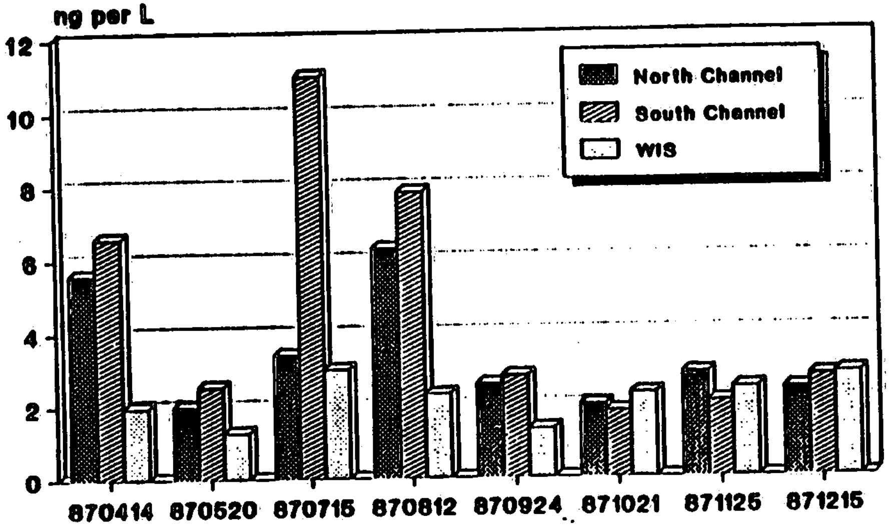
Instantaneous Surface Loading Estimates for PCBs to the St. Lawrence River.



(c)

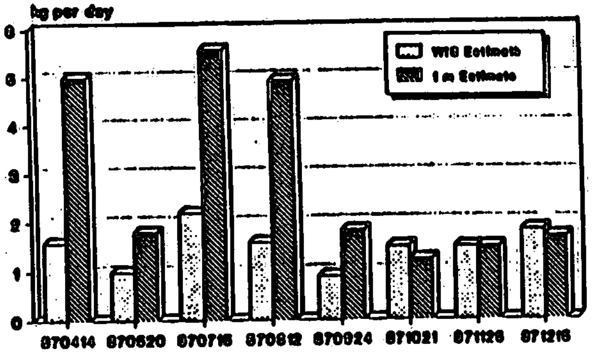
Figure 18

Measured Concentrations of total BHC (a-BHC+Lindane).



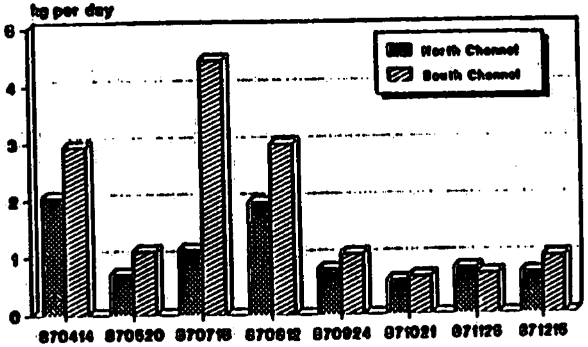
(a)

Instantaneous Loading Estimates for tBHC to the St. Lawrence River.



(b)

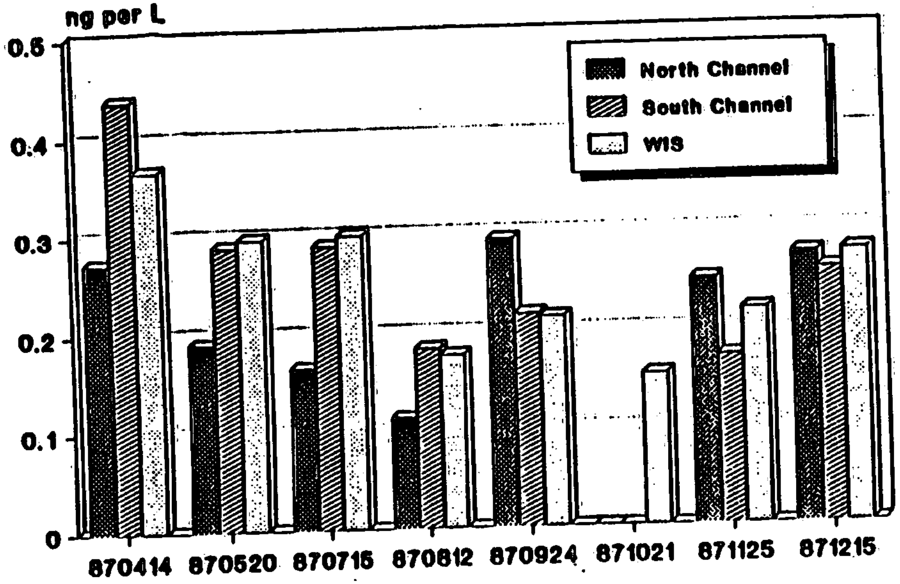
Instantaneous Surface Loading Estimates for tBHC to the St. Lawrence River.



