95-42

# Environment Canada
## Water Science and Technology Directorate

---

## Direction générale des sciences et de la technologie, eau
# Environnement Canada

# Modelling Polynya Formation by Vertical Jet Flow i Lakes

By:

M. Helsten, P. Hamblin, R. Baddour

95-42

# Modelling Polynya Formation by Vertical Jet Flow in Lakes

M.A. Helsten[1], P.F. Hamblin[2], and R.E. Baddour[3]

## Abstract

When ice cover on mid-latitude lakes prevents the replenishment of stored dissolved oxygen, which has been depleted by biological demand and reduced oxygen production in the winter, massive fish kills have been reported. The water quality in an ice-covered, eutrophic lake can be improved by creating an ice opening through the use of a flow developer. This ice opening, or polynya, provides a large area of exposed water through which the lake can be naturally aerated. The flow developer circulates warmer water from the bottom of the lake, and uses this flow to open and maintain the polynya throughout the winter months. A previous field study has shown that it is important that the circulation causing the ice free patch is minimal under the ice to prevent excessive heat loss. Thus, any flow development system would be optimized from this viewpoint as well as the operating cost . This study examines the performance of a submerged flow-developer which pumps water from a lake bottom vertically onto the underside of the ice cover.

The formulation of the polynya is investigated numerically and experimentally. The numerical model is based on an integral jet formulation and heat-transfer properties of a turbulent radial jet impinging on a flat plate.

The laboratory experiment is carried out in a 1 $m^3$ tank. The tank is well-insulated and equipped with a chiller unit capable of cooling the air above the water to -30° C. Water is removed from the tank bottom, passed through a constant-temperature bath, and discharged back as a vertical submerged jet impinging on the ice. The results of the experiment are presented in this paper and compared with numerical predictions of ice opening.

---

[1] Graduate Student, [2] Aquatic Ecosystems Restoration Branch, National Water Research Institute, and Adjunct Professor, [3] Professor., Dept. of Civil Engineering, University of Western Ontario, London, Ontario, Canada.

## Introduction

Winter ice and snow cover on mid latitude lakes creates limnological conditions greatly different than those for other seasons (Greenbank, 1945). Ice cover prevents the natural aeration normally provided by wind agitation and limits the exchange of gases with the atmosphere. The supply of light required for photosynthesis can also be entirely cut off. This situation may cause severe oxygen deficits, especially in eutrophic lakes with high biological oxygen demand (BOD) at the sediment surface (Mathias and Barcia, 1980). In extreme cases, the dissolved oxygen levels can drop to levels below the minimum requirements for fish survival, resulting in what is known as winterkill.

A method of alleviating this problem is to artificially aerate the lake by recirculating warmer water from the lake bottom, thus melting a portion of the ice cover and eventually restoring dissolved oxygen (DO) to acceptable levels. This solution has been attempted with varying degrees of success (Flick, 1968; Greenbank, 1945; Lackey and Holmes, 1972; Merna, 1965; Patriarche, 1961), using a variety of methods ranging from the injection of compressed air to create a bubble plume, to the use of outboard motors to flood and melt a portion of the ice cover. These studies have been for the most part conducted by biologists, and little attention has been paid to the actual flow and heat transfer mechanisms involved in creating and the ice-free zone, known technically as a polynya.

A laboratory investigation was carried out by Ellis and Stefan (1990) studying an aerator design which leaves the ice cover intact, reducing potential hazards for winter lake users, something which should be considered in the design. Field studies have also been performed examining the effect of an artificial flow developer on the heat budget of a mid-latitude lake (Rogers, 1992 and Rogers et al 1995) with an engineering focus in mind. In the roger's study it was found by means of a control lake that the flow developer had a profound influence on the heat transfer through the ice cover. The purpose of the present study is to measure this influence under more controlled conditions than were possible in the field.

In so far as controlling ice for the purposes of extending the navigation season and protecting coastal structures, previous studies have focused on horizontal type flow developers (Eranti et al, 1983), the use of bubble plumes (Ashton, 1979), and on the use of thermal bubblers (Baddour, 1989). This study will concentrate on the use of vertical submerged jet in a laboratory situation to melt and maintain the polynya which is similar to that used in the field study of Rogers.

