LIMNOLOGICAL ANOMALIES OF HAMILTON HARBOUR, LAKE ONTARIO

by

J. Barica

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Lakes Research Branch
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario, Canada L7R 4A6

Environment Canada

RÉSUMÉ

Le port de Hamilton, situé dans une baie à l'extrémité occidentale du lac Ontario, est une zone polluée désignée comme un secteur de préoccupation par la CMI. Il présente diverses caractéristiques limnologiques uniques (anomalies) qui ont des effets bénéfiques sur la qualité de ses eaux : 1- des échanges d'eau importants avec le lac Ontario par l'intermédiaire d'un canal, ce qui diminue le temps de séjour des polluants et contribue à l'oxygénation des eaux de l'hypolinnion; 2- des caractéristiques physiques très variables, avec des oscillations et un brassage par le vent qui provoquent une instabilité de la structure thermique, d'où une diminution de la période de stratification et une perturbation de la thermocline; 3- des concentrations élevées de matières particulaires en suspension dans la colonne d'eau, ce qui réduit la prolifération algale résultant de charges en phosphore élevées et élimine la productivité primaire; 4- un écart dans la relation entre le phosphore total et la chlorophylle et 5- des rapports azote/phosphore

extrêmement élevés (plus de 100:1) dûs aux charges en ammoniac, ce qui favorise la croissance des chlorophytes, contrairement à celle des cyanophytes présentant plus d'inconvénients.

Malgré ces conditions favorables, la qualité des eaux portuaires demeure inquiétante en raison des concentrations élevées d'ammoniac, d'autres polluants et de la DBO élevée. En l'absence de telles conditions, les paramètres seraient environ 1 fois et demie plus élevés.

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ABSTRACT

Hamilton Harbour, a polluted embayment at the western end of Lake Ontario designated as an IJC Area of Concern, exhibits several unique limnological features (anomalies) which beneficially affect its water quality. These are: 1- substantial exchange of water with Lake Ontario through a ship canal which reduces the Harbour's residence time, dilutes concentrations of pollutants and contributes to oxygenation of its hypolimnetic water; 2 - a high degree of physical variability, with oscillations and wind mixing resulting in unstable thermal structure which shortens the stratification period and perturbs the thermocline; 3 - high concentrations of suspended particulate matter in the water column which controls development of algal blooms due to high phosphorus loadings and supresses primary productivity; 4 - discrepancy in the total phosphorus vs. chlorophyll relationship and, 5 - extremely high nitrogen to phosphorus ratios (over 100:1) due to ammonia loadings, which favours Chlorophytes rather then more objectionable Cyanophytes.

Despite these favourable circumstances, the Harbour's water quality remains critical due to high ammonia, BOD and other contaminant levels. Without them, the levels would be about 1.5 times higher.

INTRODUCTION

Hamilton Harbour (also Burlington Bay, originally Makassa Lake) the westernmost embayment of Lake Ontario, separated from the main lake by a sandbar, contains about 2.8 x 10 8 m3 of water, with a surface area of 21.5 km2, max. depth of 23 m, and mean depth of 13 m. It is one of the most polluted sites in the Great Lakes, designated as an IJC Area of Concern. According to MOE (1981) data, the harbour is polluted by industries on the highly developed south shore, which use 27 m3s-1 of water and return a similar amount of effluent to the harbour. The harbour receives 4.3 m3s-1 of treated wastes from municipal utilities, and tributary flows and untreated stormwater runoff estimated at 3.5 m3s-1. Concentrations of ammonia, Zn, total P, turbidity, Fe, phenols, CN, Cu, Ni, Cr and the coliforms exceeded the provincial water quality objectives (MOE, 1985). Loadings of phosphorus and nitrogen in 1985 were 609 kg/day and 7,076 kg/day respectively, resulting in concentration ranges of total P of 40 - 200 ug/l and ammonia of 50 - 4,000 ug/l (as N). The impact of nutrient loadings on harbour eutrophication was discussed by Haffner et al.(1982), and the resulting severe hypolimnetic dissolved oxygen depletion described by Polak and Haffner (1978).Contamination by toxic organic compounds (BHC isomers, HCBs, PCBs,and PAHs was also high (Poulton,1987). Deteriorating water quality, exploitation, and competition were important factors contributing to the decline of the cold water fish community of Hamilton Harbour. The commercial fishing for lake herring, whitefish, and lake trout declined from 250,000, 30,000 and 10,000 lbs/yr respectively int the late 1800's to a combinedtotal of 550 lbs in 1950 (Holmes and Whillans, 1984).

The harbour is connected to Lake Ontario by a ship canal 107 m wide and 9.5 m deep, which facilitates a substantial exchange of water between the two water bodies and provides a significant input of a high quality Lake Ontario water as a dilutant of polluting substances. As a result of the diluting effect, the concentration per unit volume that are measured in the Harbour are substantially lower then they should be considering the loadings of the pollutants and the volume of the Harbour. Therefore, the Harbour appears to be less polluted then it actually is. Beside the obvious dilution effect, there are some additional favourable physical and chemical circumstances which contribute jointly to improve harbour water quality. These beneficial factors, termed in this paper as limnological anomalies, are responsible for an environment that would be worsee if they were not present. These factors and their benefits are discussed below.

ANOMALY # 1: WATER EXCHANGE BETWEEN THE LAKE AND HARBOUR.

Construction of the Burlington Ship Canal during 1823-1827, which cut through the sandbar at the eastern boundary of what was then a natural embayment with limited water exchange called Lake Makassa (Forde,1979) caused 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 and 9.5 m deep, became a complex dynamic process, bringing large amounts of oligotrophic Lake Ontario water into the Harbour and mixing it with more stagnant and presumably mezotrophic water of Lake Makassa. Matheson (1963) found that the flow in the canal was stratified and two-directional, with a layer of warmer harbour water flowing toward the lake at the surface, above a layer of colder lake water flowing into the harbour in the oposite direction. Dick and Marsalek (1973) expanded on Matheson's observations and attributed the exchange to two types of flow: 1-oscillatory flow driven by differences in the water surface levels at either end of the canal, and 2- densimetric flow caused by the thermal stratification, i.e. warm harbour water flowing to the lake in the top layer and colder lake water flowing to the harbour in the bottom layer underneath. The unstratified oscillatory flow was found to be the major source of water exchange through the canal, while the densimetric flow occurs only during the summer stratification.

However, the flow pattern proved to be even more complex. Palmer and Poulton (1976) found that water movements were strongly influenced by lake and harbour oscillations producing temporary displacement of the thermocline due to internal waves, and that there were temporary periods of three layer flow. Klapwijk and Snodgrass (1985) developed a model assuming three inflows to the harbour: one from land-based sources, one from the lake to the harbour's hypolimnion, and one from the lake to the harbour's epilimnion ; with one combined outflow from the harbour (Fig.1). They assumed that the harbour hypolimnion constitutes one-half of harbour's volume. Their results indicated that the magnitude of hypolimnetic exchange is generally small compared to that between the lake and the epilimnion, and that the water exchange decreases the hydraulic detention time to less than 40%. Palmer and Poulton (1976) and Kohli (1979, 1984) estimated net exchange to be of the order of 1.0 -1.1% of the harbour volume per day.

As a result of these dynamic conditions, variability of flows and flow directions in the Hamilton Ship Canal is extremely high, with flows changing in both directions, not only on daily (Fig. 2) but also on an hourly basis (Fig. 3).

Benefits:

1. Dilution of pollutants

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, phosphorus and ammonia levels, low Secchi transparency, high algal standing crops (up to 8x106 um3/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 1x106 um3/ml).

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 - 0.5% of the harbour volume per day. This corresponds to a theoretical displacement of Hamilton Harbour water by Lake Ontario water more than 3 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 directly affected by exchange is limited to the lower third of the Hamilton Harbour (Fig.4).

Therefore, if we assume that the dilution effect is at least 30%, the actual concentrations corresponding to loading figures would be 1.5 times higher or more.

2. Oxygenation

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 (MOE, 1981). 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 water of 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 02 m-2d-1 at the surface and 6.5 g m-2d-1 at 18 m below the surface. Infusion of oxygen rich lenses of Lake Ontario water reduced 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. Continuous frequent inputs of dissolved oxygen may significantly lessen periods of anaerobic conditions in the hypolimnion of the Hamilton Harbour and cause the absence of well-defined thermocline. Indeed, if we assume that the incoming water from Lake Ontario contains 10 mg/L O2, then the amount contained in typical flows in Klapwijk and Snodgrass (1985) is equivalent to 30% of the net observed oxygen depletion rate.