(c)

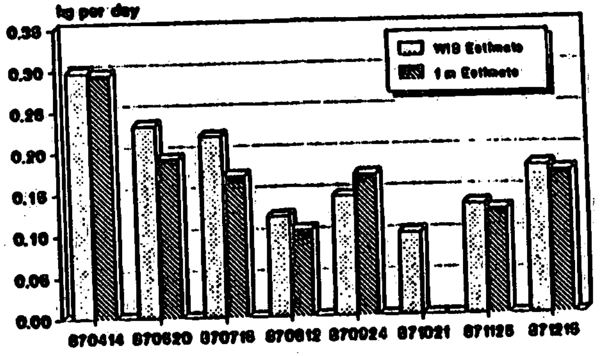
Figure 19

Measured Concentrations of Dieldrin.



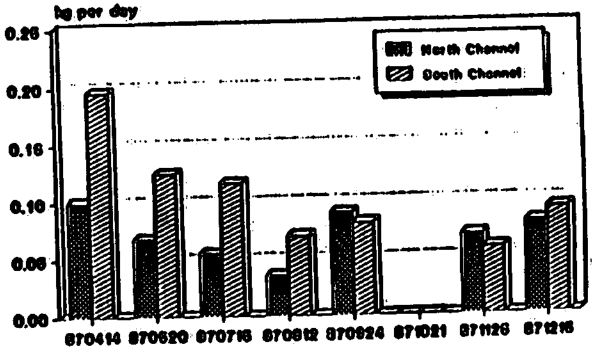
(a)

Loading Estimates for Dieldrin to the St. Lawrence River.



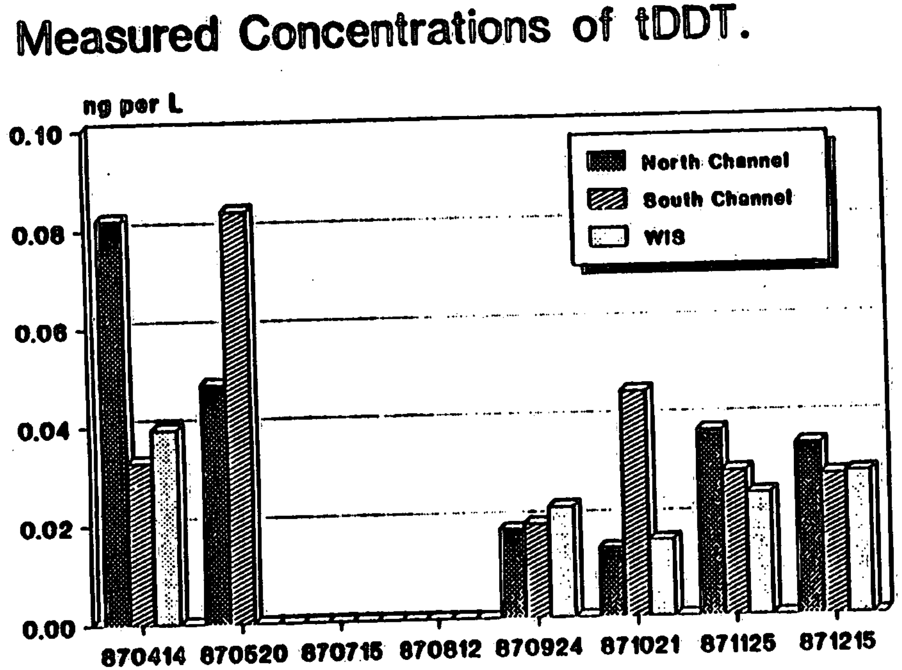
(b)

Instantaneous Surface Loading Estimates for Dieldrin to the St. Lawrence River.