## Experimental Apparatus

The tank is of acrylic construction with all sides but the front heavily insulated with styrofoam. The front viewing window is two ply acrylic with an air gap between the panes. Water is removed from the bottom of the tank, passed through a constant temperature bath, and discharged as a vertical submerged jet, impinging on the ice cover above. A rake of thermocouples connected to a data acquisition system was used to record the water and air temperatures during the experiment. See Figure 1 for details.

# Modelling Polynya Formation by Vertical Jet Flow in Lakes

by

M.A.Helsten, P.F.Hamblin and R.E.Baddour

## MANAGEMENT PERSPECTIVE

This conference proceedings paper is more detailed report of a series of laboratory experiments that we have undertaken to study the efficiency of maintaining an ice-free patch in lakes by means of a submerged jet which lifts warmer water to the surface thereby melting the ice cover. We expect that this strategy will be employed in remediating lakes which winter fishkill is prevelant as oxygen may enter the lake by means of the open water and replenish the exhausted subsurface layers. With the tested mathematical model developed here we plan to implement it in water quality model for ice covered lakes. Once the model is available we can explore two issues, namely, the efficiency and cost of operation and the minimization of heat loss from the lake. This study is supported by means of a NSERCC research grant to P. Hamblin.

## Experimental Results and Observations

The first experiments were conducted varying the distance, h, of the ice sheet above

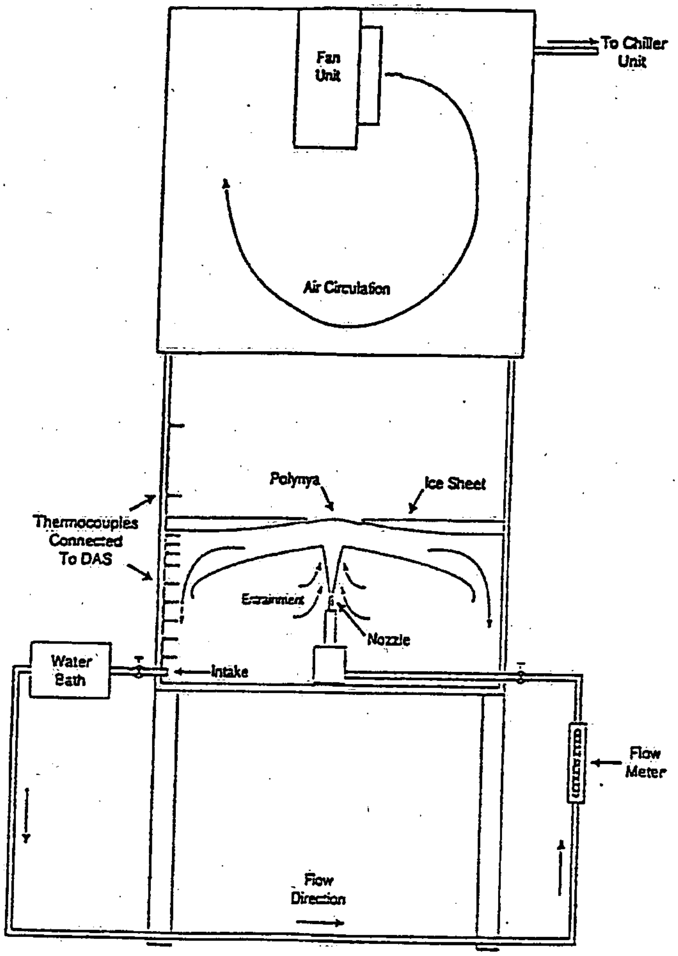

Figure 1. Experimental apparatus

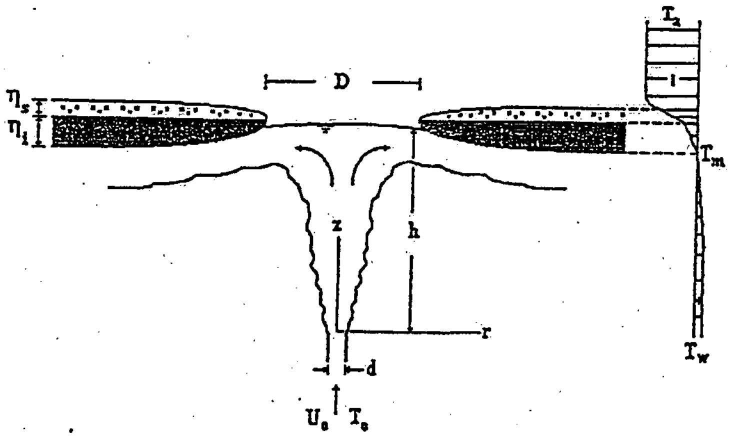

Figure 2. Definition sketch of variables used in the model and experiment.