Beside improving oxygen conditions in Hamilton Harbour, water exchange with Lake Ontario has both diluting and oxygenating effect on other contaminants present. The most abundant of them is ammonia (MOE,1985). Fig. 4 presents an aerial distribution of ammonia on May 27, 1987. It can be seen that the diluting and oxidizing effect of Lake Ontario extends about 2 km into the Hamilton Harbour (shaded area), reducing substantially ammonia levels coming mainly from the southeastern arm (Windermere Basin) where they occasionally reach levels of 10 mg/L and over.

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 the 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 NO3/NO2/N2/NH3 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 and subsequent release of phosphorus.

3. Thermocline perturbations/displacements

Vertical instability as a result of non-steady dynamics of water exchange, wind mixing and harmonic oscillations as well as modification of retention time have a strong bearing on normal development of thermal stratification in the Hamilton Harbour (Haffner et al, 1982). The time and stability required to develop full thermocline and full hypolimnetic anoxia is reduced and fluxes of warmer and oxygenated water into the harbour change existing "normal" conditions. Palmer and Poulton (1976) noted that harbour oscillations produced temporary displacements of the thermocline in both the harbour and ship canal due to internal waves, along with complex flow regimes including two and three-layer systems in the canal.

Water exchange with Lake Ontario can therefore be considered a major cause of small scale variability and rapid perturbations of thermal structures (Sephton and Harris, 1984, Zarull 1979).

This is noticeable mainly in the oxygen and temperature regimes of areas of Hamilton Harbour unaffected by the exchange (western and central part) and those affected (eastern part, near the Burlington Canal). Fig.5 presents an example of oxygen distribution curves at the deepest part of the harbour (Barica et al, 1987) demonstrating deformation of the "normal" stratification by Lake Ontario water incursion on two occasions in the summer of 1987. Exchange water seems to ameliorate low hypolimnion oxygen conditions. The input of cold Lake Ontario water helps to offset the natural warming and incorporation of the hypolimnion and epilimnion. This may have a significant effect on maintaining hypolimnion volume and prolonging stratification.

4. "Short circuiting" of wastewater discharges into Hamilton Harbour.

It is fortuitous also that the water exchange with Lake Ontario occurs in the same area - or close to - as the major wastewater discharges from Hamilton and Burlington sewage treatment plants and steel industry. (Fig.8). This results in frequent "short-circuit" discharges to the lake combined with immediate dilutions of loading effects in the Harbour. The pollutants are able to leave the harbour much faster than it would be without the shipping canal. The residence time and the pathway of pollutants is substantially shortened. Instead of gradual mixing of the wastewater discharges over the whole area and volume of the harbour, effluent remains near the eastern edge and leaves the harbour quickly. This phenomenon can be observed visually during periods following heavy rainstorms in the basin, when the plumes of turbid water follow the shoreline and leave through the canal into Lake Ontario (M. Charlton, pers.comm.). Thus, the substantial part of the load remains in less than one third of the harbour and has a limited chance to spread into the western (and recreationally utilized) area. This phenomenon is likely responsible for discrepancies in the nutrient-chlorophyll and primary productivity relationship (see separate section), and "saves" the other end of the Harbour from serious pollution.

ANOMALY # 2: EXTREME PHYSICAL VARIABILITY

Besides affecting the Harbour's stratification and hypolimnetic conditions, small scale variability and rapid perturbations of thermal structure caused by both water exchange with Lake Ontario and wind action have a strong impact on the development of phytoplankton populations. Zarull (1979) described spatial and temporal heterogeneity in phytoplankton communities of the Hamilton Harbour during stratified and unstratified conditions and found significant small scale patterns and patchiness as a function of the wind driven circulation.

Harris and his co-workers (1980 a - d) analyzed in detail the impact of physical variability on phytoplankton communities of the Hamilton Harbour. They described Hamilton Harbour as a water system in a constant state of flux. Sephton and Harris (1984) presented substantial day-to-day changes in the physical environment shown in Fig. 7 (panels A and B) , presenting daily values of two measures of water column stability namely Zeu/Zem (eutrophic zone depths and mixing depth respectively) derived from the downwelling irradiance and temperature profiles, and N2, the Brunt-Vaisala frequency of oscillation of a vertical fluid column. Both values reflect the significant variability in mixing events on a day-to-day basis.

Benefit: Reduction of primary productivity

Algal groups and species respond differently to environmental changes with different temporal lags, and result generally in reduced phytoplankton crop levels and shifts in composition. In highly variable environments, the resident population will tend to have a diverse species composition; populations which experience environmental variations with periods less than their doubling time are considered stressed (Haffner et al, 1980b).

Due to high physical variability, Hamilton Harbour's algal biomass and primary productivity is lower than would be expected from nutrient loadings, and species diversity greater. Hypothetical stagnant conditions in Hamilton Harbour under existing nutrient loading conditions would likely lead to development of algal blooms (Barica, 1980a).

ANOMALY # 3: HIGH SUSPENDED MATTER AND REDUCED LIGHT REGIME

High mixing rates and wave-induced resuspension of bottom sediments in a relatively shallow system with significant input of suspended solids from steel industry and tributaries (and partly from carp activity) create an environment with a reduced light penetration. Hamilton Harbour has a chronic problem of poor water clarity. Concentrations of suspended matter range usually from 4 to 8 mg/L and over (dry wt.) with 25-40% being in an inorganic form (M. Charlton, unpub. data). Secchi depth transparencies are frequently less than 1 m and transmissivity often over 60%.

Benefits:

1. Reduced bioavailability of phosphorus

Suspended sediments in Hamilton Harbour are known to contain high proportion of iron originating from steel industry (MOE 1980, Poulton 1987). Iron controls bioavailability of phosphorus and makes portions of the inorganic phosphorus pool in the harbour unavailable to algae, as the reactions of nonapatite inorganic phosphorus (NAIP) in aquatic systems are controlled by hydrated ferric oxides (Manning et al., 1984). NAIP is considered the main source of bioavailable P in sediments (Williams et al., 1980). Concentrations of NAIP and iron are strongly elevated in bottom and in suspended sediments of Hamilton Harbour. The natural iron compounds in the Harbour sediments are chlorite and clays containing Fe 2+ and hydrated ferric oxides; the anthropogenic compounds are, in decreasing order of abundance, hydrated ferric oxides, hematite (Fe_2O_3), wustite ($Fe_{1-x}O$) and magnetite (Fe_3O_4). The ferric oxides are probably beneficial in binding NAIP; on the other hand, concentrations of lead and zinc are strongly correlated with ferric oxide, hematite and wustite. Manganese was released from the bottom sediments in the summer of 1986, but no release of phosphorus or iron was observed at any of the six stations (T.Mayer and P. Manning, unpubl. data).

2. Reduced algal growth.

Phytoplankton are sensitive to rapid fluctuations in light regime, such as those brought about by turbulence in the mixed layer (Harris et al. 1980b). Incursions of Lake Ontario water through the ship canal, and wind stress cause vertical mixing and rapid changes in mixing depth.

Fig.7, Panel C presents daily changes in light penetration expressed as integral downwelling irradiance, E Io(uE in.m-2sec-1 PAR: from Sephton and Harris, 1984) which are a combined result of the physical variability and suspended sediment concentrations. The values vary substantially from day to day. Phytoplankton can adapt to the fluctuations in the ratio of light penetration to mixing depth (Zeu/Zm) in several ways. Physiological adaptations such as altered chlorophyll content or photosynthetic enzymes are seen during the summer in green algae. Other species, such as Cryptomonas, utilize heterotrophic processes rather than relying on photosynthetic carbon uptake. Small coccoid cells such as Chlamydomonas lose their flagella and pigment as the ratio of light penetration to mixing depth decreases and cells spend less time in the euphotic zone.

During periods of stable light and mixing depth, large cells such as Oocystis borgei predominate. This species persisted in the summer once a thermal gradient was established, but declined when lake mixing increased. Near monospecific phytoplankton blooms occur only under conditions of relatively stable physical parameters (Sephton and Harris, 1984).

Diatom growth is related to vertical mixing because, the heavy silica shells tend to sink out of the water column. The persistence of diatoms throughout the year is evidence of vertical turbulence during the stratified period (Haffner et al. 1980a,b). The survival of Stephanodiscus also depends directly on its resuspension by vertical mixing (Klapwijk and Snodgrass 1983).