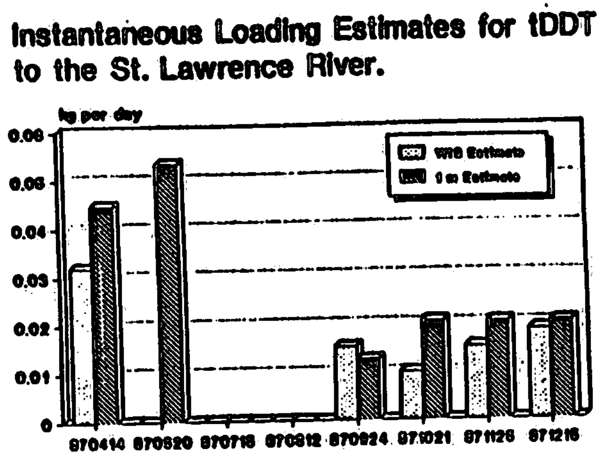


(c)

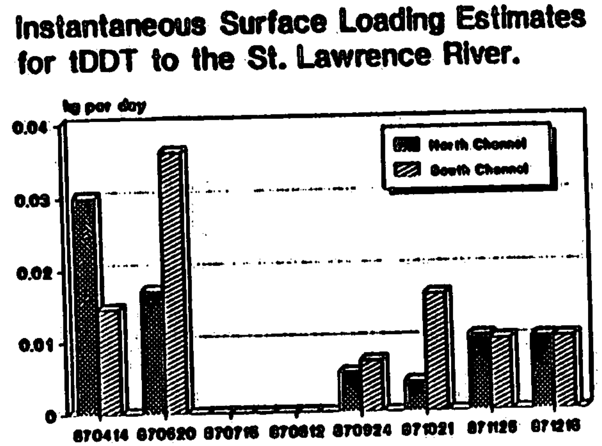
Figure 20


Measured Concentrations of tDDT.

(a)


Instantaneous Loading Estimates for tDDT to the St. Lawrence River.

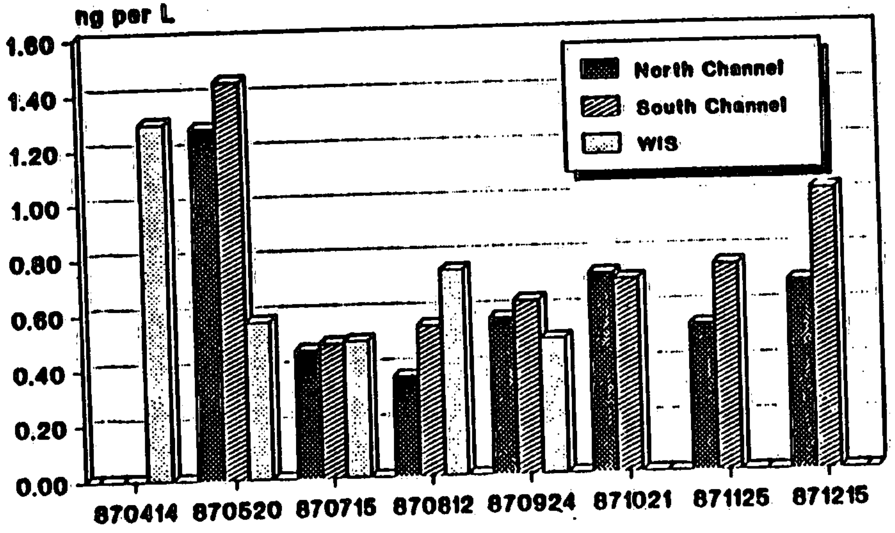
(b)


Instantaneous Surface Loading Estimates for tDDT to the St. Lawrence River.