A second set of experiments were conducted in order to more closely examine the two above-mentioned regimes. In these tests, the jet was observed using dye, without ice cover, varying the Froude number, $Fr = U_J/\sqrt{gd}$, of the jet and the ratio h/d. The experiments were videotaped for later analysis. It was found that for higher Froude numbers, and for small h/d, the above mentioned "plunging" effect was easily observed. This can be seen in Figure 4, a dimensionless plot of the results for all cases examined. As the Froude number becomes smaller, and the relative distance, h/d, becomes larger, the plunging effect is less apparent, and a radial surface jet was observed. As shown in Figure 4, for a certain range of Fr at a given h/d, a transitional behaviour was observed in which part of the jet spreads, and part tended to plunge.

This plunging action of the impinging jet is a phenomenon mainly associated with the scale at which the experiments were conducted. In the experiments it was possible to have a high Froude number with a reasonable Reynolds number to match. As the phenomenon is scaled up to a field situation, the Froude number drops considerably with the same Reynolds number. In order to have this plunging problem in the field it would be necessary to either have an unreasonably high Reynolds number, or an unreasonably low h/d ratio. It is however important to recognize this behaviour in a scaled-down laboratory situation.

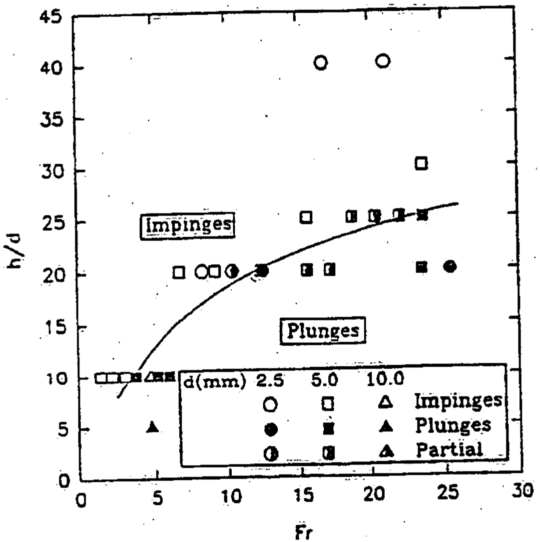

Figure 4. Graph parameterizing jet interaction with free surface. $Fr = U_J/\sqrt{gd}$

The impinging jet model to be described in the following section should be adequate before the polynya is created. In this case we have a true impinging jet. Once an opening is formed, the flow dynamics are different from that of a flat plate impingement. The surface of the water cannot be considered rigid, as a plate, and a cavity is formed. The cavity changes the direction of the flow at the edge of the polynya and tends to separate the flow from the ice. It is also suspected that the disturbance created on the surface will increase heat transfer at the edge of the polynya due to the waves and increased turbulence caused by it. The ratio of jet submergence to the thickness of ice cover would also likely affect the polynya growth rate. The smaller this value is, the more pronounced the "cavity" effect would be, making the situation more remote from the impinging jet ideal.

## Numerical model

A numerical model was used in this study to simulate the effect of a thermal jet on surface ice. The model is similar to the model by Baddour (1989) who simulated the performance of a thermal-bubble plume to control ice. The model has two components. The first component deals with the development of a vertical jet, and the second component deals with thermal effects on ice.

### *Thermal jet formulation*

The thermal jet formulation is based on the classical entrainment hypothesis by Morton et al (1956) as well as the mass, momentum, and thermal energy principles. The axi-symmetric flow considered is illustrated in Fig. 2. The radial distance, r, is measured from the centre of the jet, and vertical distance, z, is measured above the source of the jet, which is located at a distance h below the surface. The initial diameter of the jet is d = 2 $b_0$, the initial velocity is $U_0$, and the initial temperature is $T_0$. The temperature of the surrounding water, which may vary with z, is $T_w$. At z = 0, $T_w = T_{w0}$ which is greater than the melting temperature $T_m$ of ice. At the ice/water interface the temperature of water is equal to melting temperature of ice, i.e 0°C for water with negligible salinity. The thermal jet is characterized by the following integral variables:

