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WATER EXCHANGE BETWEEN LAKE ONTARIO AND HAMILTON HARBOUR: WATER QUALITY IMPLICATIONS

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MANAGEMENT PERSPECTIVE

This is a joint report prepared by National Water Research Institute (NWRI) and Ontario Ministry of the Environment (MOE) staff, summarizing data collected between 1979-87 by both organizations. NWRI's focus was on the effect of Lake Ontario on Hamilton Harbour, MOE's on the impact of Hamilton Harbour on western Lake Ontario. It was concluded that displacement of the harbour water by Lake Ontario reduces the theoretical hydraulic residence time by about 60% and contributes to the improvement of the harbour water quality through dilution and oxygenation. The beneficial effect of dilution by Lake Ontario water far exceeds contamination of Lake Ontario by Hamilton Harbour water. The latter was found to be minimal compared to that of the Niagara River. This finding may have a potential implication on Canada's negotiations with the U.S. in relation to Great Lakes Water Quality Agreement.

ANALYSE DE GESTION

Il s'agit d'un rapport conjoint préparé par l'INRE et le personnel du ministère de l'Environnement de l'Ontario, et résumant les données recueillies entre 1979-1987 par les deux organismes. L'étude de l'INRE concernait principalement l'effet du lac Ontario sur le port de Hamilton, tandis que l'étude du MDE traitait l'impact du port de Hamilton sur la partie occidentale du lac Ontario. On a conclu que le déplacement de l'eau du port par le lac Ontario réduit le temps de séjour hydraulique théorique d'environ 60 % et contribue à l'amélioration de la qualité de l'eau du port grâce à la dilution et à l'oxygenation. L'effet bénéfique de la dilution par les eaux du lac Ontario compense largement la contamination du lac Ontario par les eaux du port de Hamilton, laquelle est beaucoup moins importante que celle de la rivière du Niagara. Ces résultats peuvent avoir des répercussions possibles sur les négociatios du Canada avec les États-Unis en ce qui a trait à l'Accord sur la qualité de l'eau edea Grands Lacs.

ABSTRACT

Hamilton Harbour is an enclosed body of water situated at the western end of Lake Ontario and containing about 2.8×10^8 m^3 of water, polluted by municipal and industrial effluents. It is connected to Lake Ontario by a ship canal, which facilitates a substantial exchange of water between the two water bodies. Exchange of harbour and lake water through the canal reduces the theoretical hydraulic residence time of the harbour and contributes to improvement of the harbour water quality through dilution and oxygenation. Without it, the Hamilton Harbour water quality situation would be more critical. The beneficial effect of dilution by Lake Ontario far exceeds contamination of western Lake Ontario by Hamilton Harbour water.

RÉSUMÉ

Le port de Hamilton est une nappe d'eau intérieure qui se trouve à l'extrémité occidentale du lac Ontario et contient environ 2,8 x $10^8 m^3$ d'eau polluée par les effluents municipaux et industriels. Il est relié au lac Ontario par un canal navigable qui facilite un échange d'eau considérable entre les deux plans d'eau. L'échange d'eau entre le port et le lac par ce canal réduit le temps de séjour hydraulique théorique du port et contribue à la dilution et à l'oxygénation. Sans cet échange d'eau, la qualité de l'eau du port de Hamilton serait moins bonne. L'effet bénéfique do la dilution par le lac Ontario compense largement la contamination de cette partie du lac par les eaux du port de Hamilton.

INTRODUCTION

Bays, nearshore embayments, land-locked harbours and other enclosed parts of main lake bodies with limited water exchange and collecting runoff and wastewater from the shore areas are believed to protect the main water body of the lake from pollution and act as large stabilization ponds (Matheson 1963, Stepanek 1980). This is true as long as the water exchange with the main lake is limited; however, if it becomes more significant, the impact on water quality in both directions (i.e., embayment-lake and lake-embayment), becomes more pronounced. Exchange flows then act as a loading or as a dilutant. In Lake Ontario, the most important embayment of this kind is Hamilton Harbour.

This report presents selected results of 1979-1983 studies conducted on Hamilton Harbour by Ontario Ministry of the Environment (MOE) and 1987 studies by National Water Research Institute (NWRI) with particular focus on:

1) beneficial effects of water exchange with Lake Ontario on Hamilton Harbour water quality, and

2) potential adverse affect of Hamilton Harbour water on western Lake Ontario.

STUDY AREA AND METHODS

Experimental Site

Hamilton Harbour is located at the western end of the lake. It is triangular, about 8 km east-west and 4.8 km north-south. The harbour contains approximately 2.8×10^8 m^3 of water. Maximum depth is 23 m, and the mean depth is 13 m. It receives drainage from a watershed of 500 km^2. The harbour is polluted by the industries on the highly developed south shore, which use 27 m^3/s of water and return a similar amount of effluent to the harbour, and use the harbour for shipping raw materials and finished products. Municipal utilities use the harbour as a recipient for 4.3 m^3/s of treated wastes (MOE 1985, Poulton 1987). In addition, the harbour receives tributary flows and untreated stormwater runoff estimated at 3.5 m^3/s. Consequently, provincial water quality objectives are exceeded for ammonia and phosphorus in the harbour water. In 1982, copper exceeded the objectives two-thirds of the time, while iron, zinc and cadmium exceeded objectives less frequently. Loadings of phosphorus and nitrogen in 1985 were 609 kg/d and 7,076 kg/d, respectively, resulting in concentration ranges of total P 40 to 200 µg/L and ammonia of 50 to 4,000 µg/L. The impact of these nutrient loadings on harbour eutrophication was discussed by Haffner et al. (1982), and the resulting severe hypolimnetic dissolved oxygen depletion was studied by Polak and Haffner (1978). Contamination by toxic organic compounds (BHC isomers, HCB's, PCB's, and PAH's) is also high (Poulton 1987). For these reasons, the Hamilton Harbour was designated by U.S.-Canada International Joint Commission as an Area of Concern with a remedial action plan to improve the situation underway.

Methods

The impact of Hamilton Harbour on western Lake Ontario and vice versa was studied in a series of experiments in 1982 and 1987 which included current measurements, loading calculations and plume tracking in the lake.

Current measurements: Currents were measured by employing an Aanderaa current meter from the lift bridge at a location near the center of the canal. Preliminary tests using four current meters operated simultaneously showed no significant differences existed between mid-canal currents and those within 2 m of the canal wall. The meters were set to record data (speed, direction and temperature) at two-minute intervals. Meter operation was monitored from the bridge continuously using a "digiprint" printer. This enabled continuous display of current direction. Currents were profiled at

2 m depth increments from the surface to 8 m, with the meter kept at each depth long enough to record two valid sets of data per profile. Between eight and fifteen current profiles were obtained for each survey day; several brief gaps existed in these records due to the bridge being raised for ship passage. This procedure was repeated for several days in each of June, August and October 1982.

Pollutant loading: The above current measurements were combined with an extensive series of chemistry measurements in the canal to provide loading estimates.

Water chemistry was profiled from a boat anchored near the canal wall. A submersible pump was used to supply water to temperature and conductivity cells on board the boat. The water column was profiled at 1-m intervals, continuously while currents were flowing out to the lake and less frequently when inflowing currents (to the harbour) were occurring. In addition, water chemistry samples were taken at 2-m depth intervals about once every two hours during outflowing currents. These were analyzed for ammonia, total Kjeldahl nitrogen, nitrate + nitrite-N, total phosphorus, filtered reactive phosphorus, chloride, turbidity, suspended solids, copper, iron, manganese and zinc. (For methods see MOE 1986 procedures.)

Pollutant loads to and from the harbour were calculated separately for each 2-m depth "layer" in the canal. The load for each layer was considered to be the cross-sectional area of the layer, multiplied by the velocity of flow and the pollutant concentration within it.

Since currents moving towards the lake were assigned positive values and those toward the harbour were given negative values, the loads to and from the lake are similarly designated as positive or negative. The net load is the algebraic sum of all layer loads, including both outflowing and inflowing conditions. The total load to the lake is the sum of all loads flowing to the lake and does not take into account return flows to the harbour. Average total loads were calculated as the sum of all total loads for a survey day, divided by the number of profiles obtained. Zero values were excluded from these calculations.

Plume tracking: Plume trackings were conducted in Western Lake Ontario between June and October 1982 to assess the impact of Burlington Canal on the western end of Lake Ontario. The plume-tracking vessel was equipped with a surface-mounted pump, drawing water from an intake attached to a towed "fish". This enabled a continuous record of temperature, conductivity and fluorescence to be recorded by on-board sensors. Fluorescence was calibrated to give a continuous chlorophyll-a record. This vessel proceeded along a series of parallel tracks 0.5 to 1 km apart, until it was at a distance where the on-board parameters indicated spatially uniform conditions (plus one track to a point at least 5 km from the canal). Frequent stops were made for sample collection, both within the main plume as indicated by the on-board instruments, and outside, for comparison purposes. At these locations, samples were collected at the surface, 3 m (August and October only) and 6 m water depths, for analysis of the same parameters measured in the canal samples. Further details of the field program are given elsewhere (MOE 1986).

In addition, self-recording current meters were moored at four locations in the study area. These instruments were moored 3 to 6 m from the water surface as this layer is considered representative of the harbour plume. The meters were operated from May 1982 to November 1983, and recorded current speed and direction and water temperature (Kohli 1984, MOE 1986).

RESULTS AND DISCUSSION

Exchange Flow Between Hamilton Harbour and Lake Ontario

Construction of the Burlington Ship Canal represented a major change in the water budget of the Hamilton Harbour. The mass exchange between Lake Ontario and Hamilton Harbour through the large canal (840 m long, 107 m wide, 9.5 m deep) became a complex time variant process. Matheson (1963) provided the first evidence of stratified flow in the canal by detecting a layer of warm harbour water flowing toward the lake at the surface above a layer of colder lake water flowing into the harbour. Dick and Marsalek (1973) confirmed Matheson's observations and also found that a unidirectional whole channel flow caused by water level differences dominated in the unstratified period from September to June.

Later, the work of Palmer and Poulton (1976) and Kohli (1979) indicated that the flow pattern is more complex than that assumed by Dick and Marsalek (1973). Palmer and Poulton (1976) noted that water movements were strongly influenced by lake and harbour oscillations which produced temporary displacement of the thermocline in both the harbour and canal due to internal waves. They also observed complex flow regimes in the canal, with some evidence for temporary periods of three-layer flow (Figure 1). The net exchange was estimated to be of the order of 1% of the harbour volume per day. This is very important for maintaining water quality in the harbour because the harbour water, with its higher dissolved solids content, is discharged to the lake while better quality and oxygenated lake water flows into the harbour.

Kohli (1979, 1984) computed exchange through the Burlington Canal. Table 1 presents the data for the period of May 1979 to April 1980, covering stratified as well as isothermal conditions. The table illustrates that the water levels were maintained over the year with the normal short-term fluctuations. The mean flow towards the harbour was 2.7×10^6 m^3/d while 3.3×10^6 m^3/d flowed towards the lake. This accounted for total exchange of 1.1% of harbour volume per day, with the net water flow of 0.23% of harbour volume per day towards the lake (equivalent to the total input to the harbour).

Klapwijk and Snodgrass (1985) developed a model based on total dissolved solids (TDS) and temperature as conservative substances. TDS is diluted both in the epilimnion and the hypolimnion when Lake Ontario water enters the Harbour and this dilution rate combined with temperature observations and diffusion calculations allowed the volumes of exchanged water to be estimated. Epilimnion exchanges were equivalent to one to five times the net water inflow from industrial and municipal sources (Q) and hypolimnion exchange rates were equivalent to zero to fifteen times Q. The model results suggest that stratification enhances flushing by retention of colder Lake Ontario water in the hypolimnion.

Dilution and Oxygenation Effect of Water Exchange: Impact on Hamilton Harbour

There are substantial differences in water quality of Hamilton Harbour and western Lake Ontario: Hamilton Harbour is a contaminated hypereutrophic water body (Haffner et al. 1982, MOE 1985), with high chlorophyll-a, phosporus and ammonia levels, low Secchi transparency, high algal standing crops (up to 8×10^6 μm^3/mL) and severe hypolimnetic oxygen depletion and sediment contamination. On the other hand, western Lake Ontario is oligo- to mesotrophic, with high Secchi transparencies and low chlorophyll and algal crop values (about 1×10^6 μm^3/mL; Table 2).

As it follows from Kohli's (1979, 1984) and Klapwijk and Snodgrass (1985) estimates, about 1% of the Hamilton Harbour volume is exchanged by Lake Ontario water every day, while the net flow toward the lake is 0.23 to 0.5% of the harbour volume per day.

This corresponds to a theoretical displacement of Hamilton Harbour water by Lake Ontario water more than three times a year and decrease of hydraulic detention time to less than 40% of the value before construction of the canal. In practice, epilimnetic exchange is more significant than hypolimnetic (Klapwijk and Snodgrass 1985), and the area affected by exchange is limited to the lower third of the Hamilton Harbour. On a very conservative side, we can assume the dilution effect to be at least 30 to 50% (as opposed to theoretical potential effect of 360%). This means that the actual concentrations corresponding to loading figures would be 1.3 to 1.5 times higher (or 3.6 times higher if there was no water exchange). This puts pollution of Hamilton Harbour into a even more critical situation: what we measure there is actually much less than what would be there in the absence of exchange with Lake Ontario.

One of the major water quality problems of Hamilton Harbour has been a severe hypolimnetic oxygen depletion and extensive periods of anoxia of bottom waters during summer thermal stratification. Oxygen demands in the hypolimnetic waters of the harbour during the summer exceed the oxygen supplies. Several attempts have been made to artificially aerate or oxygenate the harbour to improve its oxygen budget (MOE 1978, T. Murphy, pers. comm.). Polak and Haffner (1978) estimated that over 80% of the oxygen supplied to the harbour was used by the water column, while sediments consumed about 18%. They concluded that while atmospheric reaeration provided the main source of oxygen, a considerable amount of oxygen enters the lake through the ship canal from oxygen-rich Lake Ontario. This amount equals the amount of oxygen produced by photosynthesis. Thus water exchange with Lake Ontario acts as a natural (and free) oxygenation system. Harris _et al._ (1980) presented vertical fluxes of oxygen computed from a layer-to-layer model, with maximum oxygen fluxes as high as 15 g O_2 m^2/d at the surface and 6.5 g O_2 m^2/d at 18 m below the surface. Infusion of O_2 rich lenses of Lake Ontario water reduces significantly the oxygen depletion rates in both epilimnion and hypolimnion of Hamilton Harbour. Without this infusion, the harbour would have become anoxic at a much faster rate than observed. Indeed, if we assume that the incoming water from Lake Ontario contains 10 mg/L O_2, then the amount contained in typical flows in Klapwijk and Snodgrass (1985) is equivalent to 30% of the net observed oxygen depletion rate.

The annual thermal stratification process of Hamilton Harbour is affected by frequent perturbations of thermal structure (Sephton and Harris 1984, Zarull 1979). This is noticeable mainly in the oxygen regimes of areas of Hamilton Harbour unaffected by the exchange (western and central part) and those affected (eastern part, near the Burlington Canal). Figure 2 presents characteristic oxygen distribution curves and shows how limnological conditions are affected by the Lake Harbour exchange. The upper profiles measured by NWRI's water quality profiler (Ford and Charlton 1984) near the entrance of the canal to the harbour show the intrusion of colder water with more oxygen and less conductivity from Lake Ontario. These observations are consistent with information on double layered canal flow (Klapwijk and Snodgrass 1985, Palmer and Poulton 1976). The lower profiles from the centre of the harbour show the net effects of oxygen consumption and mixing of the lake and harbour water. The signature of Lake Ontario water is seen in the lowered conductivity of the hypolimnion layer. Since this layer is cut off from the surface loading after stratification, conductivity or total dissolved solids are diluted relatively more than in surface waters. Minor thermoclines occur in the normal hypolimnion layer and these lenses of Lake Ontario water are also seen in the oxygen, conductivity and transmissivity profiles. Exchange water does seem to ameliorate low hypolimnion oxygen conditions as shown by the upper part of the hypolimnion oxygen curve. The input of cold Lake Ontario water must help offset the natural warming and incorporation of the hypolimnion into the epilimnion. This may have a significant effect on maintaining hypolimnion volume and prolonging stratification. The continuous frequent inputs of dissolved oxygen may also significantly lessen periods of anaerobic conditions in the hypolimnion of Hamilton Harbour.

In addition to improving oxygen conditions in Hamilton Harbour, water exchange with Lake Ontario has a diluting and oxygenating effect on other contaminants. The most abundant of them is ammonia, originating mainly in the Hamilton sewage treatment plant (MOE 1985). Figure 3 presents an aerial distribution of ammonia in Hamilton Harbour in May 1987. It can be seen that the diluting and oxidizing effect of Lake Ontario water extends significantly into the Hamilton Harbour (shaded area). Consequently, ammonia levels originating mainly in the southeastern arm (Windermere Basin) are substantially reduced within the zone of influence. This areal distribution of ammonia is similar and lies within the predicted maximum zone of effect due to lake-harbour excursions (Kohli 1984).

Klapwijk and Snodgrass (1986) estimated that 53% of ammonia is oxidized in the harbour and 47% is discharged to Lake Ontario. Twenty-eight percent of nitrification occurs in the sediments, and 50% of oxygen consumption is due to nitrification.

Together with the oxygen inputs, water exchange between the harbour and lake also plays a role in preventing the release of substances such as iron and phosphorus from the sediments during mid-summer anoxia. Poulton (1987) showed depth-time distribution of iron and manganese at a central harbour location. Although dissolved manganese was observed to accumulate in the hypolimnion, there was little if any iron accumulation. The existence of mixed redox potentials, including the $NO_3/NO_2/N_2/NH_3$ system is thought to stabilize the redox potential of the sediment-water interface at a value sufficient to allow denitrification (MOE 1985) and manganese reduction, but not low enough to allow iron reduction.

It is fortuitous that the exchange occurs in the same area as the major wastewater discharges as this may result in some "short circuit" discharge to the lake as well as immediate dilutions of loading effects in the harbour.

It can be concluded that water exchange with Lake Ontario facilitated by the Burlington Ship Canal is definitely a positive factor contributing to significant improvement of Hamilton Harbour water quality. Without it, the Hamilton Harbour water quality situation would be even more critical than it is now.

Impact of Hamilton Harbour on Western Lake Ontario

According to Kohli (1979), a net flow of about 0.5% of Hamilton Harbour volume enters western Lake Ontario daily. Considering the high level of pollution of Hamilton Harbour, this would usually represent a significant input of pollutants to the lake.

Figure 4 shows a typical succession of current profiles for summer stratification as observed on August 26, 1982. These show a progression from pulsed unidirectional "plug" flow in the morning (panel (a)) to stratified flow (outflowing harbour water overlying inflowing lake water; panels (b) and (c)) which persisted for most of the day, but returning to unidirectional flow late in the afternoon.

This stratified flow was most prevalent in August, although it was also observed on one occasion in October. In June, thermal stratification was not sufficiently advanced to permit stratified flow to persist for more than about an hour at any one time; other time periods were characterized by unidirectional "plug" flow, whose direction alternated approximately every five hours in response to the principal longitudinal seiche of Lake Ontario (Palmer and Poulton 1976, Kohli 1979).

The results for pollutant loadings (Table 3) show that, in general, total loads are variable in mass and direction, both within a survey day and from one day to another. In the majority of profiles, the net transport of pollutants was from the harbour to the lake; in only 10 of 38 was the trend clearly towards the harbour. The latter condition was found throughout the survey period and did not appear to be associated with a particular season or time of day.

Table 3 indicates the 1982 loadings to and from the harbour for some representative parameters. These were calculated excluding results representative of data collected during or immediately after reversals. Table 3 also includes loadings from Niagara River to Lake Ontario (from IJC 1985, Kuntz 1984). In all cases, the amount of contaminants contributed by Hamilton Harbour to Lake Ontario is relatively small (compared to the loadings from the Niagara River; MOE 1986). The 1982 net loadings to Lake Ontario are similar in magnitude to 1979 values (MOE 1985).

Monthly net resultant current vectors from the current meter studies are shown in Figure 5. These resultants are vector averages of currents going in all directions; it should be noted that maximum monthly speeds are of the order of 15 to 30 cm/s but persist for relatively short times (minutes to hours). In addition, the current speed at the surface may be at least twice the measured values at 3 to 6 m below the surface and the direction may differ by up to 30°. At any rate, the results indicate an overall clockwise circulation for the study period, a result consistent with the findings (Pickett and Dessett 1979) of large counterclockwise gyres in western Lake Ontario.

Figure 6 illustrates the extent (1 to 5 km) of water quality (conductivity and chlorophyll) plumes from the Burlington Canal. Included also are the mean current speed and direction obtained from the current meter records for that day.

Good agreement between the plume development and water circulation patterns is apparent. The water quality surveys were carried out on six days (June 29, 30; August 24, 26; October 22, 23). Of the survey days, current circulations exhibited clockwise movements for three days, counterclockwise movements for two days and eddy type movements on one day (June 30). The eddy-type movements appeared to take the chlorophyll plume eastward (see Figure 6b). In addition, on one survey date for which counterclockwise circulation was observed (October 23), the conductivity plume was observed to approach the Hamilton Water Treatment Plant (WTP) intake (see Figure 6d).

Since the water column during October is isothermal, the water currents at surface and lake bottom may be moving in phase. The impact of the surface plume from the Burlington Canal to the area of the Hamilton WTP intake, therefore, reflects a potential impact at the intake level. The plume from the Burlington Canal reached the Hamilton WTP intake on one occasion (October 23) during the present study. However, no such impact of the Burlington Canal on the Burlington WTP intake was observed.

The plume trackings showed better surface dilution processes compared to other coastal regions. However, the better dilution is not attributed to lake dynamics, but to the dissipation of the turbulent energy of the Burlington Canal discharge. Conductivity and chlorophyll were used as tracers; as chlorophyll levels may increase due to photosynthesis in lake waters during daylight, chlorophyll is not considered to be a reliable tracer.

Ammonia was found to be a very sensitive indicator of plume conditions even more so than conductivity. This is not surprising, since the average surface harbour concentration was over 50 times the average lake background surface value, and even higher in May and June due to the spring build-up of ammonia loadings to the harbour when biological activity is minimal.

Ammonia data for June 30 (Figure 7a) show considerable elevation at points A (surface) and E (surface and 6 m). Elevated ammonia was also found at point G, the northern extremity of the conductivity and chlorophyll plumes (Figures 6a,b).

On August 24 (Figure 7b), severe elevation of ammonia concentrations was found throughout the conductivity plume (Figure 6c), including points I and J, which are on the edge of the conductivity plume. These latter points also showed higher concentrations of ammonia at 3 m depth than were observed at points closer to the canal. The sensitivity of ammonia as a plume tracer is also shown by the results at point B (surface), well beyond the conductivity plume. Even the background point A had a slight elevation at surface to 6 m. These data clearly indicate a potential for impingement of the harbour plume at the Burlington Water Treatment Plant (WTP) intake (point J, less than 1 km from the intake), and even at the Hamilton WTP intake (very close to point B). Recent aerial distribution of ammonia (May 1987) was presented in Figure 3 and confirms these conclusions.

The surface plume from the Burlington Canal was tracked to the Hamilton WTP intake site on one occasion. This may also impact at the intake level due to the presence of the isothermal conditions in the lake during October. No such impact of the Burlington

Canal on the Burlington WTP intake was observed during the present study. There are, however, occasional visual observations of a plume towards the Burlington WTP. Based on this minimal information, the potential plume impingements on the WTP intakes will occur rarely and with only a slight increase in tracer concentration over background. The impact on Hamilton Harbour in western Lake Ontario can be therefore considered minimal. However, additional studies are necessary to confirm impact on WTP intakes.

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Table 1. Hamilton Harbour water budget 1979-1980 (Flow x 1000 m^3/d)

	To Lake	To Harbour	Net to Lake	Total Input	(Q-N)	Equivalent Water Volume Fluctuation**	Residence* Time (days)
	L	H	N	Q	(Q-N)	W	R
May 79	2112	1696	416	612	+196	+98	133
Jun 79	3234	2646	588	521	-67	-29	87
Jul 79	2464	2016	448	397	-51	-83	114
Aug 79	2844++	2327++	517	458	-59	-71	98
Sep 79	2690++	2201++	489	433	-56	-37	104
Oct 79	2651++	2169++	482	427	-55	-69	106
Nov 79	3784	3096	688	609	-79	-110	74
Dec 79	4648	3803	845	748	-97	-8	62
Jan 80	4769	4268	501	824	+223	+16	59
Feb 80	2766	2323	443	479	+36	+20	101
Mar 80	3794	2649	1145	1047	-98	-10	74
Apr 80	4032	2844	1188	1296	+108	+287	69
Total	39738	32038	7750	7751	+1	-3	1081
Mean	3316	2670	646	646	0	0	90

* Residence time = harbour volume/flow rate to lake (L).
** Equivalent harbour volume fluctuations due to water level fluctuations.
- Harbour water level decreases.
+ Harbour water level increases.
++ Estimated flows.

Harbour volume = 2.8 x 10^8 m^3; harbour area = 21.5 x 10^6 m^2; mean harbour depth = 13 m.

Table 2. **Comparison of some water quality parameters in western Lake Ontario and Hamilton Harbour. Surface, 1982 (MOE 1986)**

Parameter	Western Lake Ontario (Background Location) Mean Concentration	Western Lake Ontario (Background Location) Standard Deviation	Hamilton Harbour (Station 258) Mean Concentration	Hamilton Harbour (Station 258) Standard Deviation
NH_3-N (µg/L)	0.031	0.025	1.661	0.892
TKj-N (µg/L)	0.312	0.187	2.559	1.177
NO_3+NO_2-N (µg/L)	0.306	0.079	2.049	0.390
TP	0.013	0.002	0.070	0.025
Chlorophyll	4.2	2.75	25.3	15.8
Cl (mg/L)	26.1	1.5	68.3	15.7
Turbid. (FTU)	1.52	0.69	3.00	1.07
Suspended Solids (mg/L)	1.11	0.70	3.41	1.36
Conduct. (µmhos/cm)	333	23.2	551	57.8

Table 3. 1982 pollutant loadings from Hamilton Harbour

Parameter	1982 Gross Estimated Load to Lake Ontario (10^6 kg/yr)	1982 Gross Estimated Load from Lake Ontario to Hamilton Harbour (10^6 kg/yr)	1982 Estimated Net Load to Lake Ontario (10^6 kg/yr)	1979 Net Load to Lake Ontario (10^6 kg/yr)	1982 Load to Lake Ontario from Niagara River (10^6 kg/yr) (IJC 1985, Kuntz 1984)
NH_3-N	3.666	-2.056	1.610	-	-
Total N	9.489	-5.311	4.178	5.5	49.3
Total P	0.142	-0.076	0.066	0.122	4.87
FRP	0.099	-0.063	0.036	-	-
Chloride	137.035	-86.165	50.870	-	-
Suspended Solids	10.054	-6.492	3.562	5.8	2100.0
Copper	0.011	-0.023	-0.012	-	0.41
Iron	0.632	-0.558	0.074	0.194	79.4
Manganese	0.093	-0.076	0.017	-	4.0
Zinc	0.046	-0.037	0.009	-	0.61

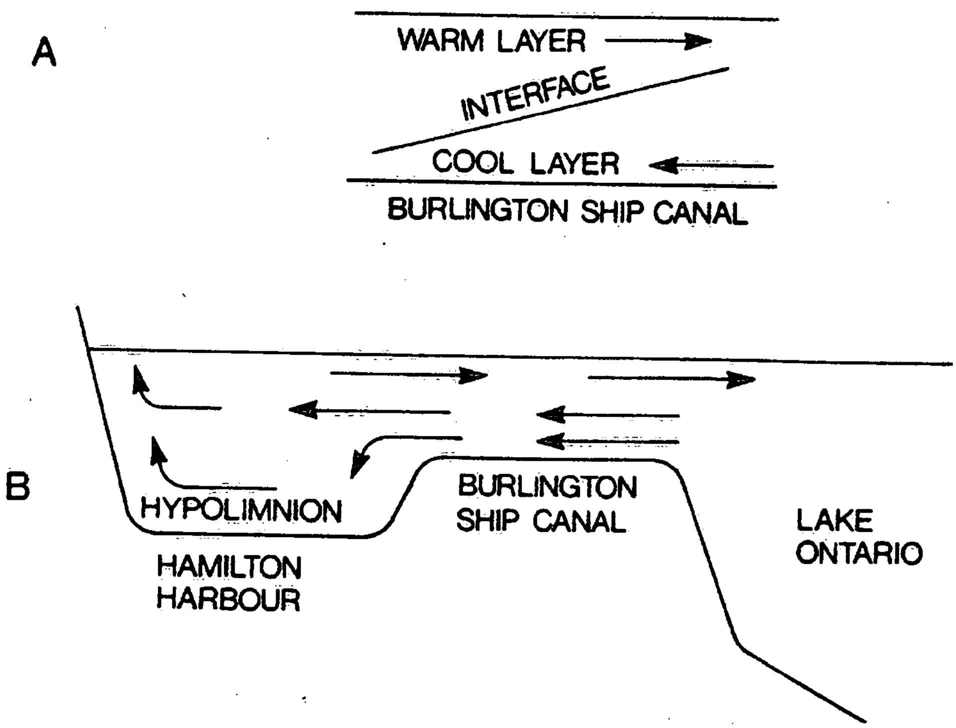

Fig. 1 Simplified models for water exchange between Hamilton Harbour and western Lake Ontario. A- Dick and Marsalek's (1973) model; B-Klapwijk and Snodgrass's (1985) model.

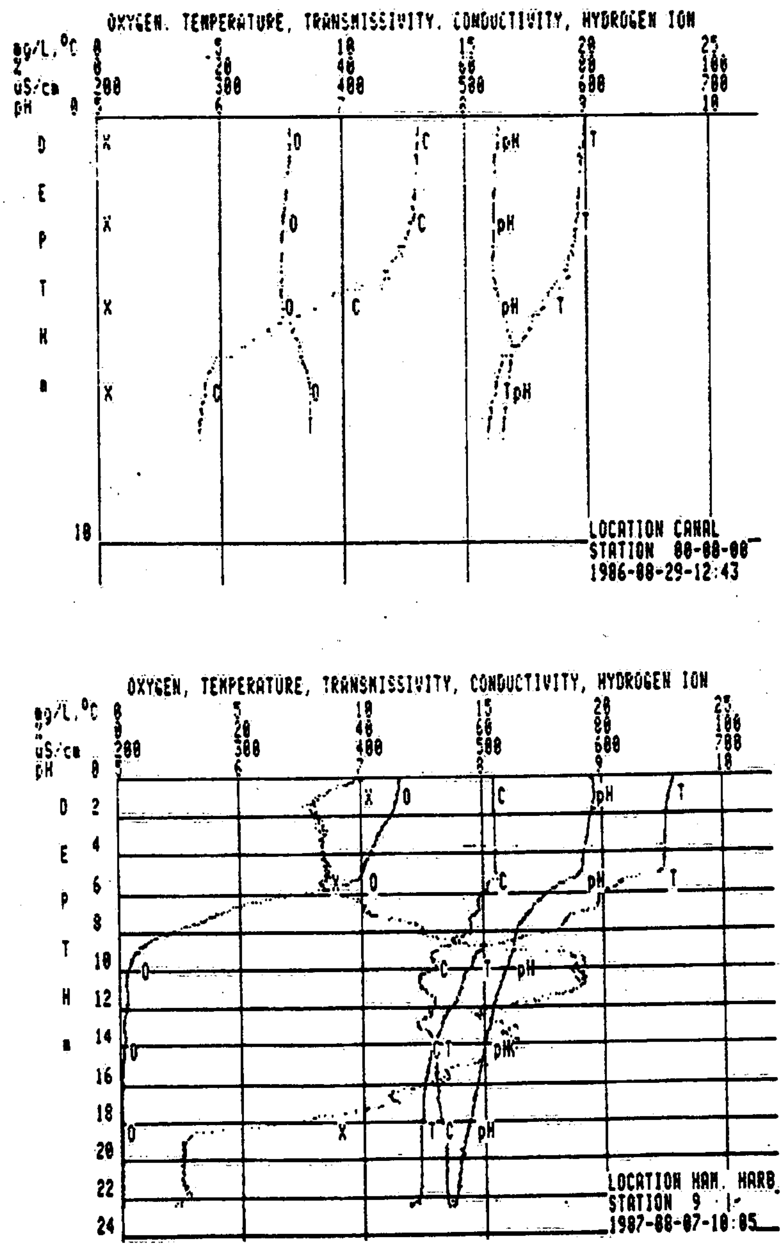

Fig. 2 Profiles of oxygen (O), temperature (T), hydrogen ion (pH), light transmission (X), and conductivity (C) in Hamilton Harbour. Upper panel is from the canal entrance to the Harbour. Lower panel is from the centre of the harbour.

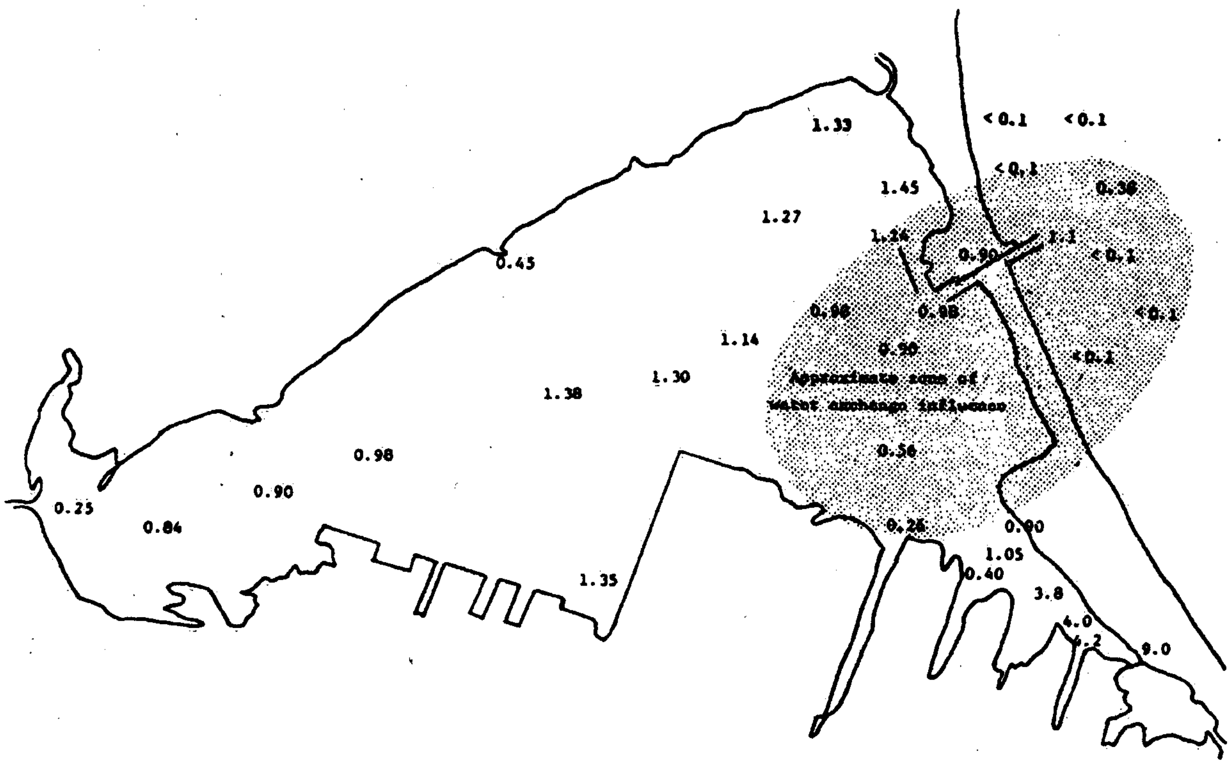

Fig. 3 Aerial distribution of total ammonia in the surface water of Hamilton Harbour (May 27, 1987).

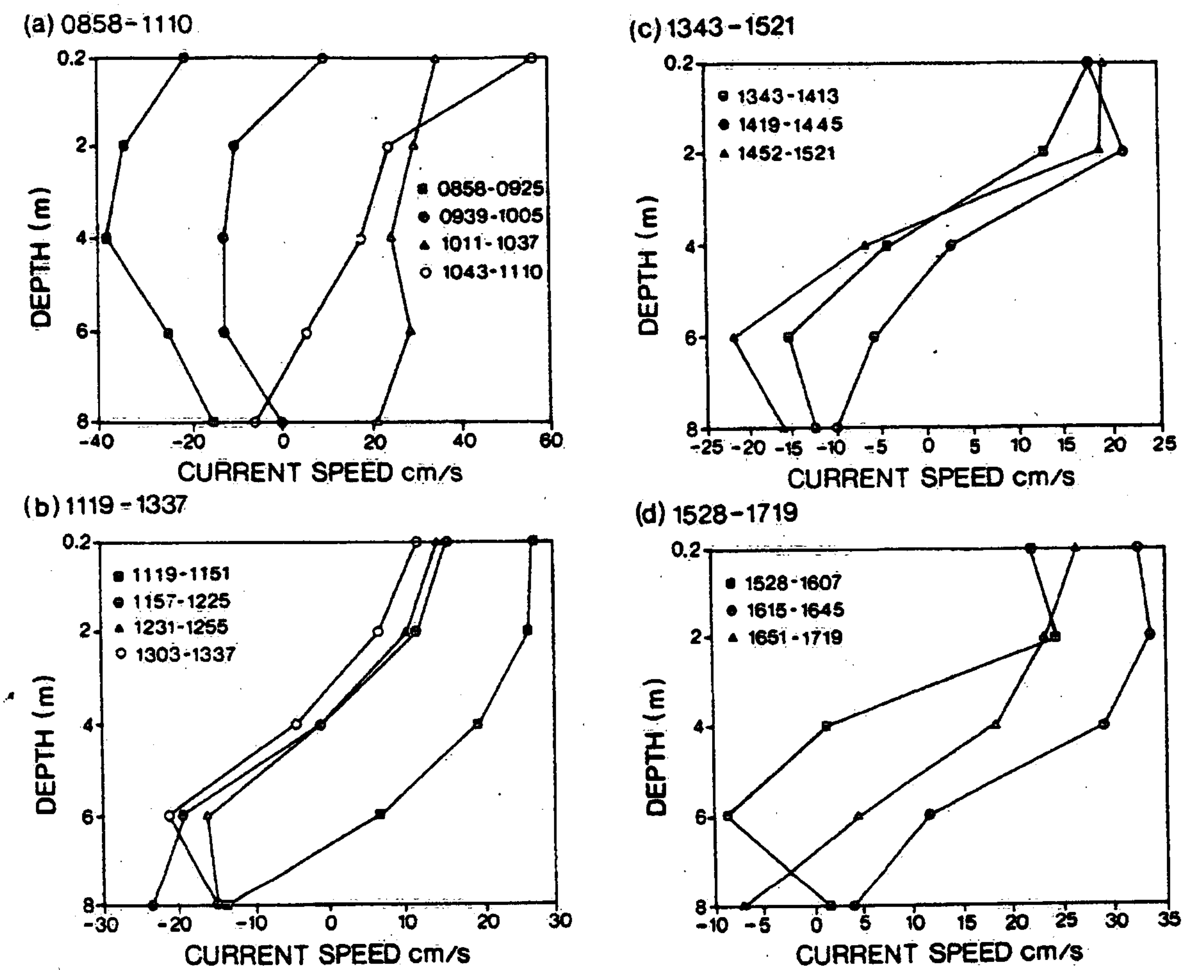

Fig. 4 Depth profiles of currents in Burlington Ship Canal August 22, 1982 (from MOE 1986).

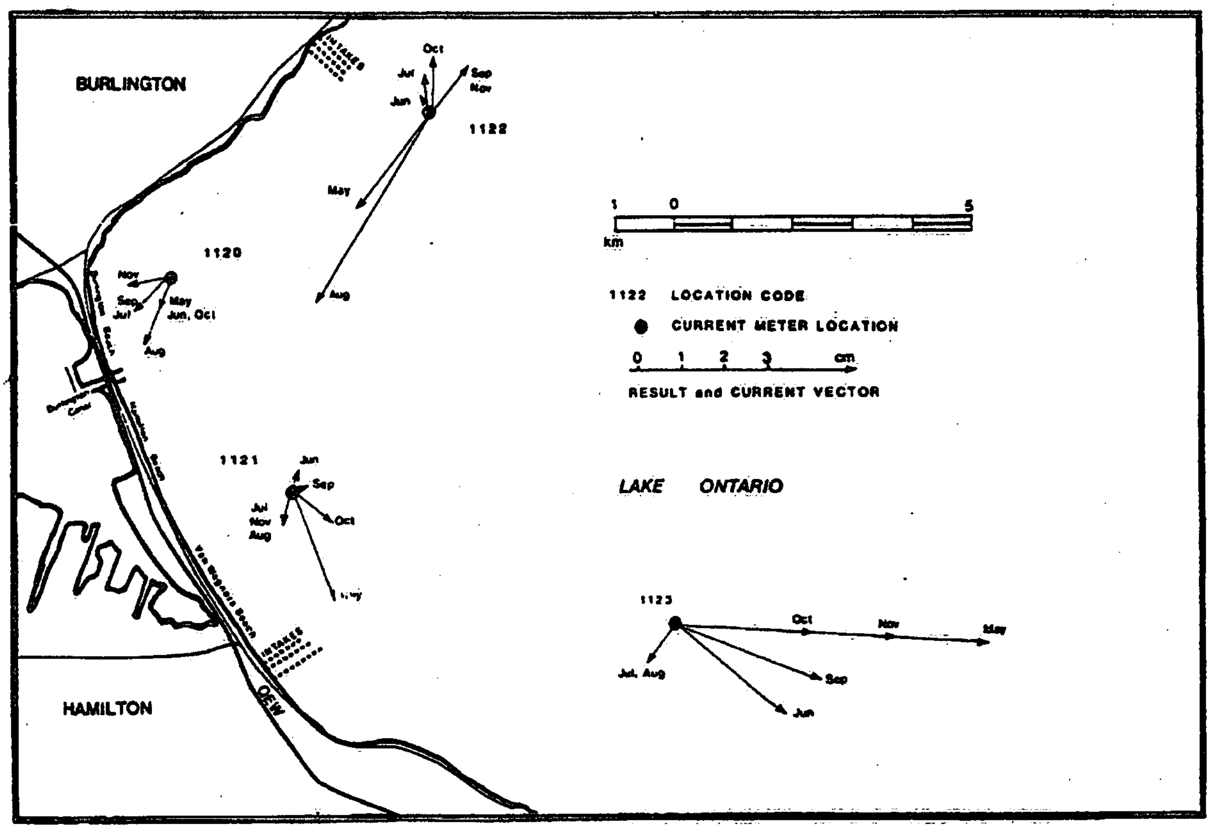

Fig. 5 Currents in western Lake Ontario, June to November 1982 (from MOE 1986).

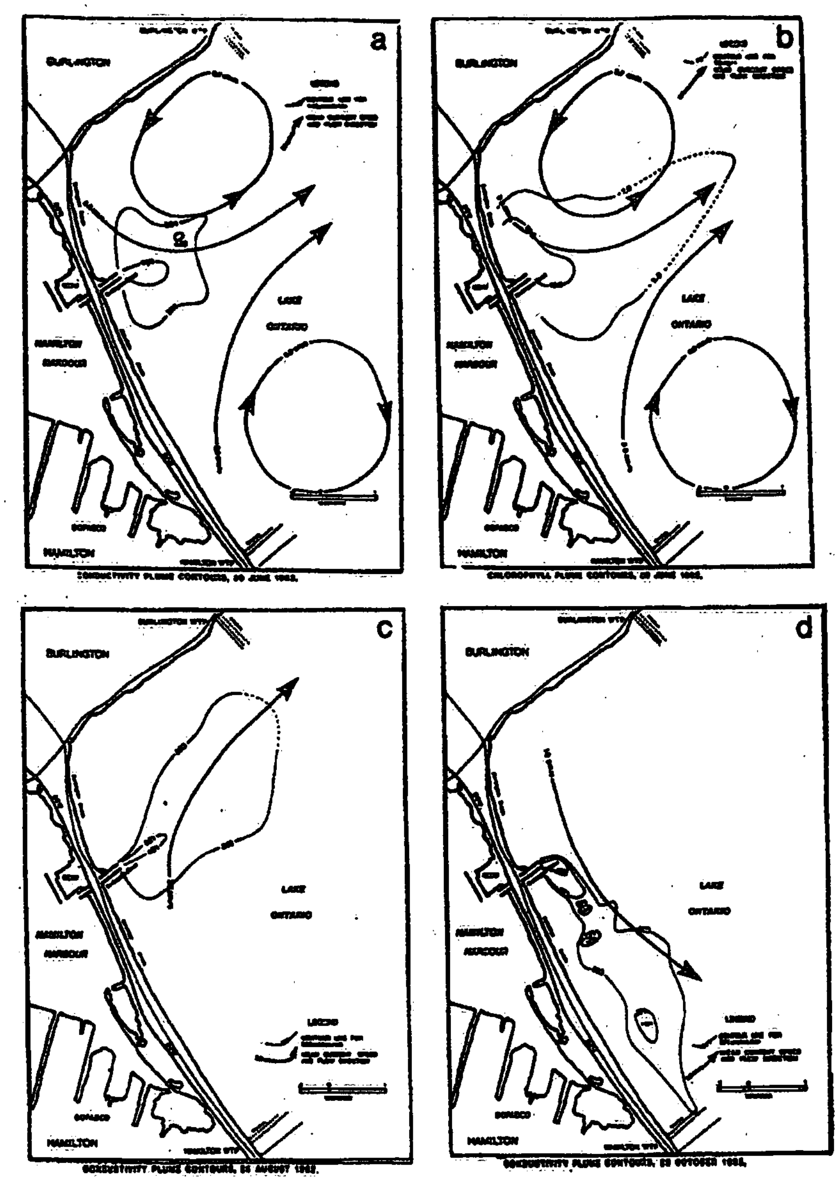

Fig. 6 Characteristic conductivity and chlorophyll plumes in western Lake Ontario in the summer of 1982 (from MOE 1986).

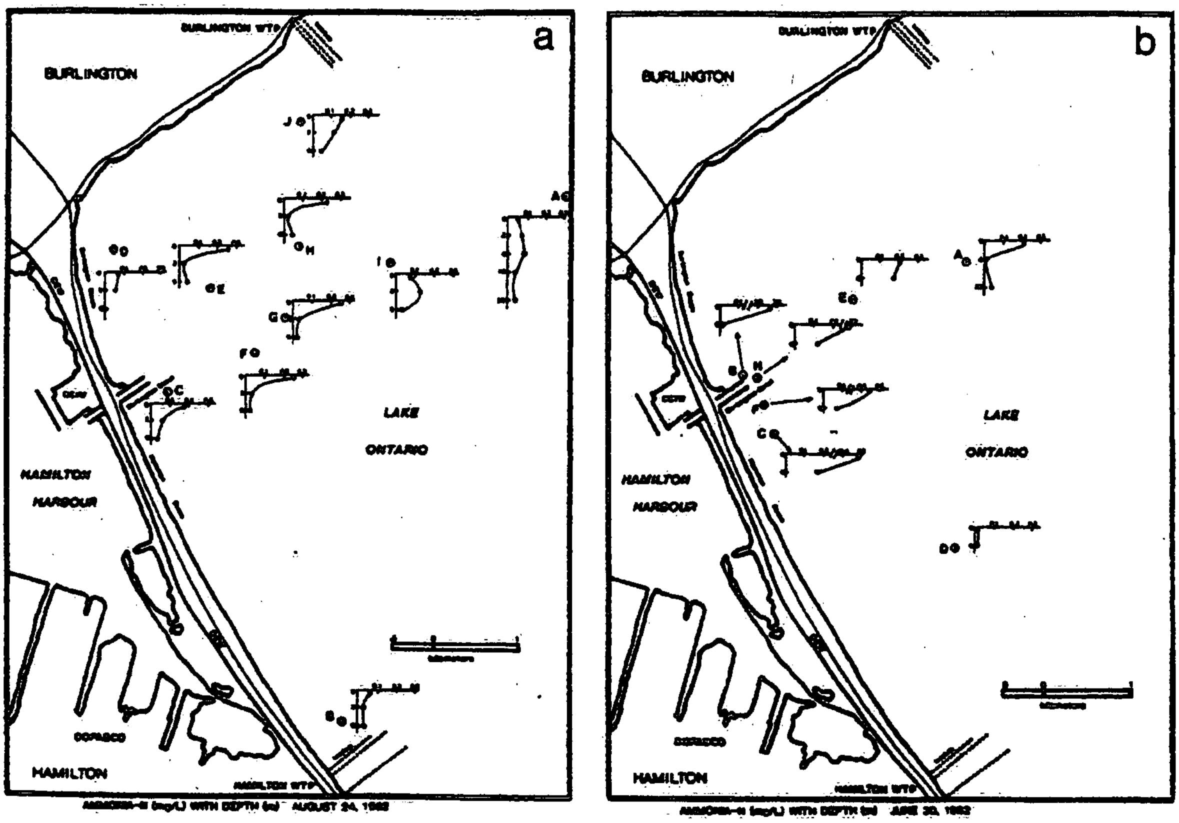

Fig. 7 **Ammonia plumes in western Lake Ontario on two occasions in summer 1982 (from MOE 1986).**

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