(c)

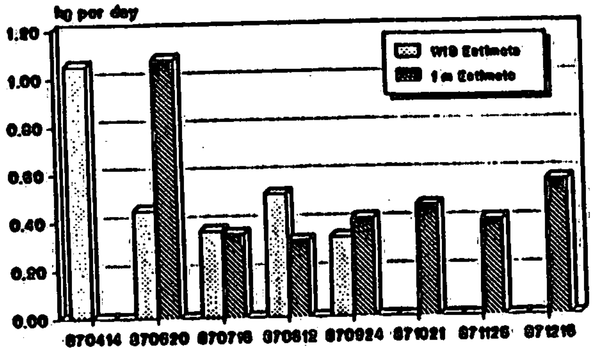
Figure 21

Measured Concentrations of Total Dichlorobenzenes (tDCB).



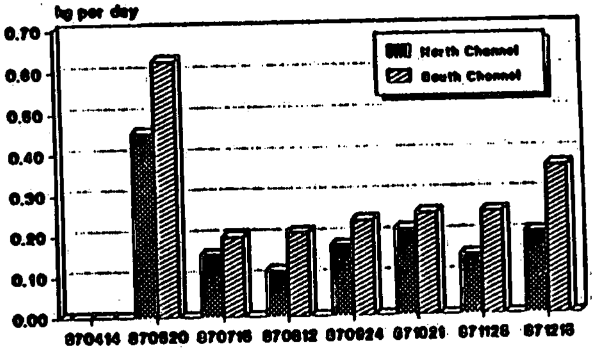
(a)

Instantaneous Loading Estimates for tDCB to the St. Lawrence River.



(b)

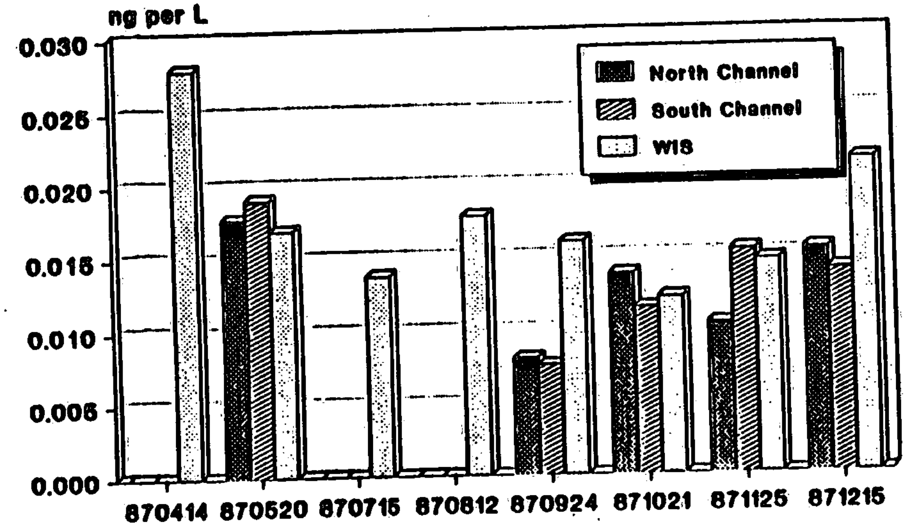
Instantaneous Surface Loading Estimates for tDCB to the St. Lawrence River.



(c)

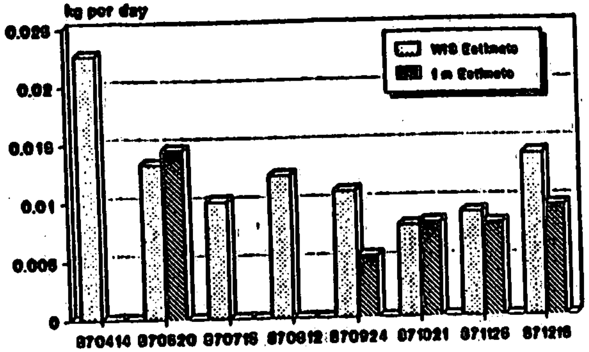
Figure 22

Measured Concentration of Pentachlorobenzene (PeCB).



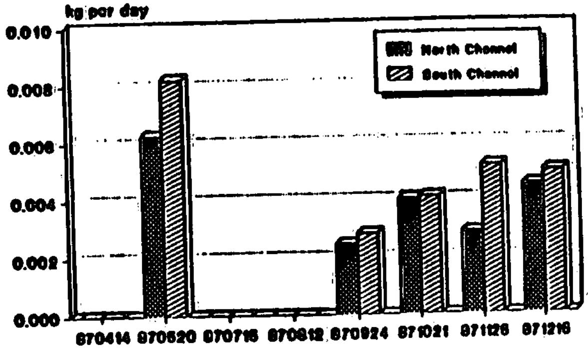
(a)

Instantaneous Loading Estimates for PeCB to the St. Lawrence River.

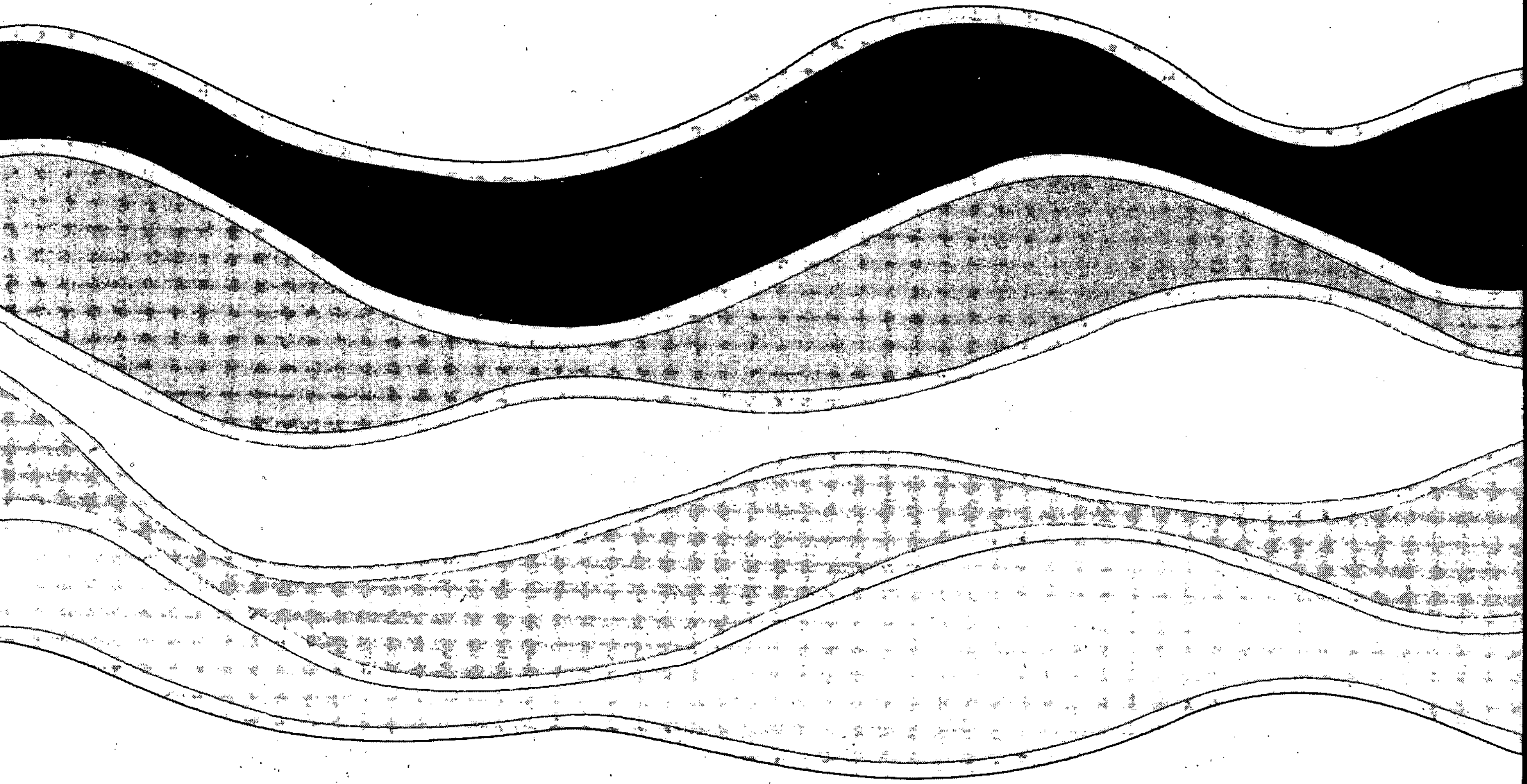


(b)

Instantaneous Surface Loading Estimates for PeCB to the St. Lawrence River.



(c)



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