$$Q = 2\pi\int_0^\infty U r\,dr = I_u \pi b^2 U_m \;;\; M = 2\pi\int_0^\infty U^2 r\,dr = I_{uu} U_m^2 b \tag{1}$$

$$\phi = 2\pi\int_0^\infty U\,\Delta T\, r\,dr = I_{ut}\,\pi b^2\, U_m\,\Delta T_m \tag{2}$$

where subscript m refers to a maximum value, and $\Delta T = T - T_w$ is the excess temperature in the jet above the surrounding water. The mean profiles of velocity and temperature in the vertical jet are assumed Gaussian and given by:

$$f_U = \frac{U}{U_m} = e^{-\xi^2} \quad;\quad f_T = \frac{\Delta T}{\Delta T_m} = e^{-(\frac{\xi}{\lambda_T})^2} \tag{3}$$

where $\xi = r/b$ and b is the characteristic radius of the velocity profile defined at $U/U_m = e^{-1}$. The characteristic radius of the temperature profile, $b_T$, is know from experiment to be larger than b, and the ratio $\lambda_T = b_T/b = 1.19$, List 1982. For the profiles given in Equ. 3 the shape parameters in Eqs. 1 and 2 are:

$$I_u = 1 \quad;\quad I_{uu} = \frac{1}{2} \quad;\quad I_{ut} = \frac{\lambda^2}{1+\lambda^2} \tag{4}$$

Applying mass, momentum and thermal energy principles, the equations governing the development of the jet are:

$$\frac{dQ}{dz} = 2\pi b\, E\, U_m \quad ; \quad \frac{dM}{dz} = 2\pi \int_0^\infty g' r dr = G \quad ; \quad \frac{d\Phi}{dz} = -\frac{dT_w}{dz} Q \tag{5}$$

Where E is the entrainment coefficient, and G the integral force produced by the thermal buoyancy g'. G is calculated in this model as a function of $\Delta T$ with a nonlinear algorithm derived by Baddour (1991). The jet entrainment coefficient is E = 0.053, List 1982. Note that the buoyancy force G is negligible and could be ignored when the source is located close to the ice.

The jet solution is obtained numerically by integrating the Eqs in 5 . The initial conditions specified at z = 0 are $Q_0 = \pi b_0^2 U_0$, $M_0 = \pi b_0^2 U_0^2$ , $\phi_0 = \pi b_0^2 U_0 \Delta T_0$. A developing region near the source is incorporated in this model where the velocity and temperature profiles vary from uniform at z = 0 to Gaussian at z = 5d. At every step of integration the local jet variables $[U_m, \Delta T_m, b]$ are calculated by solving the algebraic Equs 1 and 2. The numerical integration is terminated at z = h, and the jet properties associated with the impinging region are determined.

*Jet/ice thermal interaction*

The components of the thermal budget considered in this model are i) $\phi_{wa}$ = water/air heat transfer from open area, ii) $\phi_{ia}$ (or $\phi_{sa}$) = water/air (or snow/air) heat transfer, iii) $\phi_{ji}$ = jet/ice heat transfer, iv) $\phi_i$ = heat conduction through a layer of ice, v) $\phi_s$ = heat conduction through a layer of snow, vi) $\phi_{po}$ = heat transfer from precipitation ( snow or rain) in the open area, and vii) $\phi_{se}$ = snow melting at the edge of the open area.

Previous investigations suggest that the heat transfer properties of jets impinging normally on flat plates are given by a nondimensional equation of the form:

$$\frac{Nu}{Pr^{1/3}\, Re^{4/5}} = f\left(\frac{r}{b}\right) \tag{6}$$

In which, the Nusselt number $Nu = h_{ji}\, b(h)/k_w$ , where $h_{ji}$ = jet/ice heat transfer coefficient and $k_w$ is the thermal conductivity of water. The Prandtl number $Pr = c_w\, \mu_w/k_w$, where $c_w$ = specific heat of water, and $\mu_w$ = viscosity of water. The Reynolds number $Re = U_m(h)\, b(h)/\nu_w$ , where $\nu_w$ = kinematic viscosity of water, and the two jet parameters, $U_m$ and b, are calculated at z = h.

