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EXCHANGE FLOWS BETWEEN
HAMILTON HARBOUR AND
LAKE ONTARIO

P.F. Hamblin and G.A. Lawrence

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**EXCHANGE FLOWS BETWEEN HAMILTON HARBOUR AND
LAKE ONTARIO**

P.F. Hamblin¹ and G.A. Lawrence²

¹ Lakes Research Branch
National Water Research Institute
867 Lakeshore Road, P.O. Box 5050
Burlington, Ontario L7R 4A6

² Department of Civil Engineering
University of British Columbia
Vancouver, B.C. V6T 1W5

MANAGEMENT PERSPECTIVE

Quantification of the exchange between Hamilton Harbour and Lake Ontario is needed for water quality modelling purposes and for the interpretation of other process related studies. In this brief report, some progress in this area is outlined and the steps required for further understanding are given which will lead to calculations of the flow from environmental conditions. In particular, the mixing between the out-flowing and inflowing layers in the summer period is discussed both from a field and laboratory perspective.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Il est nécessaire de mesurer les échanges entre le port de Hamilton et le lac Ontario en vue de la modélisation de la qualité de l'eau et de l'interprétation d'autres études connexes au processus. Ce bref rapport indique les progrès réalisés dans ce domaine, et précise les étapes nécessaires à une meilleure compréhension permettant de calculer le débit à partir des conditions environnementales. Notamment, le mélange entre les couches d'eau qui sortent et celles qui entrent, pendant la période estivale, est traitée d'un point de vue pratique et d'un point de vue expérimental.

INTRODUCTION

Hamilton Harbour has been designated as one of 42 areas of concern in the Great Lakes Basin by the International Joint Commission despite the large expenditures during the 1970's on pollution abatement (Environment Canada, 1988). Although industrial and municipal sources are, in general, meeting current water quality standards in many of these areas of concern, some problems persist. A feature common to many areas of concern is that they are located in bays, fjord-like inlets (Roy, 1983), or harbours where the exchange with the open lake is more restricted than in other coastal areas of the Great Lakes. While the principal processes responsible for nearshore-offshore exchange are known on a qualitative basis, there has been little attention given to developing a quantitative understanding which then may be applied to individual areas of concern to evaluate the effectiveness of various remedial strategies. Once a quantitative capability for simulating the exchange flow is known for one type of area of concern, say a harbour, hopefully this knowledge could be applied to other harbours.

Apart from the Great Lakes quantitative understanding of exchange flows is vital to the oceanography of Mediterranean Sea (Armi and Farmer, 1989) and for engineering considerations such as the effect of a proposed bridge between Denmark and Sweden on water quality in the Baltic Sea (Ottesen-Hansen and Moeller, 1990), and the flushing of coastal marinas (Schwartz and Imberger, 1988).

In the present paper we discuss field measurements of exchange flow between Hamilton Harbour and Lake Ontario in the context of internal hydraulic theory and laboratory experiments.

THE DYNAMICS OF THE STUDY AREA

Hamilton Harbour is located at the western end of Lake Ontario (Figure 1). The harbour has a maximum depth of 25 m, an average depth of 13 m, and a surface area which has been reduced by infilling of the southern shoreline to 21.5 km². Burlington ship canal (length 836 m, width 89 m and average depth 9.55 m (Spigel, 1989)) connects the harbour to Lake Ontario.

A simplified water balance also shown schematically in Figure 1 is comprised of inflow from three tributary streams of 4 m³/s, municipal sewage effluent of 3 m³/s, and an underdetermined amount from Lake Ontario. The reader is referred to Spigel (1989) for a more detailed discussion. An industrial usage of 27 m³/s contributes a substantial thermal loading to the harbour, although the water itself is recycled. Due to this thermal loading, as well as those from municipal sewage treatment plants and tributaries, and the confined nature of the surface waters of the harbour, a large temperature difference is created in the summer months between the surface waters of Hamilton Harbour and the cooler Lake Ontario water adjacent to the ship canal. Periodically, the temperatures in Lake Ontario are decreased even further by episodes of wind-induced upwelling of cold water.

The contrast in density between the two water bodies at the depths of the ship canal drives the densimetric exchange flow. Inflows of lake water sink along the bottom of the harbour until their density matches that of the ambient water whereupon the inflow intrudes into the hypolimnion. Subsequent wind stirring and convective cooling return the inflow to the surface layer through entrainment and turbulent mixing. The

harbour outflow spreads out as a thin jet of less dense fluid beyond the exit of the canal (Poulton et al., 1986). The concept of summer circulation between Lake Ontario and Hamilton Harbour that has emerged from the early studies of Dick and Marsalek (1983) and Klapwijk and Snodgrass (1985), as well as the recent investigation by Spiegel (1989), is illustrated schematically in Figure 2.

HYDRAULIC THEORY

To model the two-layer exchange through the ship canal we apply internal hydraulic theory for flows where frictional effects are important, as developed by Schijf and Schonfeld (1953), Dick and Marsalek (1973), and Holley and Waddell (1976). The theory is presented here in a manner that makes the comparison with open channel (single-layer) hydraulics clear; see Henderson (1966) for the corresponding open channel results. The exchange flow is characterized by internal hydraulic controls at either end of the canal; i.e.:

$$G^2 = 1 \quad (1)$$

where the composite Froude number $G^2 = F_1^2 + F_2^2$, and the densimetric Froude numbers $F_i^2 = u_i^2 / g' h_i$, $i = 1, 2$. The subscript 1 refers to the upper layer (outflow from Hamilton Harbour), and the subscript 2 refers to the lower layer (inflow into Hamilton Harbour). The thickness and average velocity of each layer are denoted by h_i and u_i , respectively. The reduced gravitational acceleration is $g' = \epsilon g$, where the relative density difference between the Hamilton Harbour and Lake Ontario waters, $\epsilon = (\rho_2 - \rho_1) / \rho_2 = 0(10^{-3})$.

The inflow Q_1 and the outflow Q_2 are determined by four factors: the presence of internal hydraulic controls at either end of the canal; the relative density difference, ϵ ; the total depth of flow, $h = h_1 + h_2$; and the internal resistance equation for the case of a wide rectangular channel with zero bed slope:

$$\frac{dh_I}{dx} = -S_{fI}, \quad (2a)$$

where the internal head

$$h_I = h_1 + \frac{1}{2g'} (u_1^2 - u_2^2), \quad (2b)$$

and the internal friction slope

$$S_{fI} = K_B F_2^2 + K_I \frac{h^2}{h_1 h_2} F_\Delta^2, \quad (2c)$$

where the bottom friction factor $K_B = f/8$, and f is the Darcy coefficient. The internal friction factor K_I is a measure of the strength of the shear between the layers. The stability Froude number is defined, $F_\Delta^2 = \Delta u^2 / g' h$, where for an exchange flow $\Delta u = |u_1| + |u_2|$. The stability Froude number provides a measure of the height of instabilities that may form on the interface. For a detailed treatment of the importance of the stability Froude number, and of all the other Froude numbers used in the study of two-layer flows, see Lawrence (1990).

If the above outline were completely accurate, solution of the exchange flow problem would be relatively straightforward. However, the above outline must be qualified.

Internal hydraulic theory assumes that the flow is non-hydrostatic, but in the vicinity of the internal hydraulic controls this is not strictly true. As a result the controls are not exactly at the end of the channel, although for most purposes this complication can be ignored. More importantly, if we substitute the equation for internal head (2b) into the resistance equation (2a), we obtain

$$\frac{dh_1}{dx} = \frac{-S_f I}{1 - G^2} \quad (3)$$

In an exchange flow, this equation cannot apply at the points of control (where $G^2 = 1$).

As a first attempt at overcoming this difficulty we have assumed that the variation in interface level is linear along the entire length of the ship canal, as indicated by the field data of Dick and Marsalek (1973). Once this assumption has been made the solution to the problem depends on the values chosen for the friction coefficients K_B and K_I . A comparison between our predictions of the inflow into Hamilton Harbour and the field data of Spiegel (1989) is given in Figure 3. We have plotted the results for an inviscid flow (where the correspondence with field data is poor), and the results obtained using the coefficients recommended by Dick and Marsalek (1973) (i.e., $K_B = 0.0026$ and $K_I = 0.001$), where the correspondence with field data is, in general, very good. For further details see Hamblin (1989).

A complete understanding of the factors determining the internal friction factor has not, as yet, been obtained. Part of the difficulty comes from the fact that both bottom generated turbulence and turbulence generated by shear at the

interface are important, see Grubert (1990). Interfacial effects are perhaps the least well understood. Some of Spigel's (1989) field data suggest the presence of large scale interfacial instabilities, see Figure 4. Recent experiments by the Department of Civil Engineering at the University of British Columbia modelling exchange flow through a contraction exhibit both Kelvin-Helmholtz and Holmboe instabilities. In Figure 5a Kelvin-Helmholtz billowing is visible, and in Figure 5b the cusping Holmboe instability is visible (for further discussion of these interfacial instabilities, see Lawrence et al. 1990).

The other parameter that is difficult to specify is the relative density difference, since from Figure 4 we see that it is not immediately obvious what values to assign for the density (temperature) of each layer. The modelling carried out to date indicates that extreme density differences are more appropriate than averaged densities, but this result needs to be tested further.

FIELD MEASUREMENTS

The ten flow measurements of Dick and Marsalek (1972) are based on a single current profile at the centre of the canal and do not include a wide range of flow variation whereas the measurements taken in 1988 (Spigel, 1989) are much more detailed and encompass a wide range of exchange flows. In most cases, Spigel's data consisted of 36 individual flow measurements at four locations across the ship canal. Whenever a series of discharge measurements are made over a seasonal period it is of interest to check continuity or mass balance. From the previous discussion of the mass balance we would expect an outflow of $7 \text{ m}^3/\text{s}$ on average; whereas, the measurements of Dick and

Marsalek (1972) suggested a summer inflow of $11 \text{ m}^3/\text{s}$, and the data of Spigel (1989) indicate an average inflow of $21.4 \text{ m}^3/\text{s}$. Evaporative loss from the harbour could account for only $1 \text{ m}^3/\text{s}$ in the extreme case. It is possible that the mid-day sampling of the flow could bias the exchange flow since land-lake winds alternate on a daily basis during the summer season. Sampling of the discharge during the night or on a continuous basis would be required to check this possibility.

DISCUSSION

Although we have presented a model that provides encouraging agreement with field data, there is still work to be done to improve our ability to predict exchange flow through the ship canal connecting Hamilton harbour with Lake Ontario. There are at least four areas for potential improvement:

- (1) Prediction of the density difference between the near surface waters on either side of the canal, requiring a better understanding of the dynamics of both water bodies.
- (2) Evaluation of the internal coefficient of friction, requiring a fuller understanding of the dynamics of stratified shear flows.
- (3) Relaxation of the assumption of a linear variation in interface height, requiring a more sophisticated method of solving the internal hydraulic equations.

- (4) More extensive measurement of flows in the ship canal, so that predictions can be tested.

The nearly continuous injection of cold water into the deeper layers of Hamilton Harbour results in a pronounced vertical density stratification. This cold water is an important source of oxygen for the hypolimnion; on the other hand, the enhanced stratification decreases the downward flux of oxygen from the surface. Lee et al. (1989) have shown with a mathematical model that the elimination of the summer exchange with Lake Ontario results in a dramatic reduction in the summer stratification. Further, laboratory and mathematical modelling work should be undertaken to examine the feasibility of using an air curtain across the ship canal to prevent the exchange of Lake Ontario water, and the effect that this would have on water quality in Hamilton Harbour.

ACKNOWLEDGEMENT

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REFERENCES

- Armi, L. & Farmer, D.M. 1989. The flow of Mediterranean water through the Strait of Gibraltar. *Progress in Oceanography*, 21(1).

- Dick, T.M. and Marsalek, J. 1972. Thermal wedge between Lake Ontario and Hamilton Harbour. Proc. 15th Conf. Great Lakes Res., 563-543. Int'l. Assoc. Great Lakes Res.
- Dick, T.M. and Marsalek, J. 1973. Exchange flow between Lake Ontario and Hamilton Harbour. Environment Canada, Scientific Series No. 36, Inland Waters Directorate, Canada Centre for Inland Waters, Burlington, Ontario.
- Environment Canada 1988. Canada-Ontario Agreement Remedial Action Plan Program, Hamilton Harbour: Goals, Problems and Options. Environment Canada, Ontario Ministry of the Environment.
- Grubert, J.P. 1990. Interfacial mixing in estuaries and fjords. Journal Hydr. Eng., 116(2): 176-195.
- Hamblin, P.F. 1989. Notes on the hydraulics of Hamilton Harbour. Environment Canada, National Water Research Institute, Burlington, Ontario, Contribution No. 89-36.
- Henderson, F.M. 1966. Open channel flow. Macmillan, New York.
- Holley, E.R. and Waddell, K.M. 1976. Stratified flow in Great Salt Lake culvert. J. Hydr. Div. ASCE, 102: 969-985.
- Klapwijk, A. and Snodgrass, W.J. 1985. A model for lake-bay exchange flow. J. Great Lakes Res., 11(1): 43-52.
- Lawrence, G.A., Browand, F.K. and Redekopp, L.G. 1990. The stability of a sheared density interface. Accepted for publication in Phys. Fluids A: Fluid Dyn.

- Lawrence, G.A. 1990. On the hydraulics of Boussinesq and non-Boussinesq flows. J. Fluid Mech. (in press).
- Lee, D., Hamblin, P.F., Smith, A.A. and Snodgrass, W.J. 1989. Comparison of bottom and surface cooling withdrawals in a harbour. National Water Research Institute, Burlington, Ontario, Contribution No. 89-45.
- Ottesen-Hansen, N.-E. and Moeller, J.S. 1990. Zero blocking solution for the Great Belt link. Proc. of the NATO/ONR Workshop on the Physical Oceanography of Sea Straits. Kluwer (in press).
- Poulton, B.J., Kohli, B., Weiler, R.R., Heathcote, I.N. and Simpson, K.J. 1986. Impact of Hamilton Harbour on Western Lake Ontario. Ministry of the Environment, Ontario.
- Roy, F. 1983. Spring exchange flows Black Bay, Lake Superior. Unpublished Manuscript. National Water Research Institute, Burlington, Ontario.
- Schwartz, R.A. and Imberger, J. 1988. Flushing behaviour of a coastal marina. Proceedings 21 International Conf. on Coastal Engineering, Torremolinas, Spain, 2626-2640.
- Schijf, J.B. and Schonfeld, J.C. 1953. Theoretical considerations on the motion of salt and fresh water. In. Proc. of the Minn. Int'l. Conv., Joint Meeting of the IAHR and Hyd. Div. ASCE, 321-333.

Spigel, R.H. 1989. Some aspects of the physical limnology of Hamilton Harbour. Environment Canada, National Water Research Institute, Burlington, Ontario, NWRI Contribution No. 89-08.

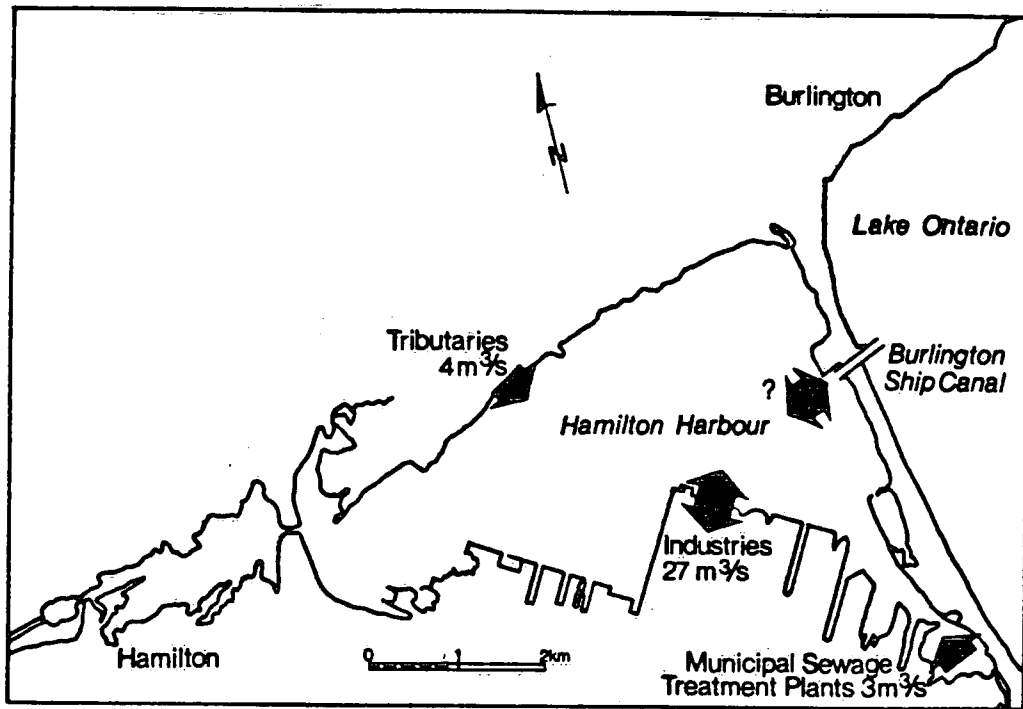


Figure 1. Map of Hamilton Harbour showing major inflows and exchanges.

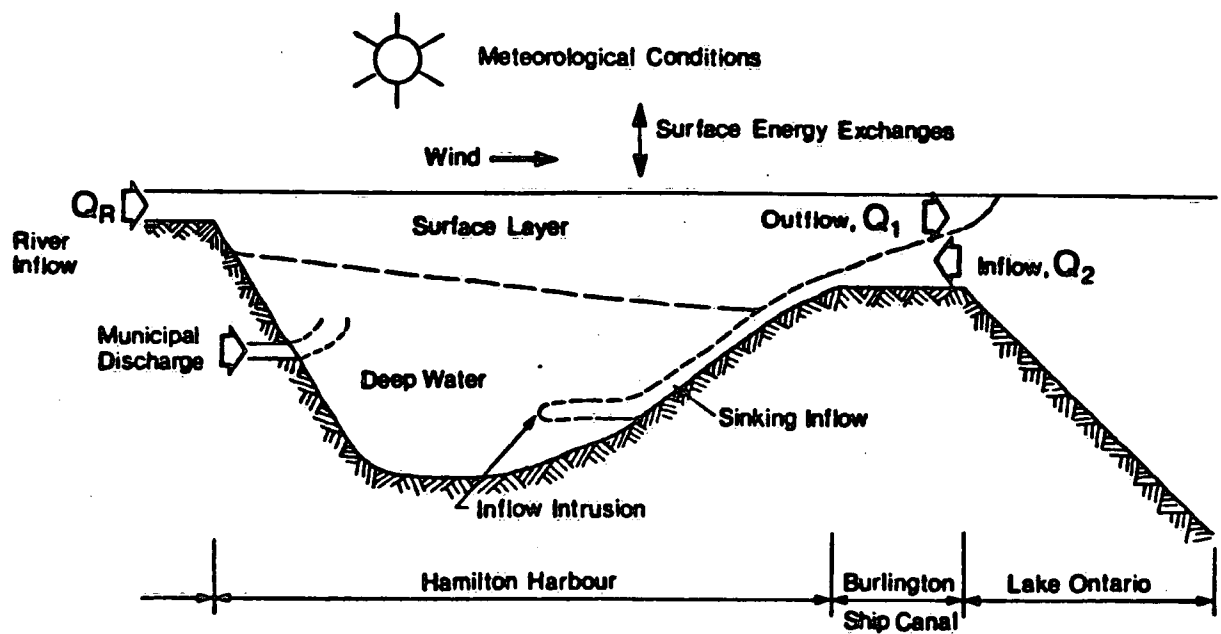


Figure 2. Schematic of the two layer exchange flow between Hamilton Harbour and Lake Ontario, applicable from May to October.

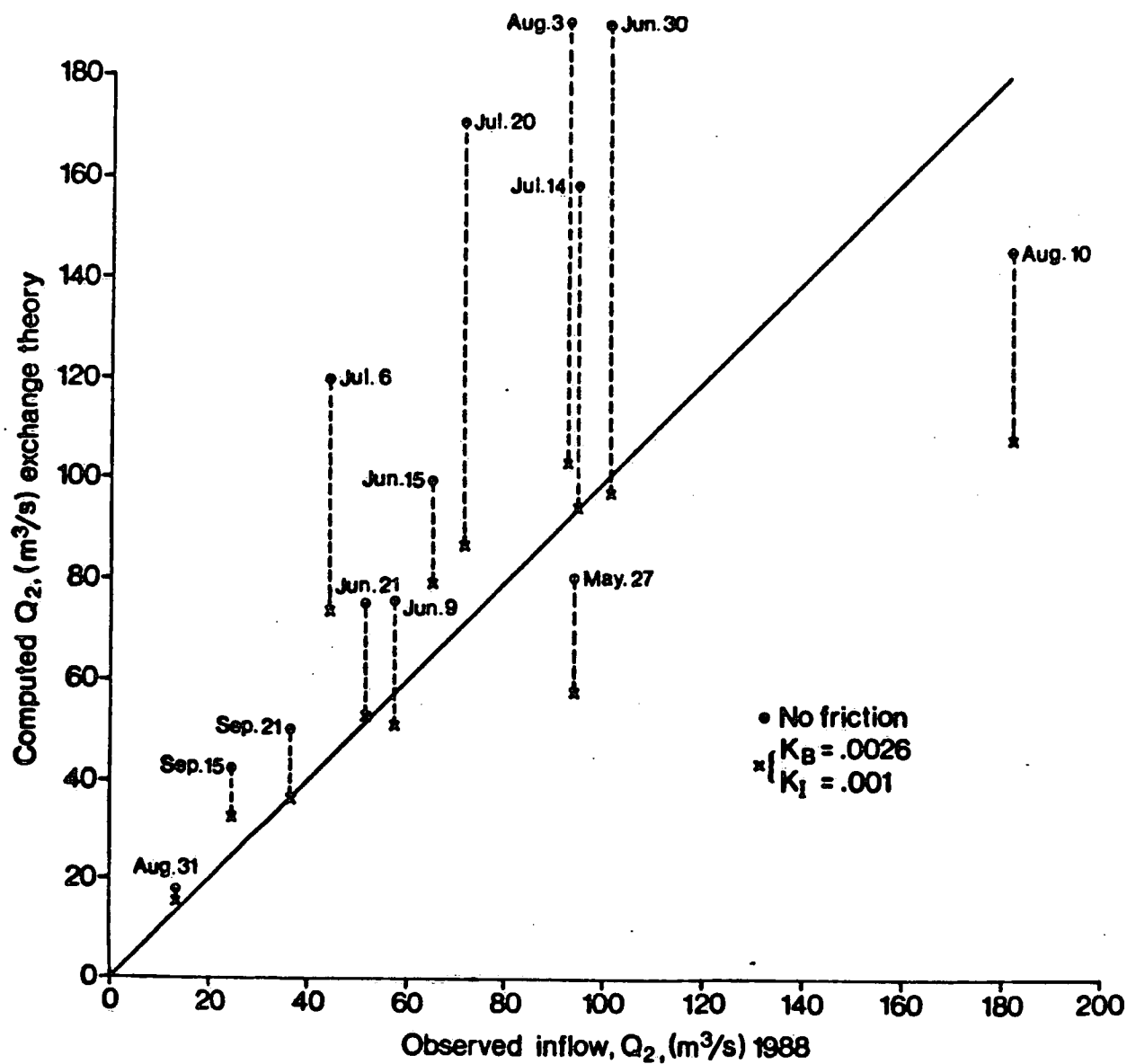


Figure 3. Computed Lake Ontario inflow, Q_2 (m^3/s), based on extreme buoyancy differences from the data of Spigel (1989), versus observed inflow

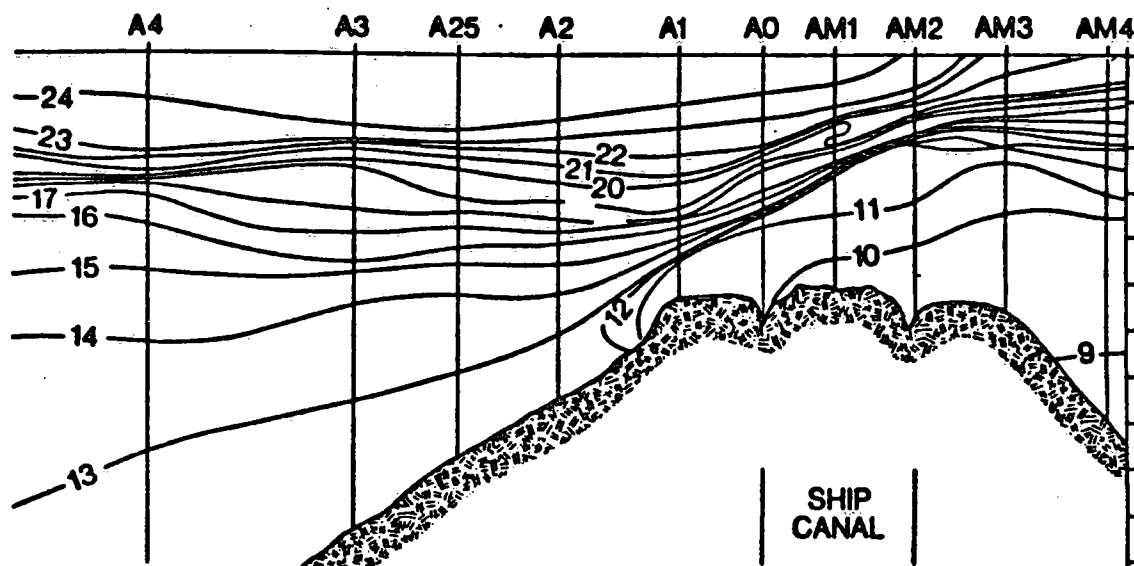


Figure 4. Temperature contours for Hamilton Harbour on August 3rd 1988. Note the overturning event at station AM1, indicating the presence of a Kelvin-Helmholtz instability.

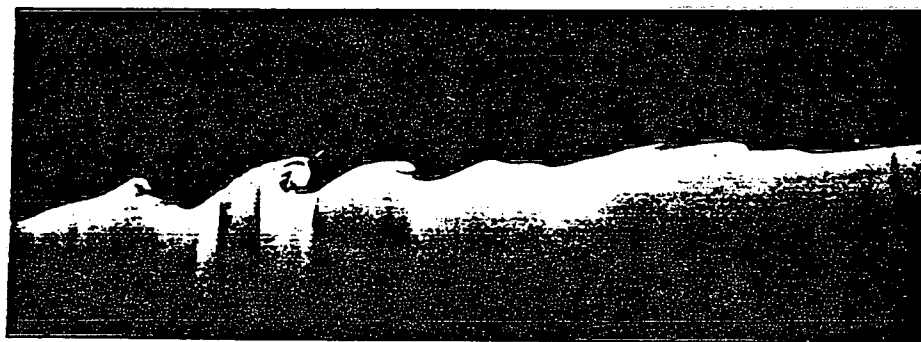
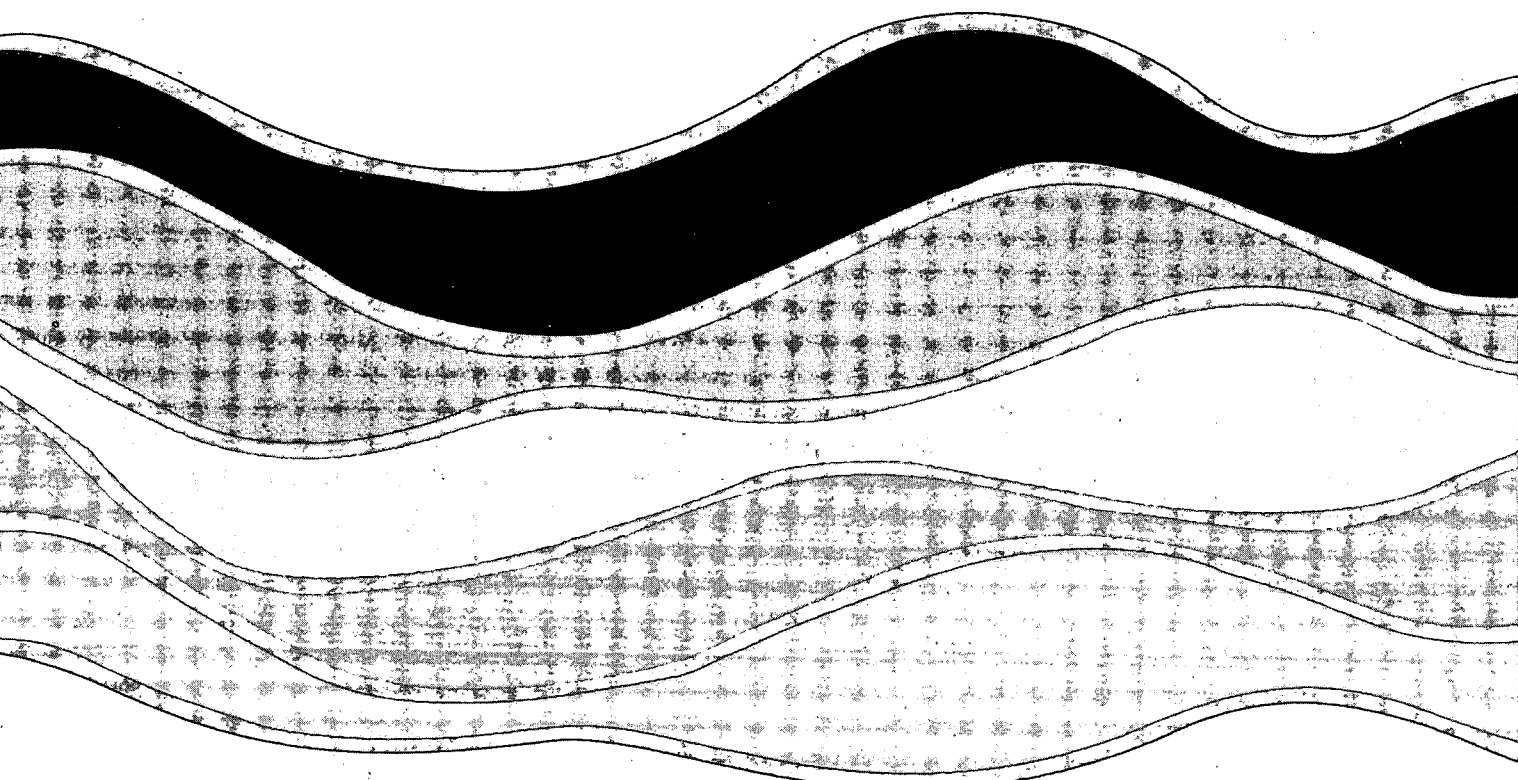


Figure 5. Photographs of exchange flow through a contraction. Kelvin-Helmholtz (billowing) instabilities are visible in (a); whereas, Holmboe (cusping) instabilities are visible in (b).

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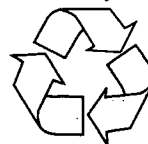
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