Diatoms are favoured also, by the fact that they can utilize energy from green light more efficiently than can green algae; green light penetrates water three times farther than blue light. They thus are less stressed when light penetration is poor.

The seasonal succession of Hamilton Harbour phytoplankton includes diatoms and small phytoflagellates early in the year, during periods of homogenous mixing. These are followed by the predomination of coccoid green algae for a short period of time, and then by a mixture of diatoms and green algae at the time when the maximum summer temperature is reached. Diatoms and flagellates later return as the dominant species. Blue green algae are noticeably absent from the harbour despite the eutrophic conditions (Harris and Piccinin 1980, Murphy 1987).

High concentrations of suspended matter provide a self-shading effect restricting algal and macrophyte growth. Light limitation favours the growth of larger algae which can optimize light utilization (Harris 1976, Piccinin 1979, Murphy, 1987). This may partially explain why the small blue-green algae are not present in the harbour.

ANOMALY # 4: DISCREPANCY IN THE NUTRIENT LOADING-ALGAL BIOMASS RELATIONSHIP

Considering the recent (1980-86) phosphorus loading of 525-1021 kg/day (MOE, 1987, the corresponding areal loading values are between 6.9-13.5 g/m2. Using the original Vollenweider (1968) model (annual phosphorus loading g/m2 vs. lake mean depth) these values fall into the neighbourhood of hypereutrophic prairie lakes (Pasqua, Katepwa, Echo, and Mission in Saskatchewan with 8-15 g/m2 of P and max. chlorophyll a over 100 ug/l; Allan and Kenney, 1978). Using the ammonia-based predictive model developed for prairie lakes (Barica 1975), the Harbour's winter ammonia maxima of 2-2.5 mg/l would correspond to predicted maximum summer chlorophyll a levels of 250-300 ug/l. Yet, Hamilton Harbour is certainly not as eutrophic as prairie lakes, and does not develop heavy blue-green algal blooms, and its summer chlorophyll a values are between 20 - 80 ug/L. L.L. Janus (1987) compared Hamilton Harbour data to OECD standards (Janus and Vollenweider, 1981) and found that observed lake concentrations of P tend to fall below the flushing corrected inflow values. It was concluded that the Harbour has a tendency for more efficient flushing and/or sedimentation than average of the OECD lakes. This comparison demonstrated the significance of flushing in Hamilton Harbour.

As described earlier, there is a significant flow short-circuiting between the discharge sites from the sewage treatment plants in the south-western arm of the Harbour and the ship canal, with highest concentrations of pollutants distributed over this arm (Fig.8). This phenomenon may also explain discrepancies in response of the Harbour to nutrient loading, entering predominantly from the Hamilton sewage treatment plant, and not mixing completely with the whole volume of the Harbour.

Benefits:

Harris et al. (1980 a,b) concluded that summer algal biomass (as chlorophyll a) and primary productivity are well below the values predicted by the loadings of total P or the concentration of total P in the water. They noted that in Hamilton Harbour the classical relationship between P-loadings and algal biomass do not apply. This discrepancy was attributed mainly to the physical regime of the Hamilton Harbour. Hamilton Harbour was classified as highly eutrophic on the basis of its nutrient loadings but only as meso-eutrophic on the basis of its algal standing crop and primary production, and was not considered to be nutrient limited (MOE, 1981). As a result of a combination of all previously described anomalies, the Hamilton Harbour exhibits lower algal biomass than expected or predicted. The flushing effect shown by Janus's (1987) analysis, and the short-circuiting, disregarded in previous considerations, explains the discrepancy in the nutrient loading-algal biomass relationship.

ANOMALY # 5: HIGH N:P RATIOS AND AMMONIA LOADINGS

Role of N:P ratios in controlling eutrophication process and algal species composition has been known for some time. Smith (1983) provided a summary of data showing that a N:P ratio of 29:1 (as total N and P) is a borderline under which lakes favour development of N-fixing Cyanophytes, while higher ratios disfavour it. Schindler (1977), Leonardson and Ripl (1980) and Barica et al. (1980b) demonstrated experimentally that manipulation of N:P ratios by addition of N (as nitrate or ammonia, or both) leads to substantial changes in phytoplankton composition, with low ratios (less than 10:1) favouring the Cyanophytes, and the higher ones favouring Chlorophytes or non-fixing blue-greens.

Due to high ammonia loadings from two municipal waste water treatment plants (Hamilton and Burlington), totalling about 7,000 kg per day, and concentration ranges of about 0.1 - 4 mg/L NH_3-N, 1.5 to 2.5 mg/L NO_3-N and TP of 0.040 to 0.020 mg/L, the N:P ratios reach values as high as 150:1 and greater (compared to about 20:1 in Lake Ontario; MOE, 1981, Stevens and Neilsen, 1987). Most of N is represented by ammonia, which causes significant oxygen demand in the water column (Murphy, 1987), and may under some conditions prevailing during summer months (high water temperature and pH values), may dissociate into unionized NH_3 gas, toxic not only to fish (Trussel, 1972) but also to algae

(US EPA, 1984).

Fig. 7 presents vertical distributions of total ammonia (A) and toxic unionized ammonia (B), calculated according to Emerson et al (1975), considering water temperature and pH values, at three sampling dates in summer 1987, under stratified conditions (deepest site). The unionized NH3-N exceeds the IJC permissable limit of 30 ug/L NH3-N in the epilimnion of Hamilton Harbour during high water temperature (22 degrees C.) and high pH values (over pH 8.5) several fold. Aerial distribution of total unionized ammonia during the same period demonstrates a distinct zonation and suggests short-circuiting of the watewater effluent through the ship canal (Fig.8). In some parts of the Harbour, it is not only the IJC acceptable level of 30 ug/L of un-ionized ammonia that is exceeded several fold, but in a few instances, the acute toxic LC50 (300 ug/L, US EPA 1984) is reached or exceeded. This is presumably caused by increased dissociation of total ammonia in areas affected by input of high temperature and high pH effluents from industry, raising lake water temperature in some sites to 26 - 30 degrees C and pH values to 8.0 - 9.5.

High total ammonia levels (in mg/L range) contribute also to additional oxygen uptake due to nitrification (Klapwijk and Snodgrass 1986; Murphy 1987). It is noteworthy that nitrate levels in the Hamilton Harbour have been dramatically increasing for the past three decades (Fig.9, Forde, 1979; Barica, 1987).

With TP levels remaining the same, N:P ratio have been increasing proportionally.

Benefits:

These extremely high N:P ratios favour development of Chlorophytes, which are indeed predominant algal species in Hamilton Harbour in summer together with Cryptophytes and Chrysophytes (Harris and Piccinin 1980b). If the N-loadings were as low as in other parts of the Great Lakes and P-loadings as high as they are now, Hamilton Harbour would likely develop heavy blue-green blooms. Toxic effect on unionized ammonia on algae may also explain reduced phytoplankton levels; as ammonia concentration over 2.5 mg/l (common concentration level in Hamilton Harbour) were reported to inhibit photosynthesis and growth of several species of algae (US EPA 1984).

DISCUSSION

Haffner et al (1982) hypothesized that physical processes of the Great Lakes play an important role in determining the biological activity of enclosed harbours and may affect the response of these harbours to nutrient control programs. They demonstrated that two embayments of similar nutrient input (Hamilton Harbour vs. Toronto Harbour) can behave quite differently under similar nutrient loading conditions, but different water exchange patterns.

Construction of the Hamilton Ship Canal completely changed the overall character of what was until then a "normal" lake, with limited water exchange over the parts of the shallow sandbar. The Harbour was turned into a highly dynamic oscillating system comparable perhaps to a large reservoir with frequent periodic and substantial water withdrawals and inputs. The water exchange phenomenon became of crucial importance for improving water quality of the harbour because the more polluted harbour water is discharged to the lake while better quality and high oxygen content lake water flows into the harbour.

Exchange of harbour and lake water through the canal reduces also the the theoretical hydraulic residence time of the harbour (from 180 - 200 days before the construction of the canal down to 73 -107 days, depending on the season of the year; T. Murphy and K. Rodgers, pers. comm.) and contributes to the improvement of the harbour quality through dilution and oxygenation. On the other hand, the harbour effluent plume adversely affects water quality of western Lake Ontario to about 5 km offshore (MOE 1986). However, the beneficial effect of dilution by Lake Ontario far exceeds contamination of Western Lake Ontario by Hamilton Harbour water (Barica et al 1988). The phytoplankton communities in the harbour did not have adequate conditions to respond to rapidly increasing loadings of nutrients, and became inhibited by constant physical perturbations, input of suspended solids, resuspension of sediments, decreased light penetration and anomalous N:P ratios and toxic effects of ammonia and likely other metals and contaminants. The latter factor can hardly be considered beneficial, as the harbour's contamination is the main water quality problem. However, toxic compounds and metals certainly inhibit algal growth. Wong et al. (1978) found that mixtures of metals in low concentrations inhibited harbour algae. Goudey (1983) noted that copper and mercury at concentrations found in the harbour could inhibit photosynthesis and that some harbour algae (Scenedesmus and Coelastrum) are more tolerant to copper and zinc than are similar laboratory strains.

These beneficial effects of otherwise adverse environmental factors may appear a paradox, but they can be credited for the fact that the Hamilton Harbour has not shown the true extent of its concentrated pollutant load. Hypothetically, the harbour could look as bad as any hypereutrophic lake in Western Canada, with obnoxious blooms of blue-green algae and periodic massive

Figure Captions

Fig. 1 A simplified model for water exchange between Hamilton Harbour and Western Lake Ontario (after Dick and Marsalek, 1973, and Klapwijk and Snodgrass, 1985)

Fig. 2 Daily changes in flows and flow directions in the Hamilton Ship Canal during Feb. 10 - April 9, 1987

Fig. 3 Variability of current speeds (cm/sec) within a 6 hour interval (Feb. 10, 1987)

Fig. 4 Approximate exchange zone of Hamilton Harbour (shading) affected by dilution by lake Ontario water, defined from ammonia aerial distribution (less than 1 mg/l NH_3-N; from Barica et al., 1988). Arrows indicate major nutrient loads (after Klapwijk and Snodgrass, 1985).
STP= municipal sewage treatment plants

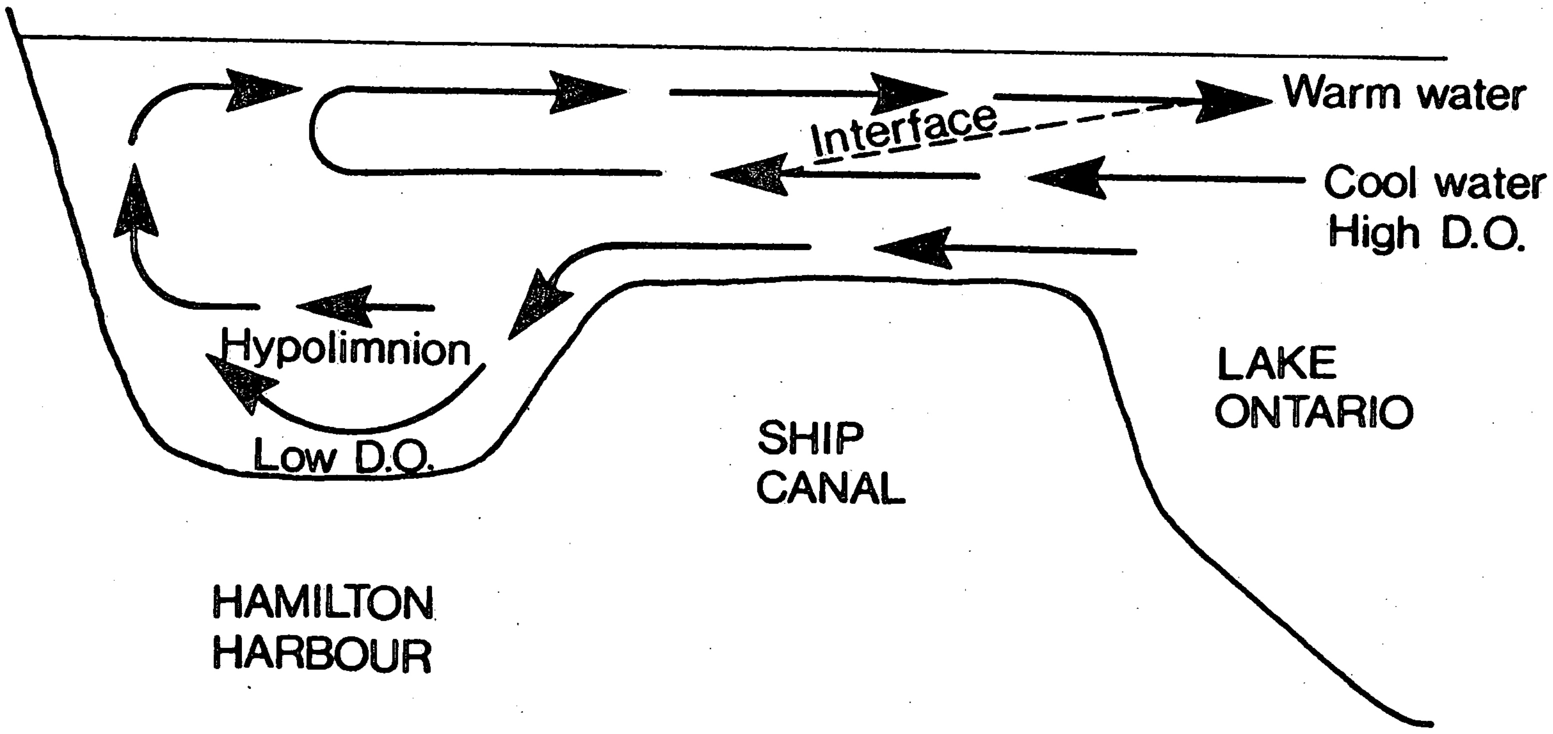
Fig. 5 Characteristic dissolved oxygen, temperature, transmissivity, conductivity and pH curves indicating thermocline perturbations in the deepest part of Hamilton Harbour (23 m), on two different sampling days. Obtained by NWRI water quality profiler (Ford and Charlton, 1984). Note differences between reestablished normal stratified conditions (Sept. 18, 1987, A) and their deformation due to Lake Ontario water incursion a week earlier, Sept.10,1987 (B). Courtesy of M. Charlton.

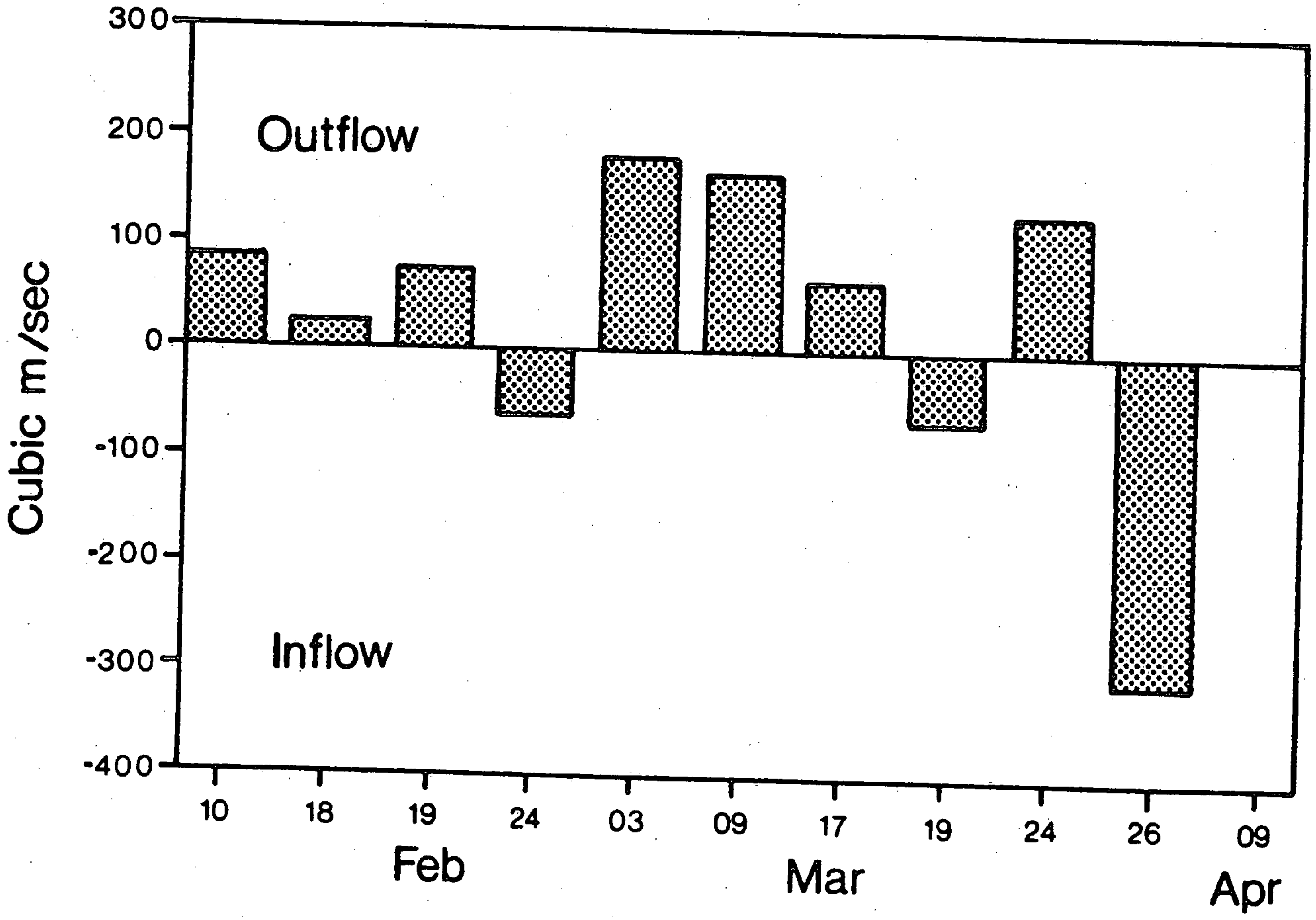
Fig. 6 Daily changes in some physical parameters. A - Zeu/Zm, B - water column stability-N2 , C - light irradiance Io. Modified from Sephton and Harris, 1980.

Fig. 7 Characteristic vertical ammonia distribution during 3 weeks of the summer stratification period .

Fig. 8 Aerial distribution of total (bold numbers) and unionized (italicized numbers in brackets) ammonia - nitrogen in Hamilton Harbour (surface layer) on June 24, 1987. Underlining indicates numbers exceeding IJC permissible level of 30 ug unionized ammonia - N (single line) and toxic LD50 level of 200-300 ug/L (double line). Shading indicates zone of wastewater short-circuiting.

Fig. 9 Average increases of nitrate in Hamilton Harbour between 1948-1979. From Forde, 1979.


Warm water
Interface
Cool water
High D.O.
Hypolimnion
Low D.O.
LAKE
ONTARIO
SHIP
CANAL
HAMILTON
HARBOUR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Cubic m/sec
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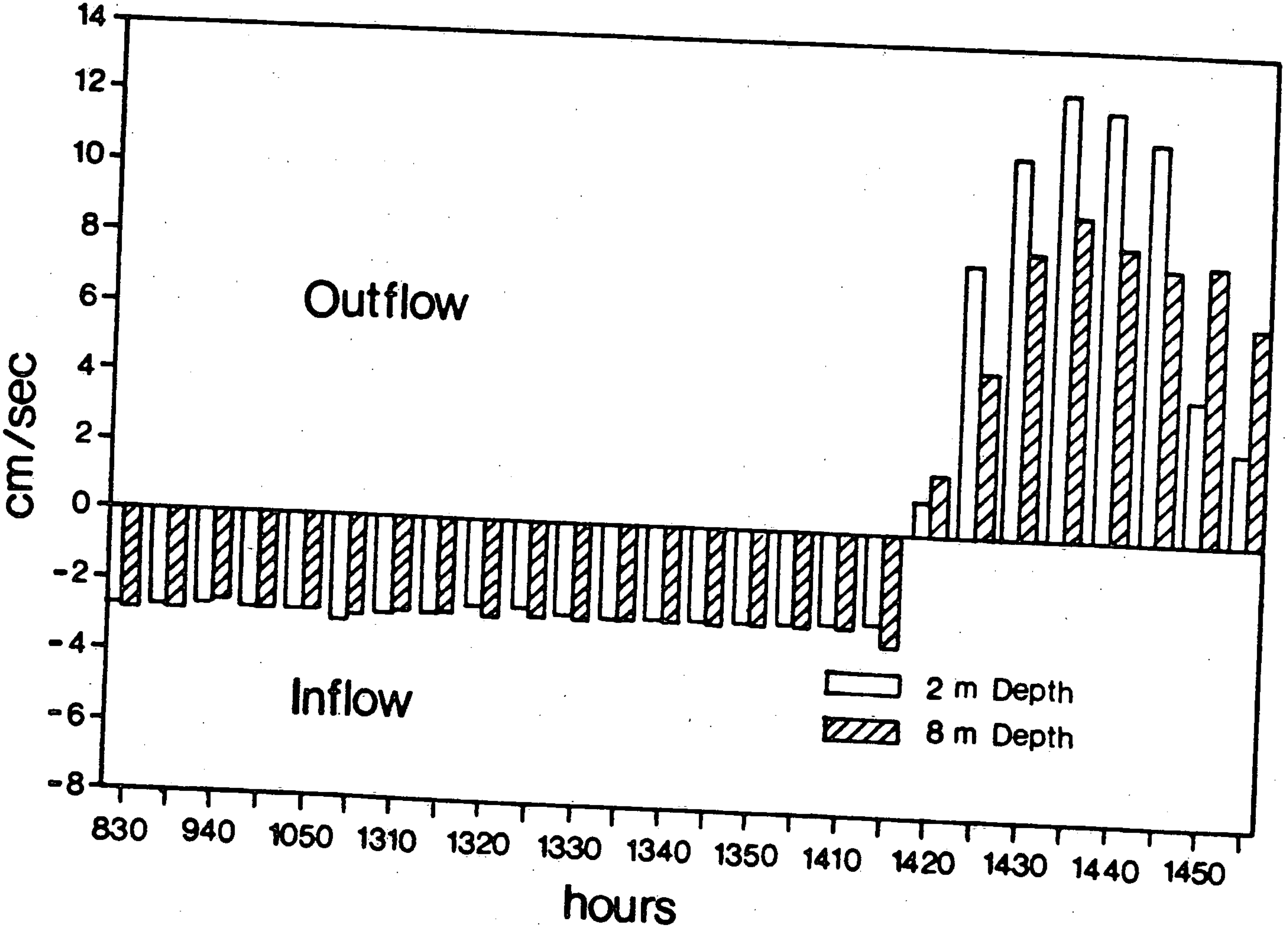
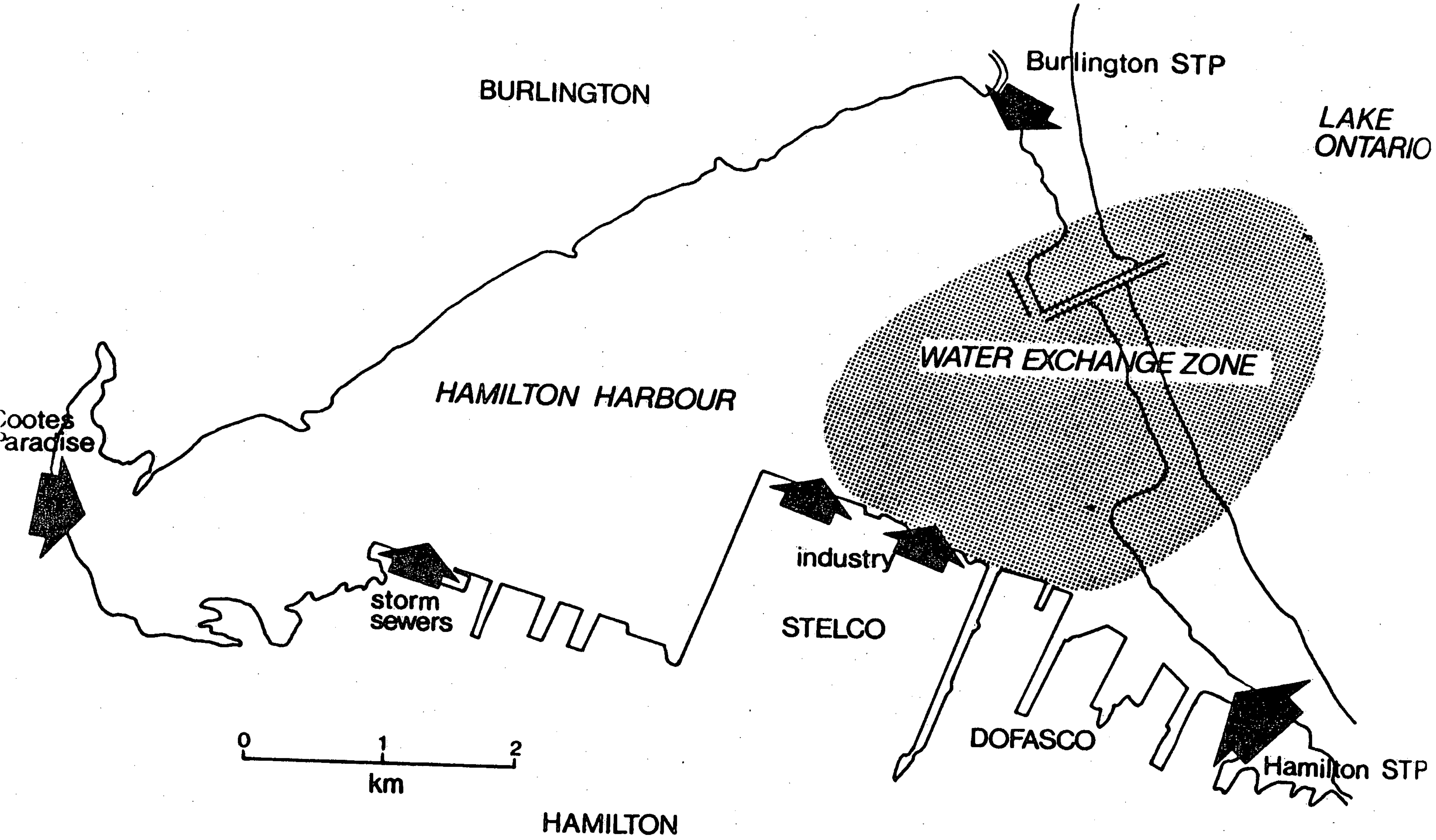
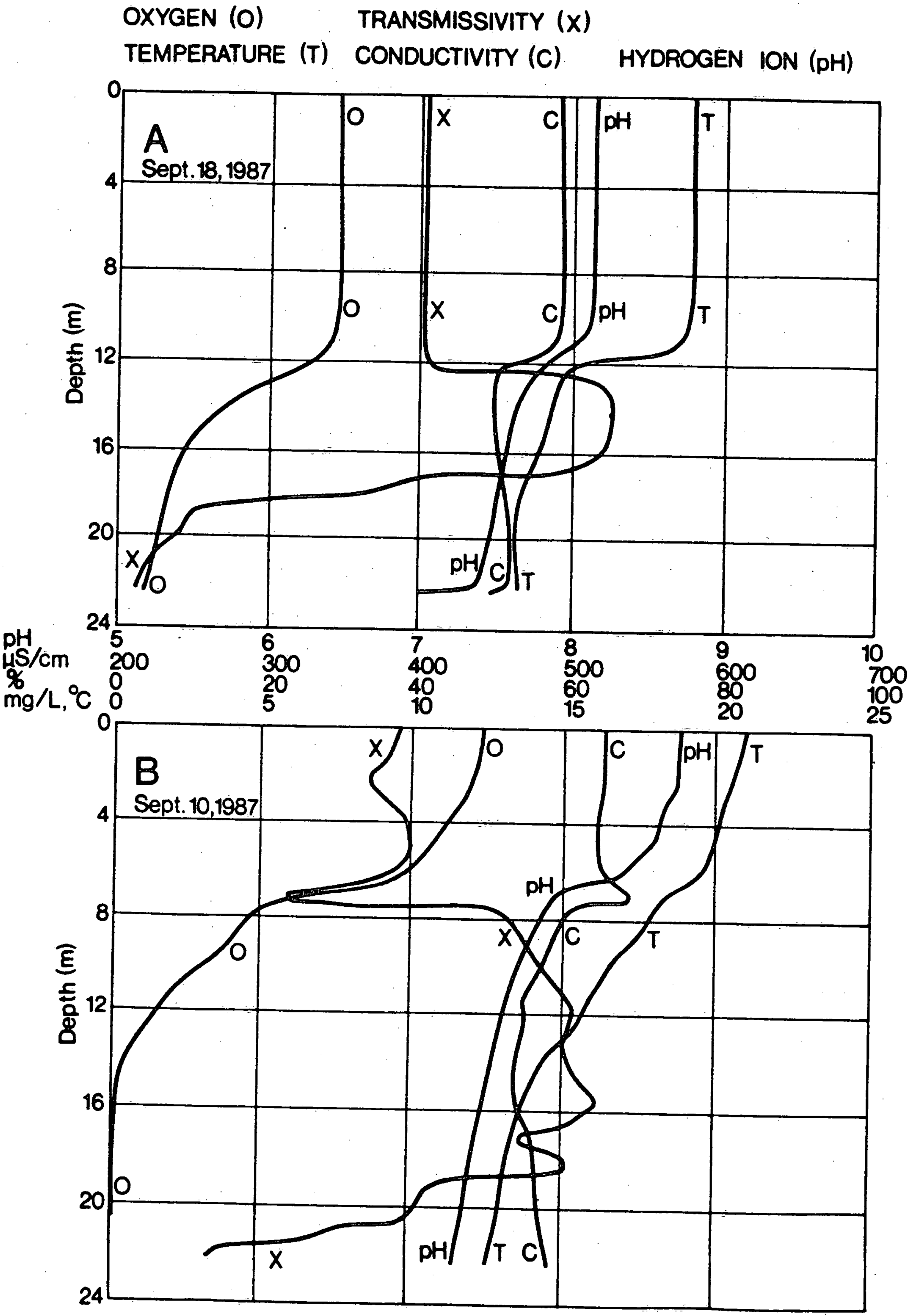
Apr

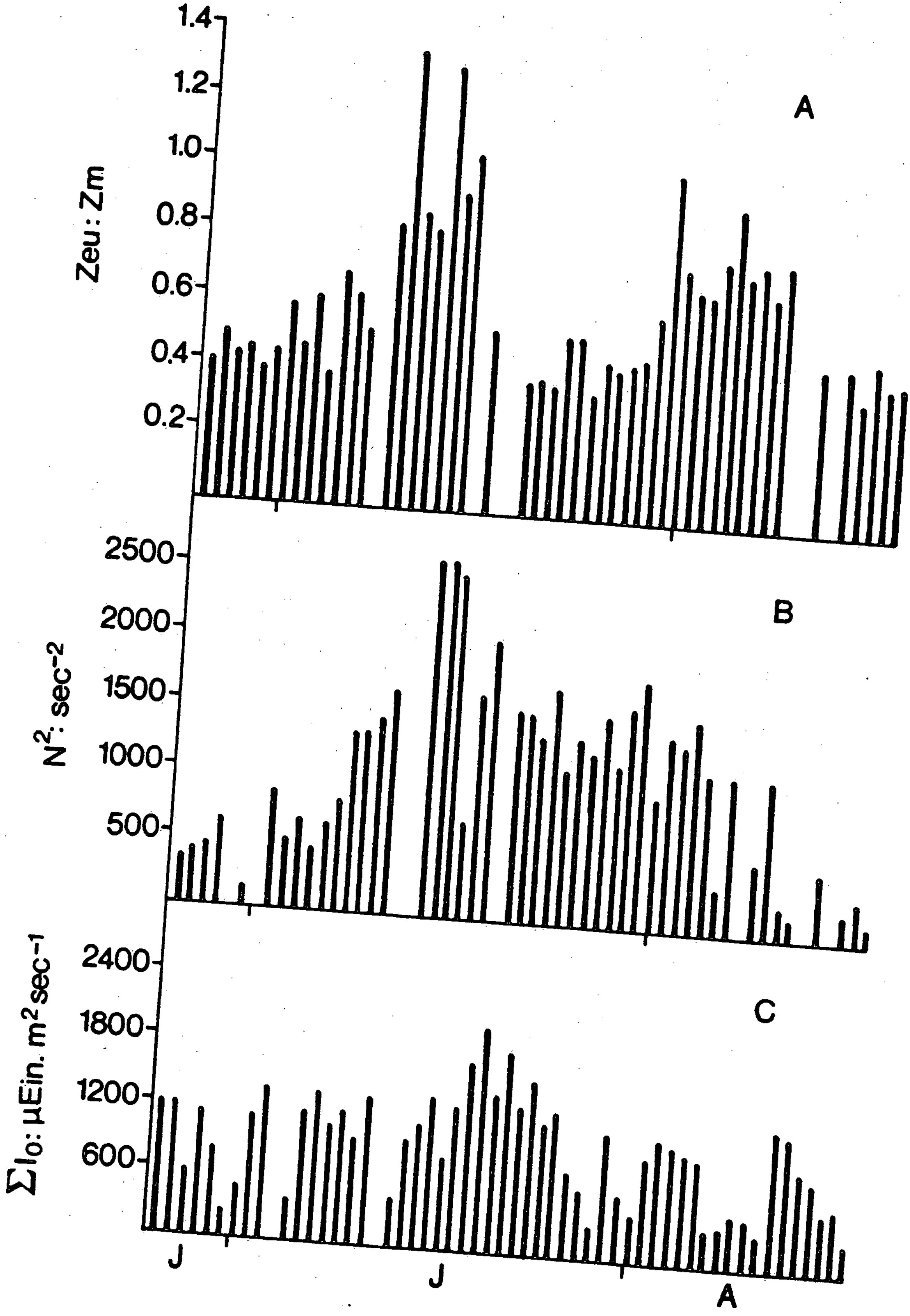
[illegible]



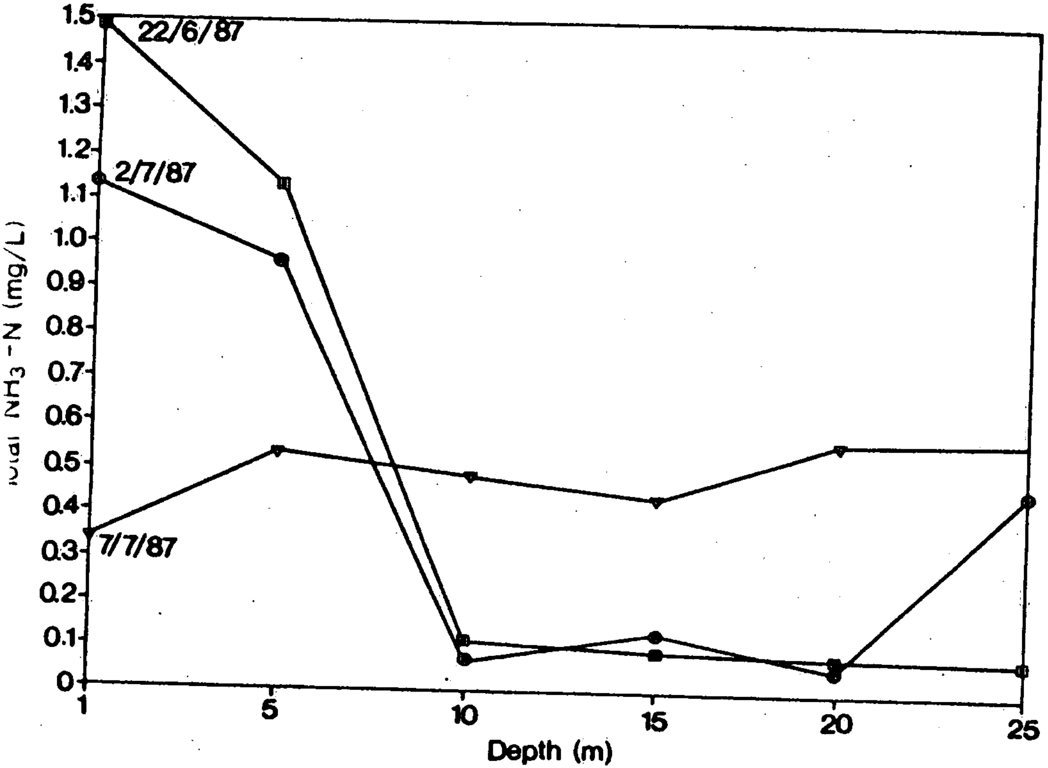
14
12
10
8
6
4
2
0
-2
-4
-6
-8
cm/sec
Outflow
Inflow
2 m Depth
8 m Depth
830
940
1050
1310
1320
1330
1340
1350
1410
1420
1430
1440
1450
hours

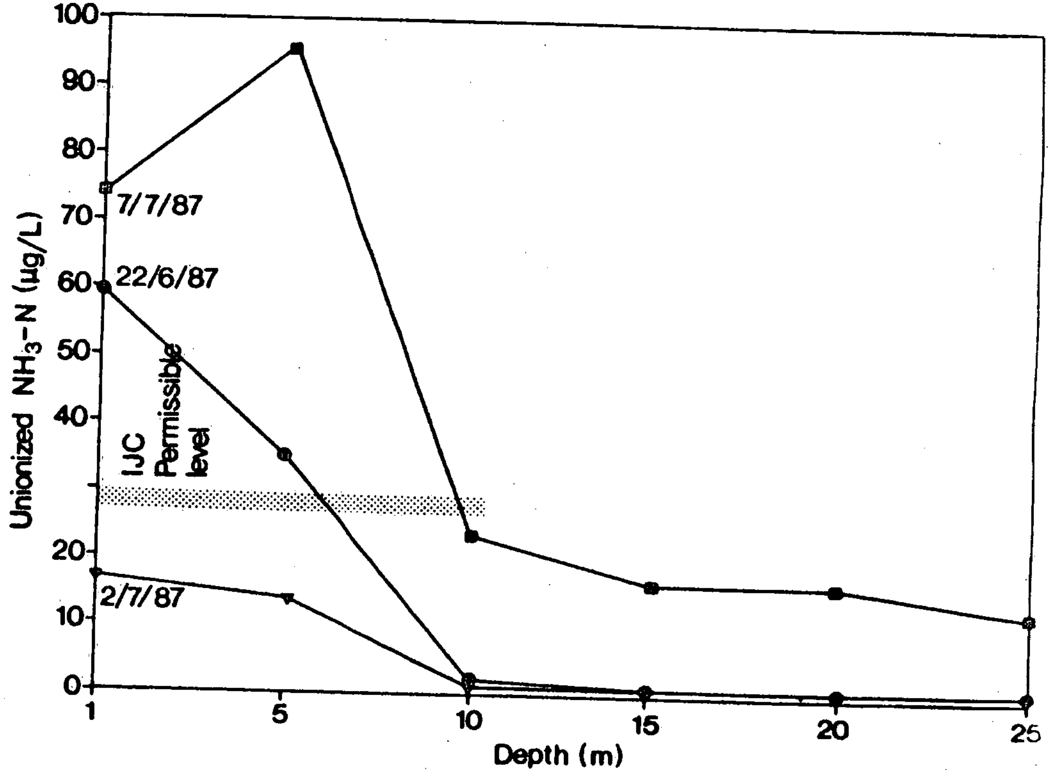

Burlington STP
BURLINGTON
LAKE ONTARIO
WATER EXCHANGE ZONE
HAMILTON HARBOUR
Cootes Paradise
industry
storm sewers
STELCO
DOFASCO
Hamilton STP
0
1
2
km
HAMILTON

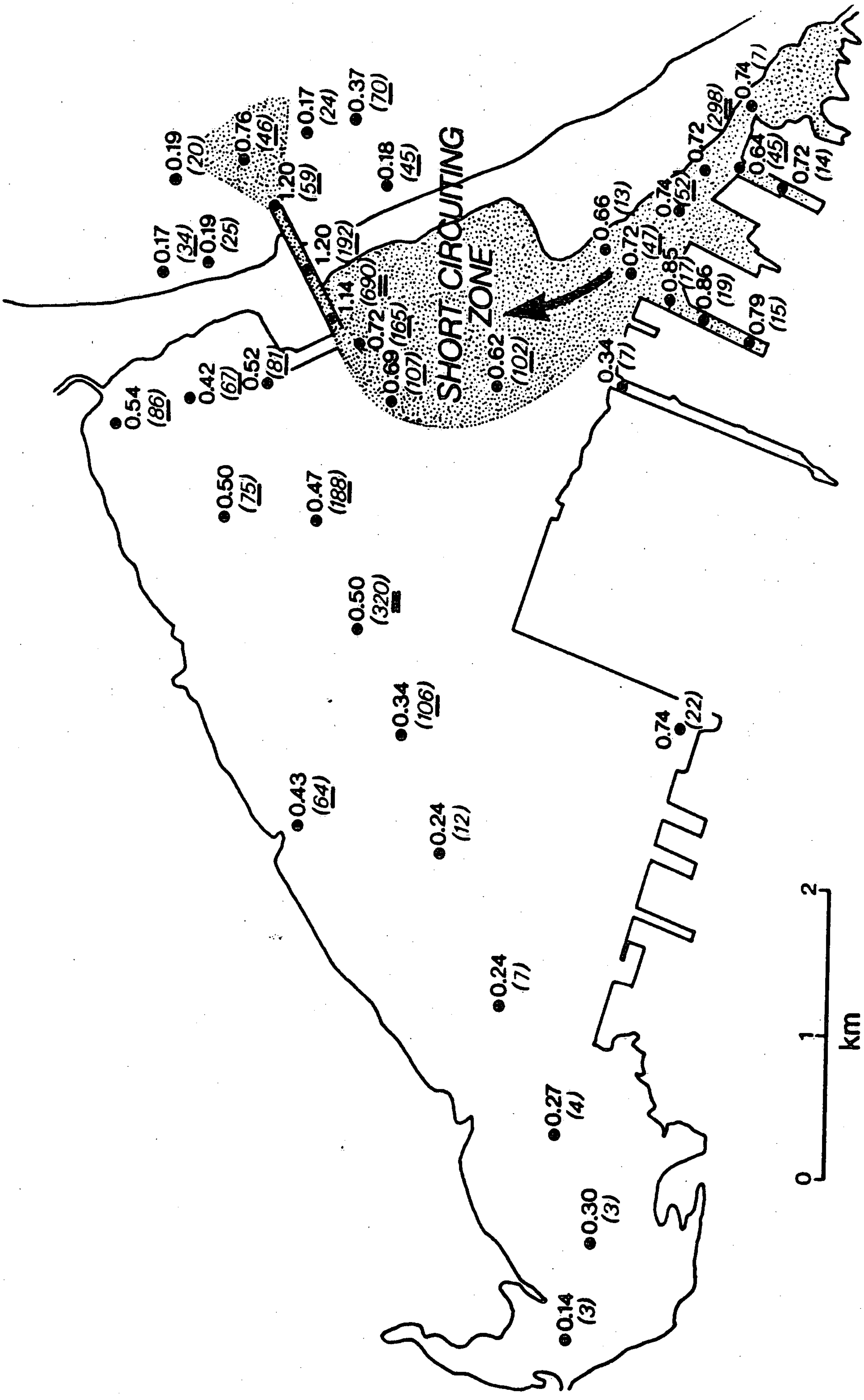

OXYGEN (O)
TRANSMISSIVITY (X)
TEMPERATURE (T)
CONDUCTIVITY (C)
HYDROGEN ION (pH)
A
Sept. 18, 1987
O
X
C
pH
T
pH
C
T
X
O
Depth (m)
0
4
8
12
16
20
24
pH 5 6 7 8 9 10
µS/cm 200 300 400 500 600 700
% 0 20 40 60 80 100
mg/L, °C 0 5 10 15 20 25
B
Sept. 10, 1987
X
O
C
pH
T
pH
X
C
T
O
O
X
pH
T
C
Depth (m)
0
4
8
12
16
20
24

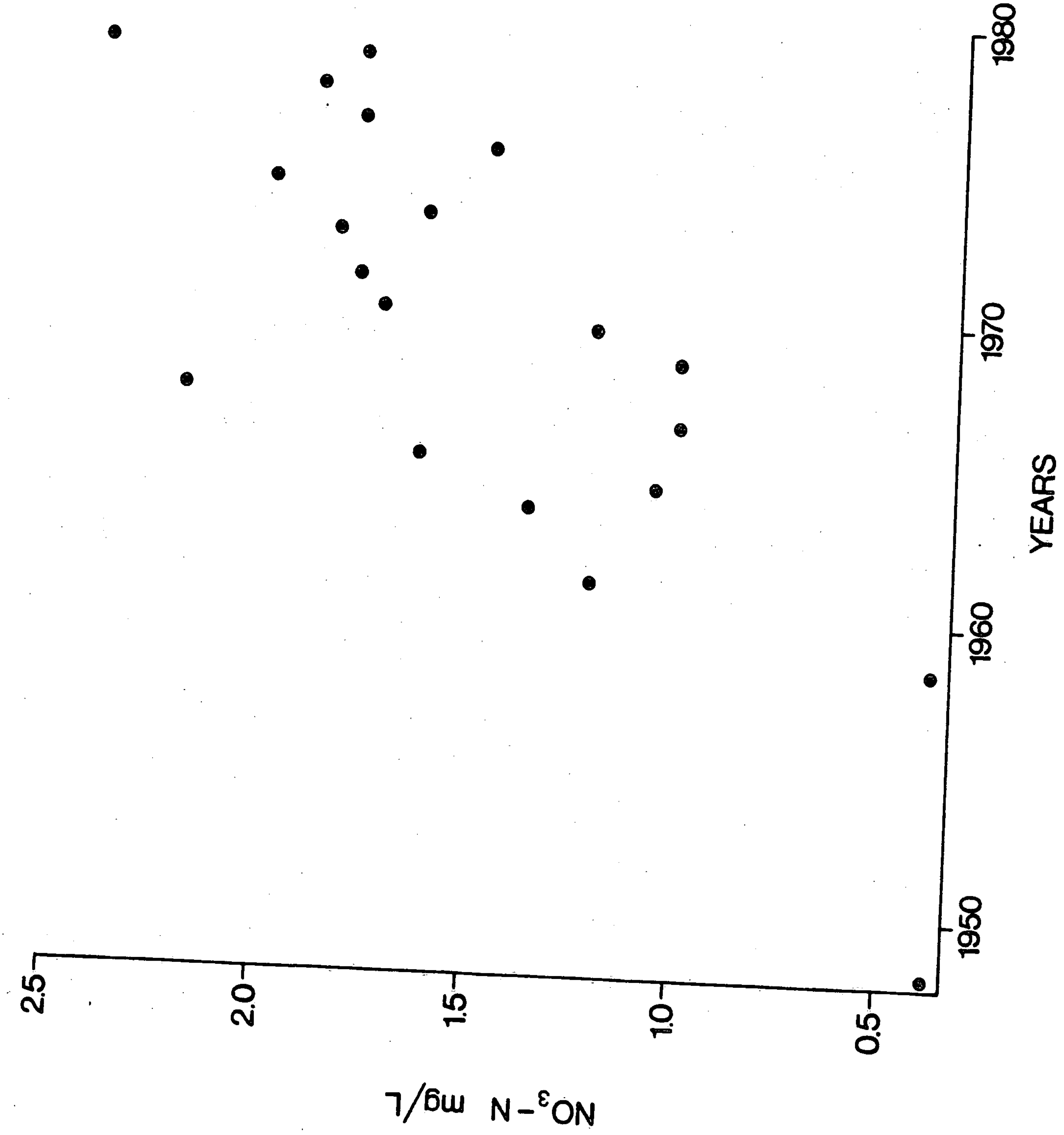

A
Zeu : Zm
1.4
1.2
1.0
0.8
0.6
0.4
0.2
B
N²: sec⁻²
2500
2000
1500
1000
500
C
ΣI₀: μEin. m² sec⁻¹
2400
1800
1200
600
J
J
A

6


otal NH3 -N (mg/L)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
22/6/87
2/7/87
7/7/87
1
5
10
15
20
25
Depth (m)


Unionized NH3-N (µg/L)
100
90
80
70
60
50
40
20
10
0
7/7/87
22/6/87
2/7/87
IJC Permissible level
1
5
10
15
20
25
Depth (m)


SHORT CIRCUITING ZONE
0.17 (34)
0.19 (25)
0.19 (20)
0.76 (46)
1.20 (59)
0.17 (24)
0.37 (70)
0.18 (45)
1.20 (192)
1.14 (690)
0.72 (165)
0.69 (107)
0.62 (102)
0.66 (13)
0.72 (47)
0.74 (52)
0.72 (298)
0.74 (71)
0.64 (45)
0.72 (14)
0.85 (17)
0.86 (19)
0.79 (15)
0.34 (71)
0.54 (86)
0.42 (67)
0.52 (81)
0.50 (75)
0.47 (188)
0.50 (320)
0.34 (106)
0.74 (22)
0.43 (64)
0.24 (12)
0.24 (7)
0.27 (4)
0.30 (3)
0.14 (3)
0
1
2
km


NO$_3$- N mg/L
2.5
2.0
1.5
1.0
0.5
1950
1960
1970
1980
YEARS

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