The comprehensive set of data by Donaldson et al (1971) suggest that Equ. 6 can be approximated by:

$$\frac{Nu}{Pr^{1/3}\,Re^{4/5}} = 0.055\; e^{-0.184\frac{r}{b(h)}} \tag{7}$$

Once the Nusselt number Nu and the corresponding heat transfer coefficient $h_{ji}$ are calculated, the local convective heat flux transferred from the jet to the ice is determined by the equation

$$\phi_{ji} = h_{ji}\,(T_j - T_m) \tag{8}$$

The thermal budget in the impingement region controls the jet temperature below the ice. Accordingly, the average jet temperature at the edge of the open area is:

$$T_j = \frac{\phi(h) - \phi_{wa} - \phi_{po} - \phi_{se}}{Q(h)} \tag{9}$$

where Q(h) and $\phi$(h) are the jet volume flux and thermal flux, respectively, calculated at z = h.

The components of the heat budget in Equ. 9 which reduce the flux of heat transferred under the ice are:

$$\phi_{wa} = h_{wa}\,[\,T(h) - T_a\,]A_0 \tag{10}$$

$$\phi_{p0} = \rho_s i_s [c_s(T_m - T_a) + \lambda_s] A_0 \tag{11}$$

$$\phi_{se} = \rho_s \eta_s [c_s(T_m - T_a) + \lambda_s]\frac{dA_0}{dt} \;\; ; \;\; \frac{dA_0}{dt} > 0 \tag{12}$$

$$\phi_{se} = 0 \;\; ; \;\; \frac{dA_0}{dt} < 0 \tag{13}$$

$h_{wa}$ is the water/air heat transfer coefficient, which was constant in the laboratory experiment. In field applications, however, the flux $\phi_{wa}$ can be calculated from well established parameters which characterize solar and long wave radiations, and climatic and wind conditions ( e.g. Ashton 1986). The average surface temperature in the open area is $T(h) = \phi(h)/Q(h) + T_m$. The air temperature $T_a$ was also constant in the laboratory experiment. In practice, $T_a$ is measured at a reference height above the surface of the water ( usually 2m or 10 m depending on the equations adopted to calculate the various surface heat fluxes). The other variables in the above equations are $A_0$ = surface area of open water, t = time, $\rho_s$ = density of snow, $i_s$ = rate of snow precipitation, $c_s$ = specific heat of snow, $\lambda_s$ = heat of fusion of snow, an $\eta_s$ = thickness of the layer of snow.

The final step in this model is to calculate the ice thickness and the development of the open area with time. The physical equation governing the change in ice thickness, $\eta_i$, with at distance r is:

$$\rho_i \lambda_i \frac{d\eta_i}{dt} = \phi_i - \phi_{ji} \tag{14}$$

where the flux transferred by conduction through the ice and snow is

$$\Phi_i = \phi_s = \frac{T_m - T_a}{\frac{\eta_i}{k_i} + \frac{\eta_s}{k_s} + \frac{1}{h_{sa}}} \tag{15}$$

and the flux, $\phi_{ji}$, transferred convectively from the jet to the ice was defined in Equ. 8

Equ. 14 is integrated numerically. The atmospheric and water conditions can be updated at each time step to perform long term simulations. At each time step, the ice thickness is calculated at a large number of point in the radial direction. From these data, a radial profile of ice thickness is obtained, and the outer boundary of the domain where $\eta_i = 0$ defines the radius of the open water, $R_0$.

## Concluding Remarks

Work is currently in progress to link the polynya simulation developed in this study to a dynamic water quality model DYRESM, developed by Imberger and Patterson (1981). This model was developed initially to predict various water quality parameters linked to mixing in temperate lakes and reservoirs. The effects of ice cover on mixing mechanism, and the interaction between ice formation and mixing, have been incorporated into the model by Patterson and Hamblin (1988), and an ice cover routine incorporated for mid latitude lakes (Rogers, 1992; Rogers et al., 1995). One of the key findings of the latter study was that in a lake with an artificially maintained polynya much of the total heat loss to the atmosphere occurred through the ice, presumably due to increased sensible heat transfer from the water to the ice caused by the underice circulation associated with the stirrer. We intend to incorporate a laboratory tested far field solution of the jet model in the water quality model. This underice circulation will allow the sensible heat transfer to be calculated using the standard bulk formulae (Hamblin and Carmack, 1990). As well, the expressions developed herein for the polynya formation and area will be included in the model of Patterson and Hamblin (1988). Finally, this model will extended to treat the effect of pumping warmer water from the subsurface layers on the temperature of these layers. Once such a model is developed and validated it may be employed in specific applications to determine the most efficient design of lake aeration in winter.

## References

**Ashton, G.D.** (1979). Point source bubbler systems to suppress Ice. *CRREL Report* 79-12, U.S. Corps of Engineers, Hanover, NH.
**Ashton, G.D.** (1986) *River and Lake Ice Engineering*, Ed., Water Resources Publications
**Baddour, R.E.** (1989). Computer simulation of ice control with thermal bubbler plumes: point source configuration. *Proceedings, Ports '89*, ASCE, Boston, 550-559.
**Baddour, R.E.** (1991) Thermal hydraulic jump: theory and experiment. *J. Fluid Mech.*, 226, 243-256.
**Donaldson, C. dup., Snedeker, R.S., and Margolis, D.P.** (1971). A study of free jet impingement. Part 2. free jet turbulent structure and impingement heat transfer. *J. Fluid Mech.*, 45(3), 477-512.
**Ellis, C.R., Stefan, H.G. (1990).** Hydraulic design of winter lake aeration system. *J. Environ. Engng.*, 116(2), 376-393.
**Eranti, E., Leppänen, E., Penttinen, M. (1983).** Ice control in finnish harbours. *Proceedings, 7th International Conference on Port and Ocean Engineering Under Arctic Conditions*, Vol. 1, Espoo, Finland, 370-380.
**Flick, W. (1968).** Dispersal of aerated water as related to prevention of winterkill. *Prog. Fish Cult.*, 30(1), 13-18.
**Gilpin, R.R., Lipsett, A.W. (1978).** Impingement melting: experiment and numerical simulation. *Proceedings of the 6th International Heat Transfer Conference*, Vol. 3, Hemisphere, Washington DC. 43-47.
**Greenbank, J.** (1945). Limnological conditions in ice-covered lakes, especially as related to the winterkill of fish. *Ecological Monographs*, 15(4), 344-392.
**Hamblin, P.F., Carmack, E.C. (1990).** On the rate of heat transfer between a lake and an ice sheet. *Cold Regions Science and Technology*, 18, 173-182.
**Imberger, J., Patterson, J. (1981).** A dynamic reservoir simulation model: DYRESM5, In H.B. Fischer [ed.], *Transport Models for Inland and Coastal Waters*. Academic, 310-361.
**Lackey, R.T., Holmes, D.W. (1972).** Evaluation of two methods of aeration to prevent winterkill. *Prog. Fish Cult.*, 34(3), 175-178.
**List, E.J.** (1982). Turbulent jets and plumes. *Ann. Rev. Fluid Mech.*, 14, 189-212.
**Mathias, J.A., Barcia, J.** (1980). Factors controlling oxygen depletion in ice-covered lakes. *Can. J. Fish. Aquat. Sci.* 37(2), 185-194.
**Merna, J.W. (1965).** Aeration of winterkill lakes. *Prog. Fish Cult.*, 27(4), 199-202.
**Patriarche M.H. (1961).** Air-induced circulation of two shallow Michigan lakes. *Journal of Wildlife Management*, 25(3), 282-289.
**Patterson, J.C., Hamblin, P.F.** (1988). Thermal simulation of a lake with winter ice cover. *Limnol. Oceanogr.* 33(3), 323-338.
**Rogers, R.K. (1992).** *Impact of an Artificial Circulation Device on the Heat Budget of an Ice-Covered Mid-Latitude Lake*. M.A.Sc. Thesis, University of British Columbia, Vancouver, B.C., Canada.
**Rogers, R.K., Lawrence, G.A., Hamblin, P.F. (1995).** Observations and numerical simulation of a shallow ice-covered mid-latitude lake. In Press, *Limnol. Oceanogr.*

Environment Canada Environnement Canada

Canada

**Canada Centre for Inland Waters**
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

**National Hydrology Research Centre**
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

**St. Lawrence Centre**
105 McGill Street
Montreal, Quebec
H2Y 2E7 Canada

**Place Vincent Massey**
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

**Centre canadien des eaux intérieures**
Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

**Centre national de recherche en hydrologie**
11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

**Centre Saint-Laurent**
105, rue McGill
Montréal (Québec)
H2Y 2E7 Canada

**Place Vincent-Massey**
351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada