CIVIL ENGINEERING REPORT NO. 18.4
FACULTY OF ENGINEERING AND APPLIED SCIENCES
STATE UNIVERSITY OF NEW YORK AT BUFFALO

LAKE ONTARIO HYDRAULIC MODEL STUDY

(Preliminary Results)

by
Ralph R. Rumer, Jr.
Kenneth Kiser
C. Y. Li

DECEMBER 1972

Prepared under the support of
New York State Sea Grant Program
NOAA Office of Sea Grant
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Notation

D = Ekman depth of frictional influence

L = horizontal length

M = subscript denoting model quantity

P = subscript denoting prototype quantity

r = subscript denoting ratio of model quantity to prototype quantity

t' = dimensionless time

T = period of uninodal seiche

T_r = time ratio in model to prototype

U = velocity

U_s = surface wind drift velocity

V_w = wind velocity

Z = vertical length

α = decay modulus

β = decay rate

ϵ_z = turbulent momentum transport coefficient in vertical direction (eddy viscosity)

η = amplitude of seiche

η_o = initial amplitude of seiche

ϑ = Proudman number

υ = molecular momentum transport coefficient (molecular viscosity)

ρ = fluid density

$\Delta\rho$ = density difference in stratified fluids

φ = latitude

ω = angular velocity

Ω = angular velocity of earth

I. INTRODUCTION

Bordered on the north by Canada, and on the south by New York State, Lake Ontario is the easternmost of the Great Lakes. Water from the other Great Lakes drains into Lake Ontario through the Niagara River and leaves by way of the St. Lawrence River. The Lake has the following physical characteristics: length, 190 miles; average width, 53 miles; average depth, 283 feet; maximum depth, 840 feet; volume, 403 cubic miles; and surface area, 7,520 square miles. The Niagara River inflow averages just over 200,000 cubic feet per second while the outflow through the St. Lawrence River averages about 238,000 cubic feet per second. The difference is accounted for by tributary inflows from the Lake Ontario drainage basin which covers approximately 27,300 square miles and the net accumulation of rainfall.

The purpose of this physical model study is to acquire understanding and provide new information regarding the behavior of the Lake Ontario water mass in response to wind stress at the free surface, thermal stratification, and the major inflow and outflow. [See Rumer and Hoopes (1970).] The model is rotated to incorporate the Coriolis force.

In many respects, this model study is similar to a previous investigation of Lake Erie [Rumer (1970)]. This earlier study provided information on seiching and on circulation patterns resulting from the inflow of the Detroit River, the outflow of the Niagara River, and the Coriolis force [Rumer and Robson (1968)]. Subsequently, the wind-driven circulation observed in the Lake Erie model was reported by Buechi and Rumer (1969). The results of these model studies were utilized in the development of an empirical approach to predicting pollutant distribution in the Western Basin of Lake Erie [Howell et al (1970)].

Two important questions arose from this earlier work on Lake Erie. The first pertains to the difficulty of simulating frictional resistance in a hydraulic model; a problem not very new to hydraulic engineers. The second pertains to the effects of model scale distortion on dispersion phenomena. The latter problem has been discussed recently by Fischer and Holley (1971) with particular attention given to the analysis of dispersion in distorted models of rivers and estuaries. Their study is limited to one-dimensional flows in which either vertical velocity gradients or horizontal velocity gradients predominate and to oscillatory flows in estuaries. The results of the study are not directly applicable to the highly two-dimensional and often three-dimensional wind-driven flows occurring in lakes, but they do give some insight into the possible effects of scale distortion.

The first-mentioned problem of scaling boundary friction in a hydraulic model of a lake has been discussed by Rumer (1970) and by Shiau (1972). Scaling the wind stress at a liquid free surface is a trial and error process. This is due not only to model scale distortion but also to the lack of a complete understanding of the momentum transfer process in both the prototype and the model. Rumer (1970) circumvented the details of this transfer process by requiring correct scaling of wind set-up in model and prototype. Shiau (1972) investigated the damping of seiches as one avenue for calibrating bottom friction in a model. Scaling boundary friction requires selected field data systematically collected from the prototype for model verification. In both cases the necessary prototype data requires a record of the transient response of water level elevations to known wind conditions at specific points in the lake.

The resolution of these two problems, i.e., scale distortion and boundary friction, is fundamental to the continued development and utilization of hydraulic models of large lakes. In passing, it is worth noting that small portions of large lakes are being modelled with increasing frequency. Many of these models are designed to examine the temperature changes to be expected in the vicinity of a thermal waste discharge from electric power generating plants. Bottom friction and wind stress simulation are not considered to be important factors in these hydraulic models. For the most part, such models are designed and operated conservatively so that reasonable assurance can be given that proposed warm water discharges will not violate established standards for the receiving body of water.

This report briefly discusses the hydraulic model and its operation. The experiments conducted thus far are reported in preliminary form. Time has permitted neither the completion of the experiments nor the final analysis of the collected data. The experiments have included a study of seiche damping in the model of Lake Ontario, a study of the circulation pattern resulting from the inflow of the Niagara River and the outflow of the St. Lawrence River, and a study of the circulation resulting from a superposed, steady westerly wind. In all cases the model was rotated about its center of mass to simulate the Coriolis force: the model fluid was homogeneous and isothermal. It is planned to continue this model study, concentrating on the wind-driven circulation of the epilimnion during summertime stratification.

Mathematical modelling of lake circulation with the accompanying schemes for numerical solution is progressing at a significant rate. Rao and Murty (1970) have investigated the steady-state wind-driven circulation of Lake Ontario using a finite-difference scheme for the numerical solution of the governing equations. Paskausky (1971) has reported the results obtained from a "barotropic, prognostic, numerical circulation model that includes topographic, Coriolis, lateral and bottom friction, inertial, and wind terms" simulating the wintertime circulation of Lake Ontario. Simons (1971) recently summarized the status of numerical models for lake circulation including an analysis of wintertime circulation in Lake Ontario resulting from a prevailing westerly wind. Later in this report, the results of these studies will be compared with the present hydraulic model results.

II. MODELLING CONSIDERATIONS

Harleman et al (1962) first outlined the basic principles for achieving dynamic similarity in a hydraulic model of a large lake in which the effect of the earth's rotation is important. More recently, Rumer and Hoopes (1970) recounted the criteria for similarity of such models including discussions of the simulation of frictional resistance, thermal stratification, wind stress, and mixing. A review of the experimental procedures used in studying fluid motion in a rotating system was also included.

The essential criteria for similitude between model and prototype is the equality of the Froude numbers and the Rossby numbers. The use of these criteria lead to the following relationships:

$$U_r = Z_r^{\frac{1}{2}}$$
$$T_r = L_r/Z_r^{\frac{1}{2}} \qquad (1)$$
$$\omega_r = Z_r^{\frac{1}{2}}/L_r$$

Here, U_r is the velocity ratio in model and prototype, T_r is the time ratio, ω_r is the ratio of angular velocity in model and prototype, Z_r is the vertical scale ratio, and L_r is the horizontal scale ratio. Since the ratio of horizontal to vertical dimensions in the prototype (Lake Ontario) is so large, distortion of scale is necessary. For model simulation of stratification the additional requirement is

$$\left(\frac{\Delta\rho}{\rho}\right)_r = 1 \qquad (2)$$

where $(\Delta\rho/\rho)_r$ is the ratio of density differences in model and prototype. Taken together, equations (1) and (2) specify that the densimetric Froude number ratio be unity, i.e.,

$$\frac{U_r}{\left(g_r \left(\frac{\Delta\rho}{\rho}\right)_r Z_r\right)^{\frac{1}{2}}} = 1 \qquad (3)$$

g_r is the ratio of gravitational acceleration in the model and the prototype.

Based on modelling oscillatory flows such as seiches, Shiau (1972) introduced the added requirement that the Proudman number ratio, θ_r, be unity, i.e.,

$$\theta_r = \frac{\upsilon_r^2 L_r^2}{g_r Z_r^5} = 1 \qquad (4)$$

This requirement leads to a constraint on the ratio of eddy viscosity in model and prototype, which is

$$\upsilon_r = \frac{g_r^{\frac{1}{2}} Z_r^{5/2}}{L_r} \qquad (5)$$

When $\theta_r \neq 1$, similarity of frictional resistance is lost and a so-called "scale effect" is introduced. Shiau (1972) outlines a procedure for adjusting boundary roughness in a model when $\theta_r \neq 1$ in order to minimize the "scale effect".

Yale (1972) recently reviewed the status of the various procedures for modelling wind-induced water currents. His investigation led him to conclude that the most straightforward approach is to adjust model winds until the model surface currents are correctly scaled according to equations(1). In the prototype the best evidence is that the surface currents, U_s, are closely approximated by

$$U_s = 0.033\ V_w \tag{6}$$

where V_w is the wind speed measured 10 meters above the water surface. However, due to the presence of developing boundary layers at the air-water interface in the model, this relationship underestimates the surface currents associated with a wind speed scaled according to equations (1). By working with models, Yale developed correction factors for equation (6). A comparison between observed results using this approach and the approach used by Buechi and Rumer (1969) wherein the wind set-up is scaled, has not been made. Such a comparison should help to clarify the essential scaling requirements for simulating wind-driven currents in model lakes.

The "state-of-art" pertaining to the design and operation of rotating vertically distorted Froude models is still in the development stage. The problems of scaling boundary friction and simulating wind drift currents in a three-dimensional flow are also far from being solved. The exact role for such models and their ultimate usefulness will gradually be determined as these and other questions are resolved.

III. EXPERIMENTAL EQUIPMENT AND PROCEDURES

III.1 General Considerations

The experimental work was conducted in the rotating laboratory facility at the State University of New York at Buffalo [Rumer and Robson

(1968), Rumer (1970)]. The distorted hydraulic model of Lake Ontario (Fig. 1) was designed with the scale ratios of L_r = 1:100,000 and Z_r = 1:800. As with previous models built in this laboratory [Rumer and Robson (1968), Stewart and Rumer (1970)], the Ontario model was carved out of rigid polyurethane foam. All essential topographic features in the prototype were reproduced in the model according to the distorted scale. The Coriolis effect was simulated by rotating the laboratory at 1.71 RPM about the center of gravity of the model lake.

The flow of the Niagara River into the model lake was scaled to 2.25 cc/sec. The inflow was pumped from a collecting sump through a rotameter to a small reservoir that connected to the modelled river channel. All other tributary streams entering the prototype are small by comparison to the Niagara River flow and were neglected. Thus, the St. Lawrence River outflow was equal to the Niagara River inflow in the model. Generally, about two hours are required for the model flow circulation to become fully developed.

A stilling basin with a micrometer point gage was attached to the model and provided the means for minor adjustments of the volume of water in the model lake. Also, evaporative losses could be checked by monitoring the water level in the stilling basin.

III.2 Studies of Mass Oscillations (Seiches)

The seiche experiments were conducted without model rotation. The model basin was supported by a rigid frame such that a linear variation of the model bottom from the supporting floor was obtained when one end of the basin was elevated slightly in the manner illustrated in Figure 2. Raising one end of the model in this manner causes the water to slosh back and forth and a standing long wave (or seiche) is produced in the basin.

A capacitance gage mounted above the water surface was used to sense the water level changes. The position of the gage is illustrated in Figure 2. Calibration of the gage was accomplished by precisely positioning the gage electrode at various distances above the still water surface. The changes in capacitance were amplified and recorded on a strip chart recorder. A typical calibration curve is given in Figure 3.

III.3 Studies of the Circulation Patterns

Several techniques were used to chart the water movements in the model: electrolysis in the presence of a pH indicator, colored dye injection and aluminum powder dusted onto the water surface. The electrolytic technique for generating a neutrally buoyant colored tracer was developed by Baker (1966) and is the primary technique for this study.

In this technique a pH indicator, Bromo-thymol blue (Bromo thymolsulphonaphthalein), is added to deionized water to make a 0.05 (weight) percent solution. This solution is then titrated with NaOH until the color of the solution just turns orange; any small increase in the hydrogen ion concentration will, at this point, cause the color to revert to a dark blue. In this study the hydrogen ions are generated locally at wire electrodes immersed in the solution. The wires were 20 gauge magnet wire from which the lacquer insulation had been stripped for ½ inch at ½ inch intervals. These wires were strung at intervals across the lake model approximately ½ inch below the water surface. The arrangement of the wires are depicted in Figure 1. When a DC voltage (about 10V) is impressed across alternate wires, hydrogen ions are formed continuously at the negative electrodes and the indicator is changed in color locally from orange to dark blue. This "tagged" fluid is convected by the motion of the fluid producing path lines much like the hydrogen bubble technique. Unlike the hydrogen bubble technique, however, the colored fluid is neutrally buoyant and thus truly remains with the initially tagged fluid. Eventually the hydrogen ions recombine with hydroxyl radicals in the water and the orange color reappears.

A Bolex 16 mm reflex movie camera mounted above the model basin was used to record the movement of the tagged fluid. After sufficient time, the polarity of the electrodes was reversed and the motions at the intermediate stations was recorded. Time was recorded continuously on the film by placing a clock, face up, on the model. Due to restrictions on the headroom and on the optical field of view in the laboratory only about half of the basin could be filmed at a given time. The developed film was studied using a 16 mm L and W Photo-Optical Analyzer and the patterns of water movement traced onto paper. An example of the developed film can be seen in Figure 4.

Wind simulation was accomplished by a shutter-type control on the discharge side of a battery of four centrifugal fans. The fans were installed on the eastern end of the model lake such that ambient laboratory air would be drawn eastwardly across the model liquid surface. A plexiglass cover, 6" high, was placed over the model to contain the air stream. A convergent nozzle located at the western end of the model permitted a smooth entrance of the air flow. Wind speeds were measured at several positions inside the cover using a vane type anemometer. Wind speeds of 2.9 fps, 3.9 fps, and 5.8 fps were used in these studies.

Since the wires were placed ¼ inch below the liquid surface (approximately 17 ft. in the prototype), the observed flow patterns were subsurface. Aluminum powder was released at different points on the water surface and the paths followed by this material were recorded. This procedure was followed until the whole lake surface circulation pattern was mapped. In future studies, it is planned to utilize the electrolysis technique (using a vertically positioned stripped wire) as a point source for tracing surface and subsurface currents.

IV. PRESENTATION AND DISCUSSION OF RESULTS

IV.1 Seiche Studies

The results obtained from the mass oscillation studies were quite different when the shallow basin north of Main Duck Island was isolated (the closed condition; see Figure 5) from the main basin than when it was not (the open condition). When the basin was open the relatively shallow embayment entrance region to the St. Lawrence River north of Main Duck Island acted as an effective energy dissipator or damping mechanism for the energy contained in the oscillating mass of the main basin. The observed decay modulus for the seiche in the open basin was 0.25 while for the closed basin the decay modulus was 0.023.

The experimental data illustrating the different rates of decay are presented in Figure 6.

The decay modulus, α, is defined as follows:

$$\alpha = \frac{1}{t'} \ln \frac{\eta}{\eta_o} \tag{7}$$

where $t' = t/T$ (dimensionless time) and η/η_o is the ratio of wave amplitude at time t to the initial wave amplitude, η_o, at time $t = 0$; T is the period of the oscillation. The decay rate, β, is defined as the ratio of successive wave amplitudes spaced one period apart, i.e.,

$$\beta = \frac{\eta_{t+T}}{\eta_t} \tag{8}$$

The decay modulus and decay rate are related by the following expression:

$$\beta = e^{-\alpha} \tag{9}$$

The decay rate for the open basin is β = 0.77 and for the closed basin, β = 0.98.

The observed period of oscillation in the open model basin was T_M = 5.14 secs. and in the closed model basin T_M = 4.60 secs. In Table I, a comparison between these results and analytical results is presented. In Table I, the model results have been scaled up to prototype times. The analytical results listed under present study were obtained employing the method outlined by Stewart and Rumer (1970) for free undamped oscillations. In this method, the open basin was divided into 44 sections while the closed basin had 42 sections. (See Figure 5.)

Prototype observations were reported by Simpson and Anderson (1964) for one brief event occurring on March 5, 1964. The observed period at Port Weller was 5.3 hrs ± 0.2 hrs. and at Toronto it was 5.0 hrs. ± 0.4 hrs. Their discussion of these observed results indicates that this seiche episode was probably not a free damped oscillation and that other factors such as wind and higher harmonic oscillations were in effect. Hamblin (1968) analyzed the spectra of water level variations in Western Lake Ontario for a three month winter period and found a period of 5.4 hrs. and that the uninodal surface seiche was amphidromic.

Based on the above results, it is evident that the prototype period is just over 5 hours. When the shallow basin north of Main Duck Island is excluded in the calculations, the seiche period reduces to less than 5 hours.

TABLE I

Lake Ontario Seiche Periods

	Model Results	Analytical Results		
		Rockwell (1966)	Simpson & Anderson (1964)	Present Study
Basin Open	5.05 hrs.	4.91 hrs.	5.4 hrs.	5.22 hrs.
Basin Closed	4.52 hrs.	4.55 hrs.	-	4.89 hrs.

Using the criterion that the Proudman number ratio must be one, the requirement for vertical eddy viscosity becomes

$$\upsilon_r = Z_r^{5/2} / L_r \qquad (10)$$

Assuming that the flow in the model is essentially laminar, the viscosity of the fluid in the model is closely approximated by $\upsilon_M = 10^{-5}$ ft^2/sec. Equation (10) requires that $\upsilon_p = 1.8 \times 10^{-3}$ ft^2/sec. This compares with 10^{-4} ft^2/sec. to 10^0 ft^2/sec. [Murthy (1972)] reported in the upper layers of the prototype. Actually the vertical distribution of fluid density and local velocity gradients markedly affect the value of the viscosity; it is well known, for example, that the eddy viscosity decreases significantly with depth as the thermocline region is approached.

The prototype observations deal mainly with wind-generated drift currents and the turbulent mixing resulting therefrom. The oscillatory motion of the entire lake mass during seiching, on the other hand, gives rise to bottom shear-generated turbulence and a local eddy viscosity dependent upon this bottom shear. It is likely that this eddy viscosity will differ from the observed values measured in the upper regions of the lake near the free surface. Since the objective of the study of seiche decay is to adjust bottom friction, the shear-generated eddy viscosity is precisely the coefficient of interest and not the wind-generated turbulent eddy viscosity. Unfortunately, however, this coefficient is unknown for the prototype.

Assuming laminar flow in the model during seiching (the Reynolds number was less than 500), the calculated Proudman number for the model is $\vartheta_M = 6 \times 10^{-9}$. Using the hydraulic radius instead of the average depth, the calculated Proudman number for the model is $\vartheta_M = 2 \times 10^{-8}$. The calculated Proudman number for the prototype is equal to the former of these two. This follows naturally, since the prototype eddy viscosity used in the calculation was determined on the basis of $\vartheta_r = 1$. According to the theory developed by Shiau (1972) for rectangular basins, the decay modulus for a Proudman number equal to 10^{-8} is $\alpha = 0.02$, which corresponds to the measured value, $\alpha = 0.023$, for the basin operated in the closed condition. This indicates that the seiching results obtained for the Lake Ontario model in the closed condition are more representative of the actual prototype behavior and that boundary friction did not need major adjustment in the model.

IV.2 Circulation Studies: No Wind

In the absence of wind the only driving forces causing motion in the model lake are the momentum of the incoming Niagara River flow and the gravitational force resulting from free surface gradients required to conduct this flow through the lake basin to the St. Lawrence River. The motion resulting from these driving forces will, of course, be influenced by the topography of the basin, the boundary friction, and the Coriolis force. In particular, the topography of the Niagara River must influence strongly the circulation in the western end of the lake. For this reason, great care was taken in the construction of this portion of the model in order that the flow in this region be simulated as accurately as possible.

The observed circulation patterns for the zero wind condition are illustrated in Figures 7 and 8 for the subsurface (¼" deep) flow and in Figure 9 for the surface flow. The close similarity between the flows at the two levels is to be noted. Because the measurements reflect the circulation only in the upper 5 percent or less of the model lake, they must not be interpreted as depth averaged conditions. In fact it appears that the circulation in the model is unstable in the absence of the wind and tends to be three-dimensional. Additional experiments in which currents are mapped at greater depths will be required before final conclusions can be drawn regarding depth averaged circulations.

The experiments demonstrated that the electrolytic technique is a satisfactory method for observing relatively slow motions and tracking water movement. Future experiments should be conducted with a portable electrode that can be placed at any depth. The experimenter could position this "probe" as required to delineate the details of the circulation pattern and thus reduce the level of conjecture in the interpretation of the results.

Paskausky (1971) has presented analytical results for the steady state circulation in Lake Ontario resulting from just the inflow of the Niagara River and the outflow of the St. Lawrence River; wind shear was neglected. The circulation pattern obtained by Paskausky for this condition is shown in Fig. 10. This result is clearly quite different from that portrayed in Figures 7 - 10 for the present model. Although vertical motion is not accounted for in the analysis of Paskausky, this is not felt to be a serious defect of his analytical model. The effect of scale distortion in the model could be a significant factor. It would seem desirable to make additional experimental observations for greatly reduced distortion ratios. The present physical model distortion ratio is $Z_r/L_r = 125$. If the vertical scale ratio were changed to $Z_r = 1:10,000$, the distortion ratio would reduce to 10, a value commonly used with some confidence in river and estuary models. Unfortunately, this would give an average depth in the physical model of just under 1 cm. The effects of bottom friction would be greatly exaggerated and surface tension effects would probably be introduced. Based on the seiche measurements, it would appear that boundary friction in the present model is already a reasonable first order approximation to prototype boundary friction. A significant reduction in the average depth in the model would require further smoothing of the boundary, a nearly impossible task since the present model already is quite smooth.

Comparison of these experimental data for the no wind condition with prototype observations is not reasonable since the prototype circulation pattern is strongly influenced by wind stress.

IV.3 Circulation Studies: With Wind

Wind-driven circulation patterns were examined for model wind velocities of 2.9 fps, 3.9 fps, and 5.8 fps. The observed circulation pattern for the wind velocity of 3.9 fps is shown in Figures 11, 12, and 13 for the subsurface flow. The surface currents can be seen in Figure 14 and are generally what would be expected. Sinking along the southeastern shore and upwelling along the northwestern shore were observed using dye tracers as an adjunct to the regular filming of the streamers emitted from the electrodes.

The circulation pattern observed at ¼" depth is complex (see Figs. 12 and 13). Based on repeated observation of the films the major features of the pattern at this depth are depicted in Figure 13. These results resemble the analytical results of Rao and Murty (1970) in which they solved numerically for the steady state wind-driven circulation with a uniform westerly wind (see Fig. 15). However, their results are for depth averaged velocities and the correspondence may be fortuitous. Nevertheless, the gyres obtained in both cases are similar in direction of rotation and in their geographic location. The equilibrium water surface profile for this condition has also been calculated by Rao and Murty for a wind speed of 16 feet per second. It would be of interest to compare the water surface profile in the model with that predicted by the analysis of Rao and Murty. This is planned in future experiments. More could be learned about scaling winds by adjusting model wind speeds and/or wind friction coefficients used in analysis until good correspondence was obtained between the two approaches.

The Ekman depth of frictional influence derived for the case of wind shear on a liquid of infinite depth with no horizontal boundaries is given by

$$D = \pi \sqrt{\frac{\epsilon_z}{\Omega \sin \varphi}} \qquad (10)$$

where ϵ_z is the coefficient of vertical eddy viscosity and $\Omega \sin \varphi$ is the local angular velocity component. For laminar flow in the model, $\epsilon_z = 10^{-5}$ ft^2/sec. and $\Omega \sin \varphi = .179$ rad/sec. This gives D = .023 ft. or .28 inches. For greater values of ϵ_z, D increases. Therefore, it can be assumed with certainty that the observed currents at ¼" depth are within the depth of frictional influence in the model. Near the boundaries the Ekman theory would be invalid.

V. SUMMARY

The experimental results obtained for seiche decay indicate that boundary friction in the model is reasonably simulated for the main basin but exaggerated in the shallow entrance region to the St. Lawrence River. The observed period and frictional dissipation of the uninodal seiche were found to be strongly influenced by this shallow region north of Main Duck Island.

The electrolytic technique for observing water movement has proven to be highly satisfactory but it would be premature to make any final conclusions regarding the observed circulation patterns in the prototype based on this study.

Additional work is planned for experimenting with the Lake Ontario model. This work will concentrate on the study of the wind-driven circulation of the epilimnion for the summertime stratified condition. The effects of model distortion will be minimized by confining future work to the circulation in the epilimnion.

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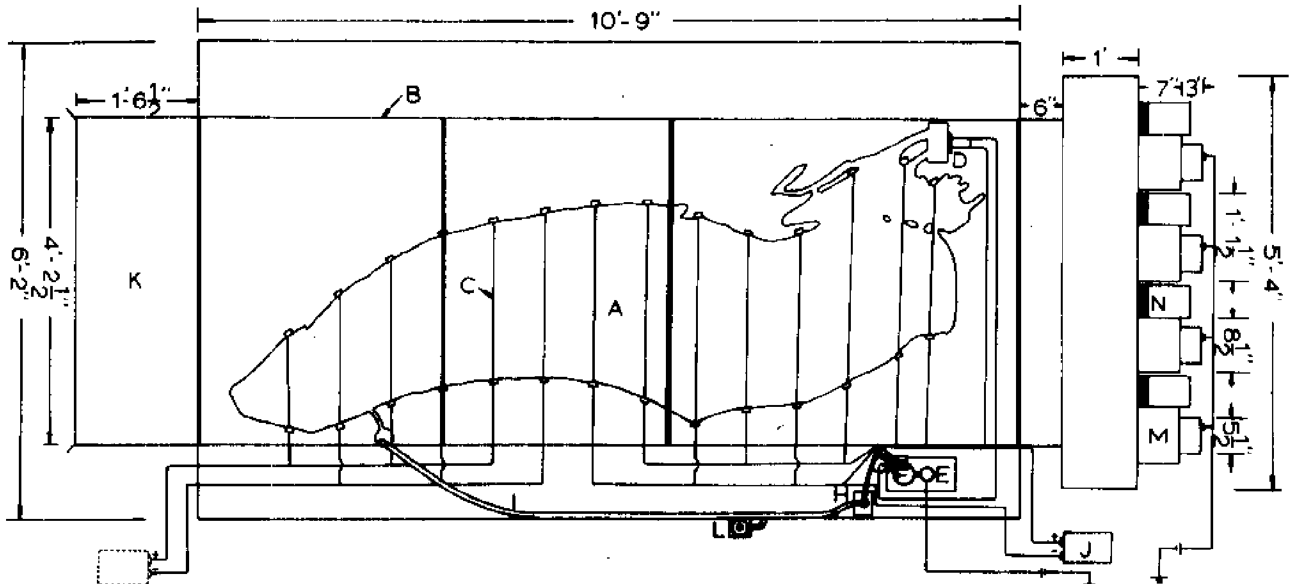
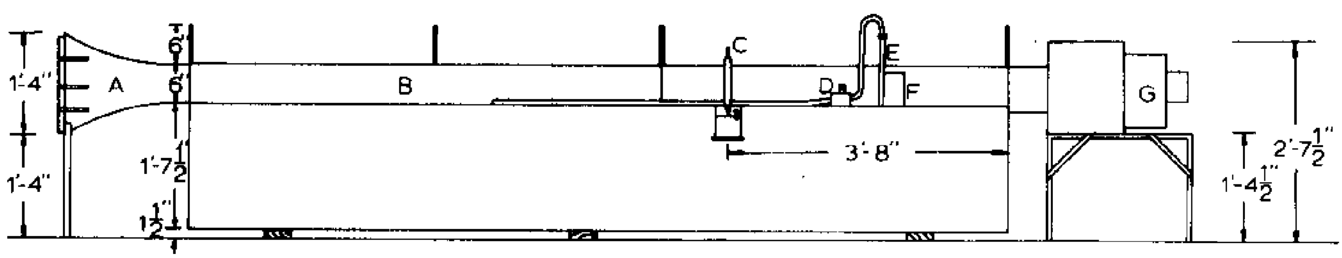


(A) LAKE ONTARIO MODEL; (B) PLEXIGLASS COVER; (C) ELECTRODE WIRE; (D) V-NOTCHED WEIR (E) WATER PUMP; (F) CONSTANT HEAD TANK; (G) ROTAMETER; (H) CONTROL VALVE, (I) TYGON TUBING; (J) D. C. POWER SUPPLY; (K) CONVERGENT NOZZLE, (L) POINT GAUGE, (M) BLOWER; (N) BLOWER DISCHARGE GATE

(Plan View)



(A) CONVERGENT NOZZLE; (B) PLEXIGLASS COVER, (C) POINT GAUGE; (D) CONTROL VALVE, (E) ROTAMETER, (F) CONSTANT HEAD TANK; (G) BLOWER

(Elevation View)

Figure 1 – Schematic Diagram of Experimental Set-up for Circulation Studies

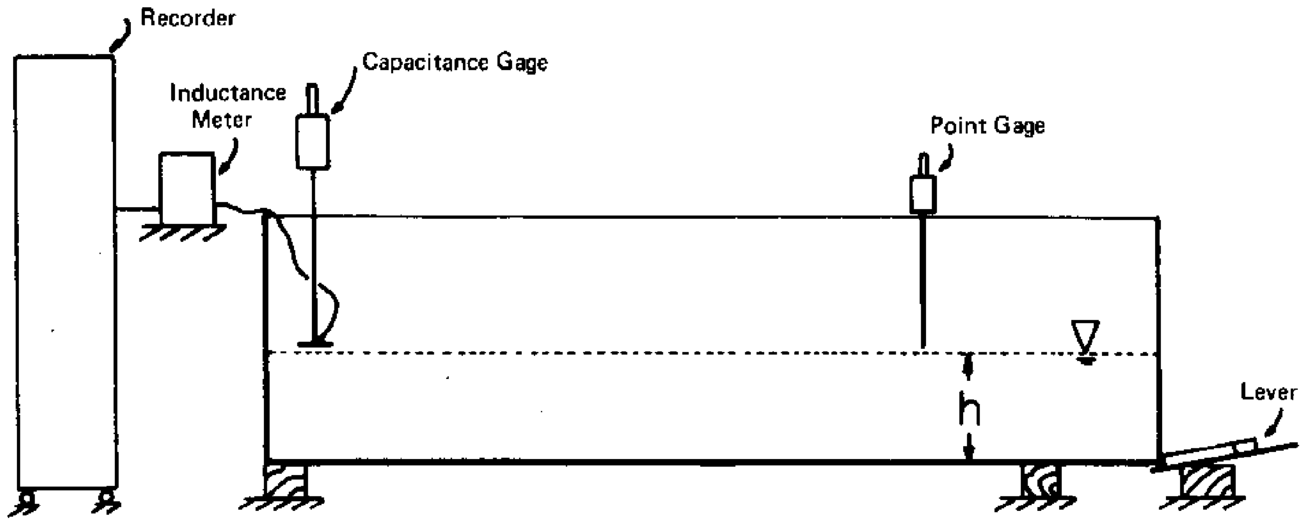


Figure 2 – Schematic Diagram of Experimental Set-up for Seiche Studies

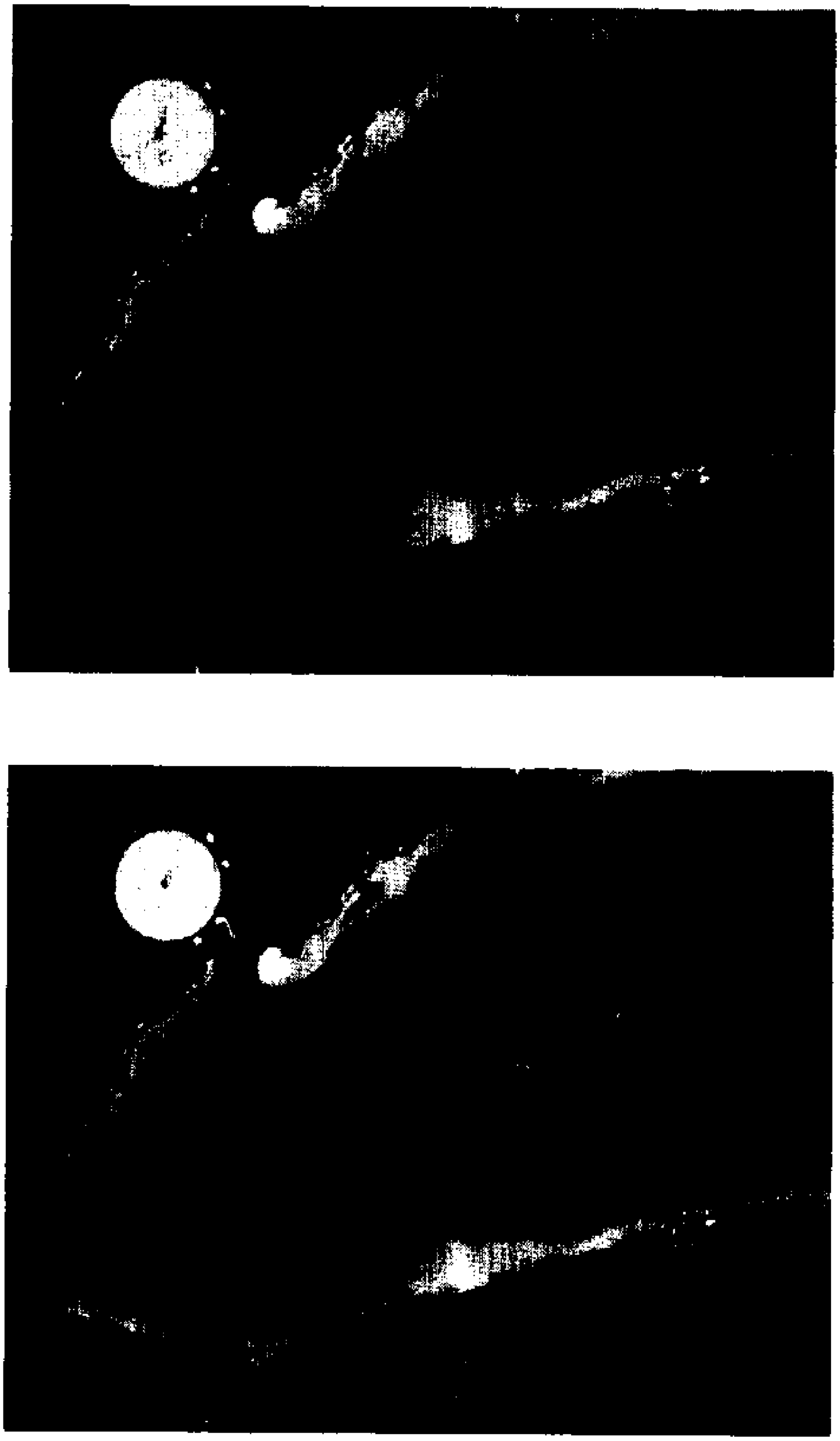
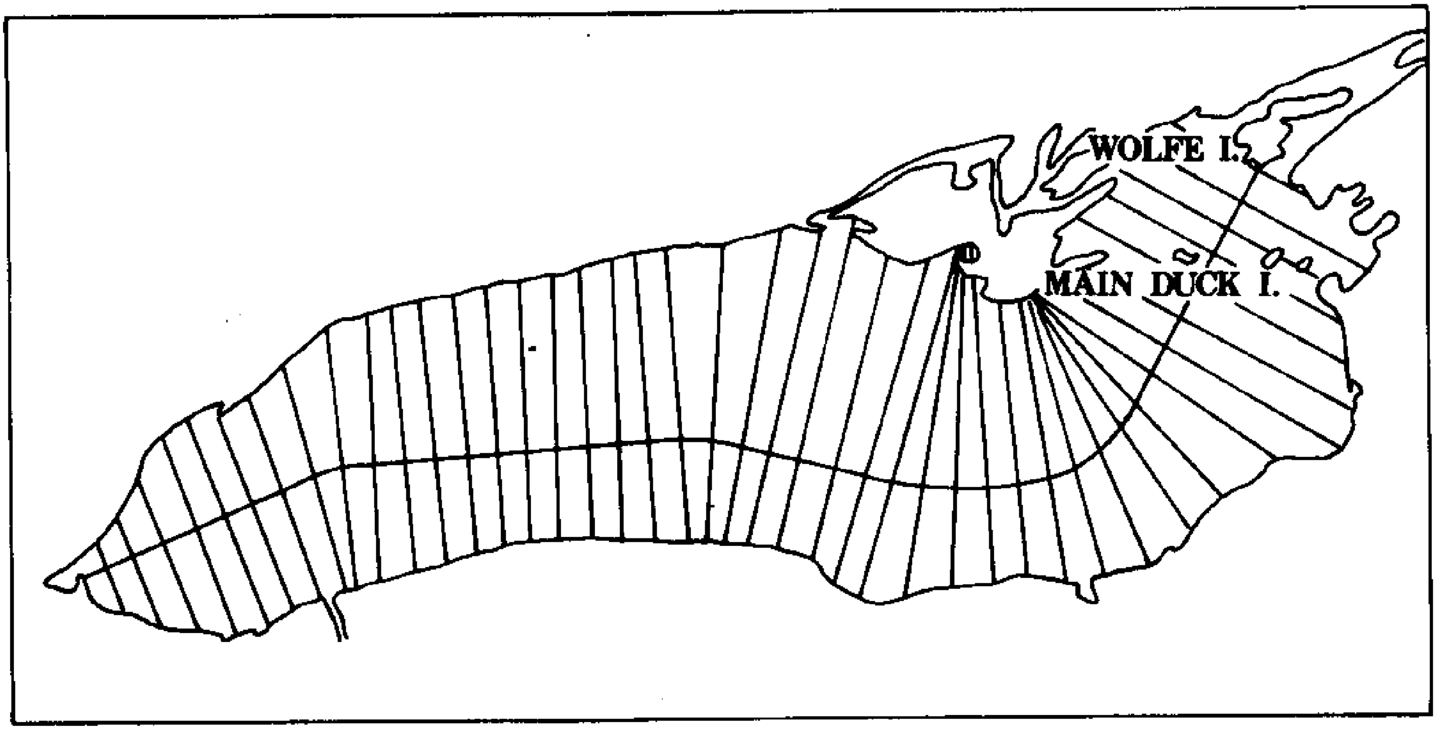
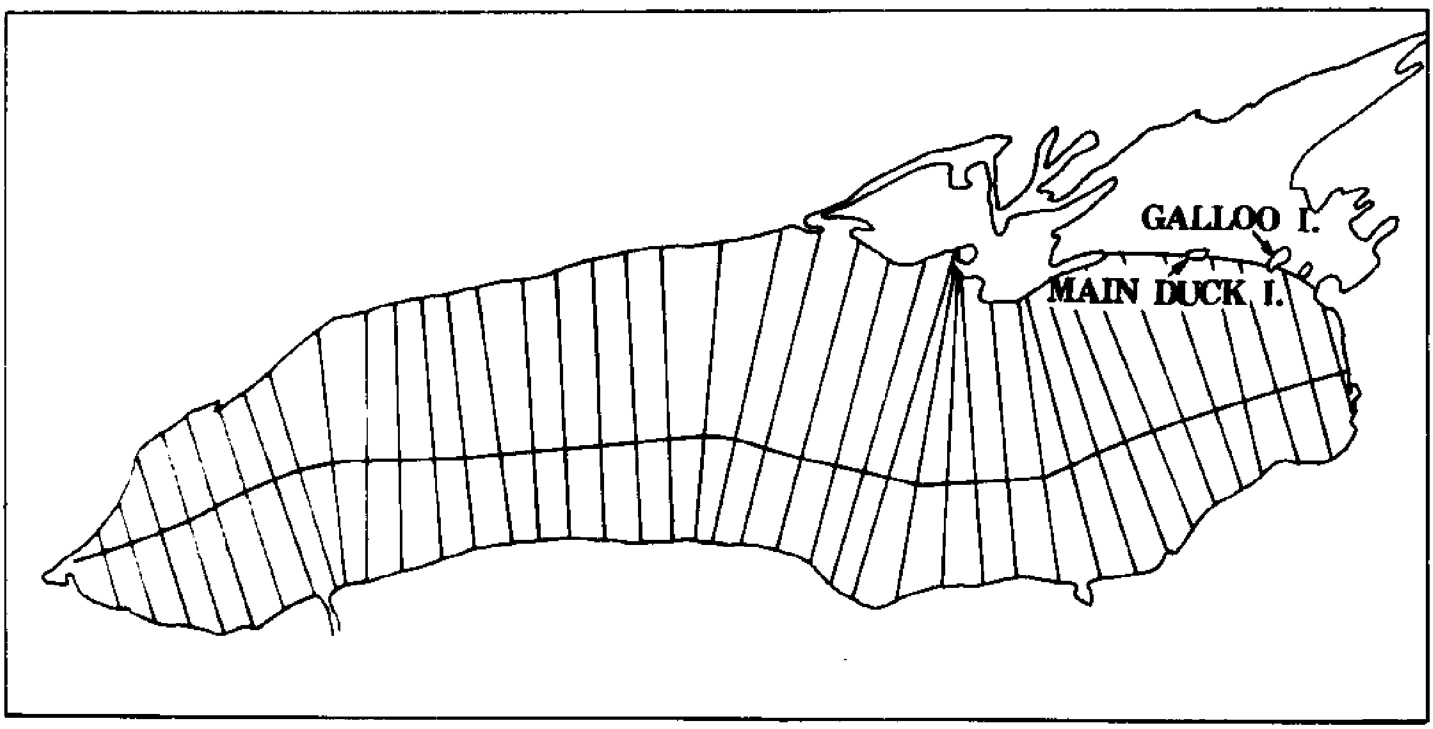


Figure 4 – Sample Frames from Film Record of Circulation Pattern
(Dark streamers are "tagged" fluid emanating from electrodes)



(Open Condition)



(Closed Condition)

Figure 5 – Section Layouts for Analytical Study of Seiches in Lake Ontario

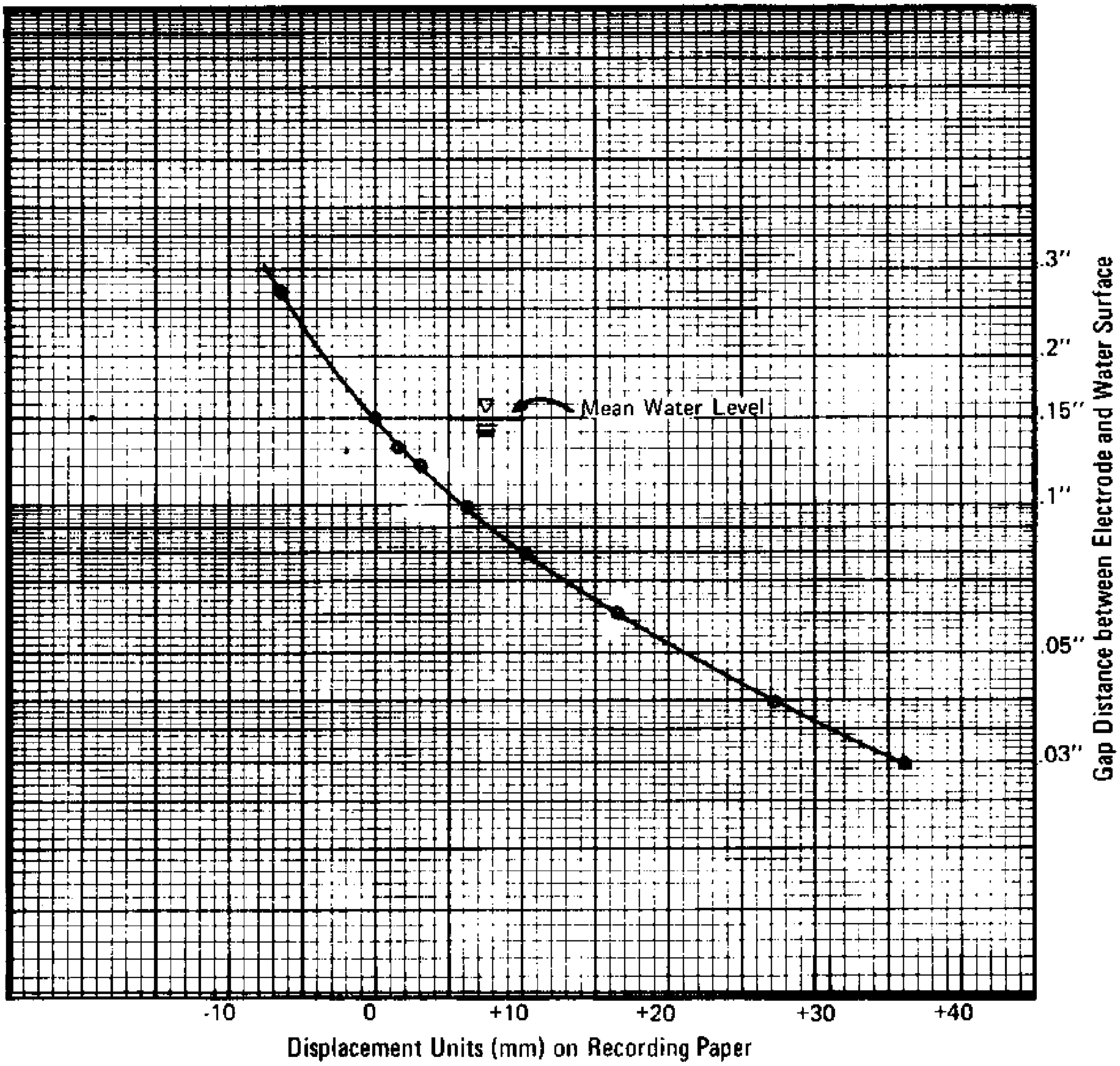


Figure 3 – Sample Calibration Curve for Capacitance Gage used in Sensing Water Level Changes

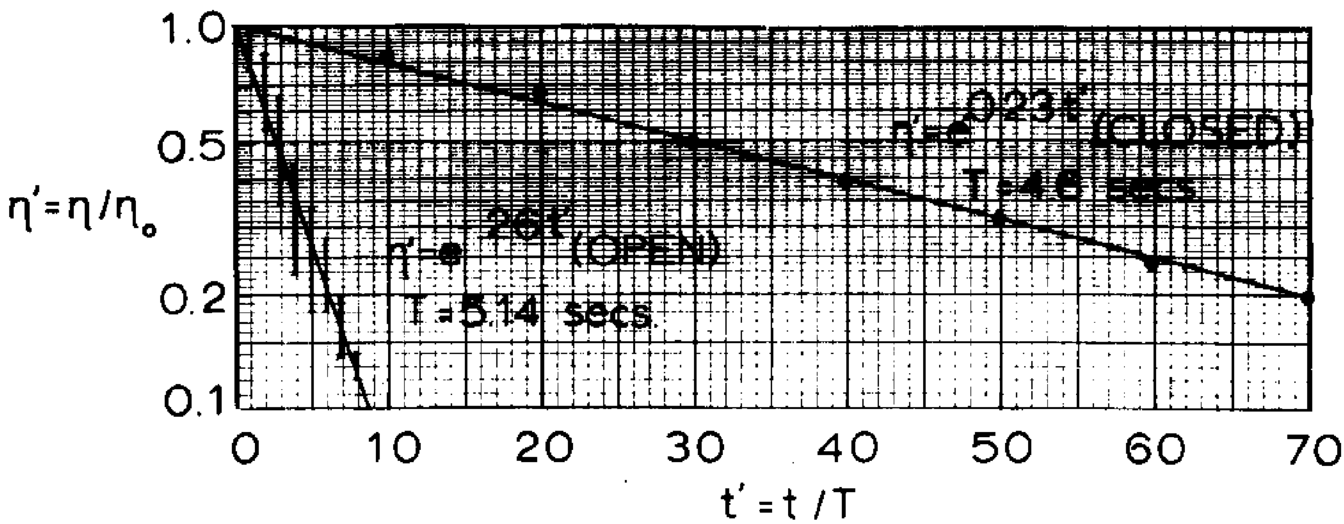


Figure 6 – Experimental Results for Seiche Decay in Model Basin of Lake Ontario

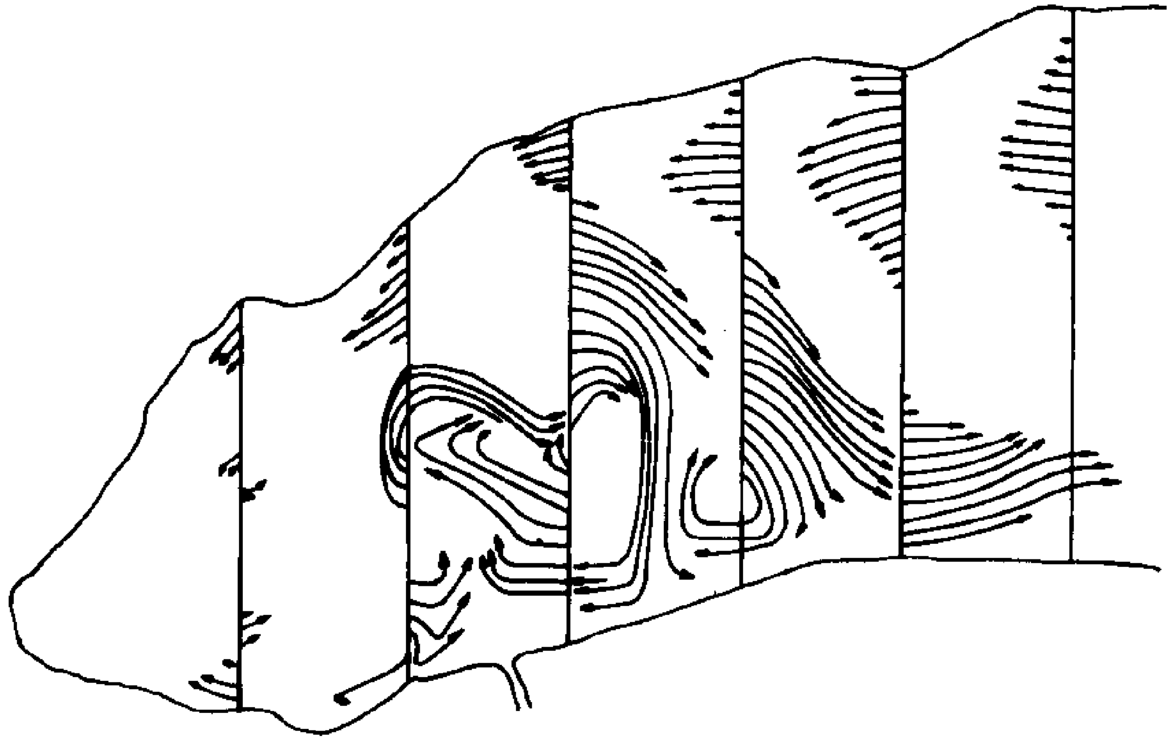


Figure 7 – Subsurface Circulation Observed in Model: No Wind (Western Basis)

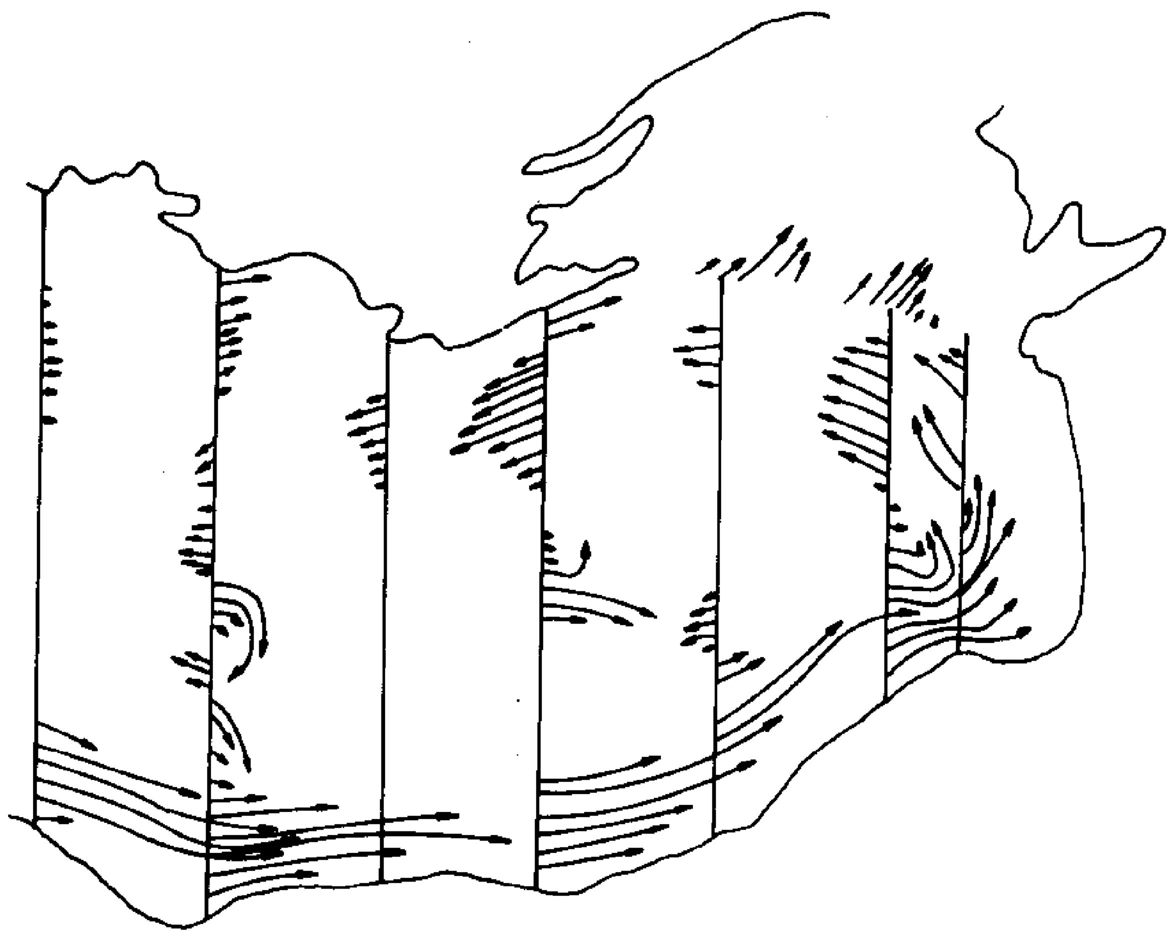


Figure 8 – Subsurface Circulation Observed in Model: No Wind (Eastern Basin)

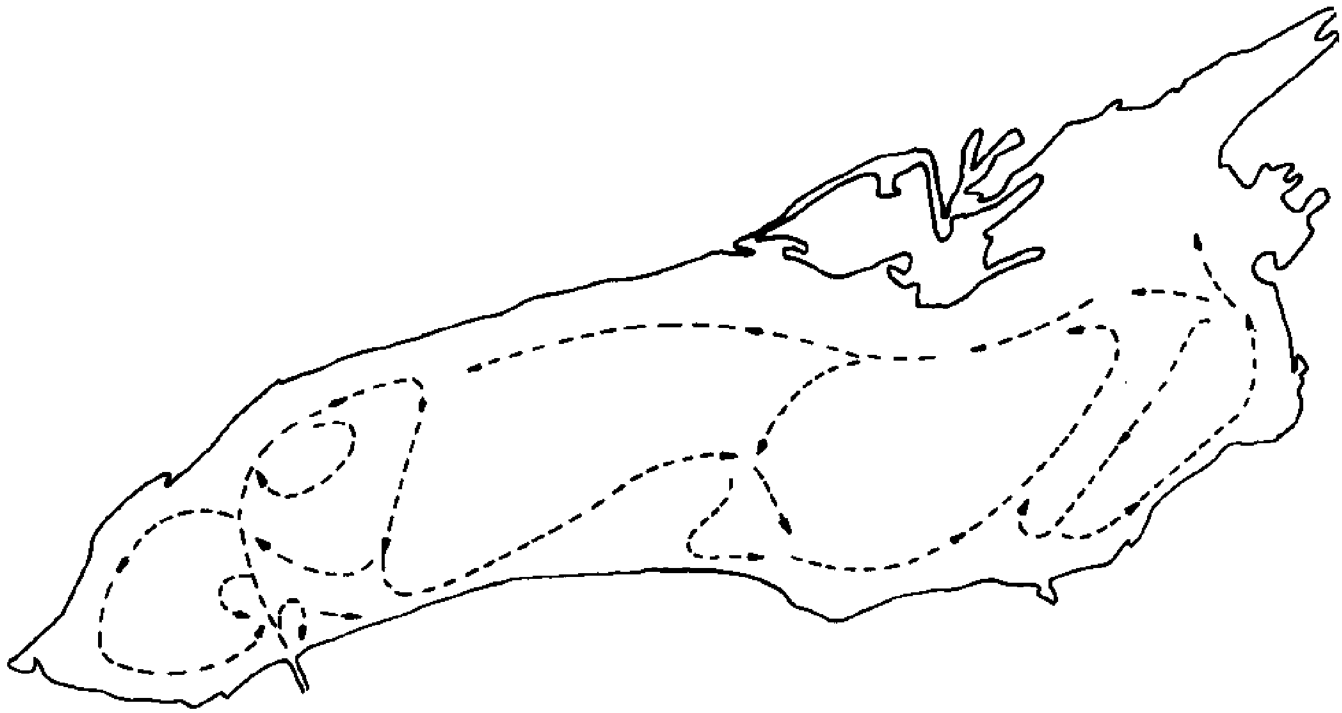


Figure 9 – Surface Circulation Observed in Model: No Wind

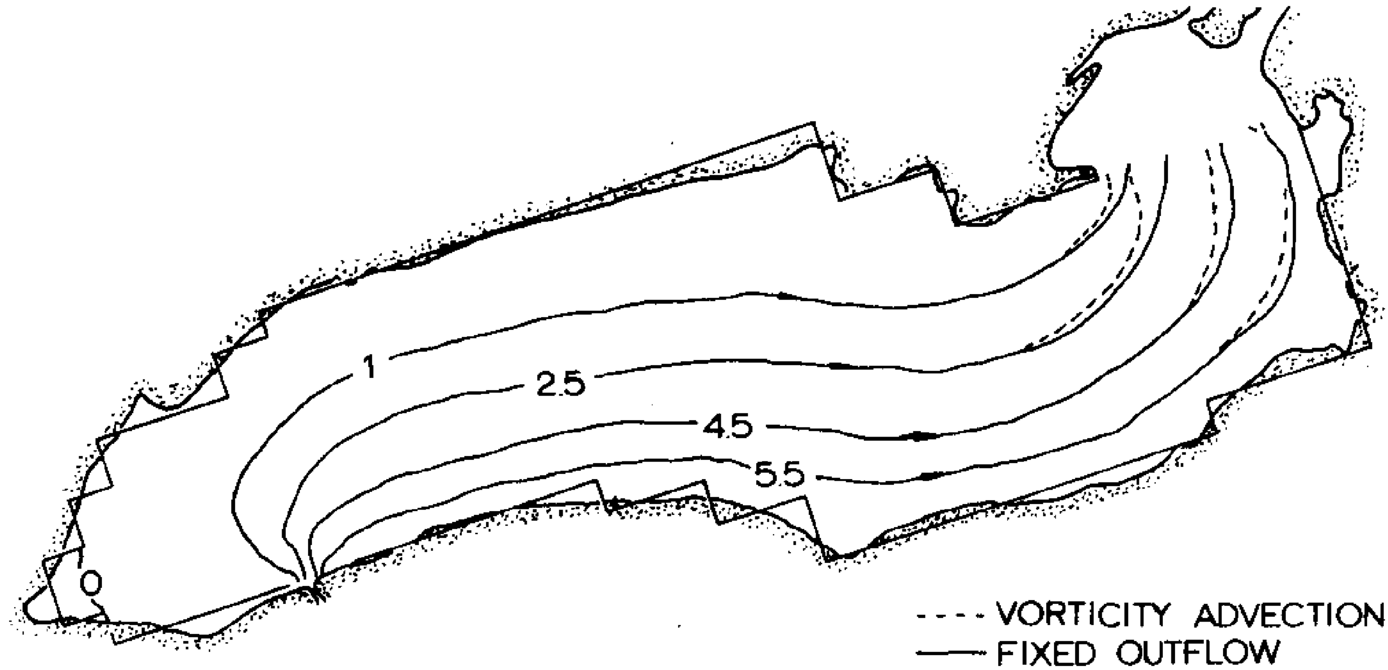


Figure 10 – Numerical Model for Steady State Wintertime Flow in Lake Ontario (after Paskausky, 1971)

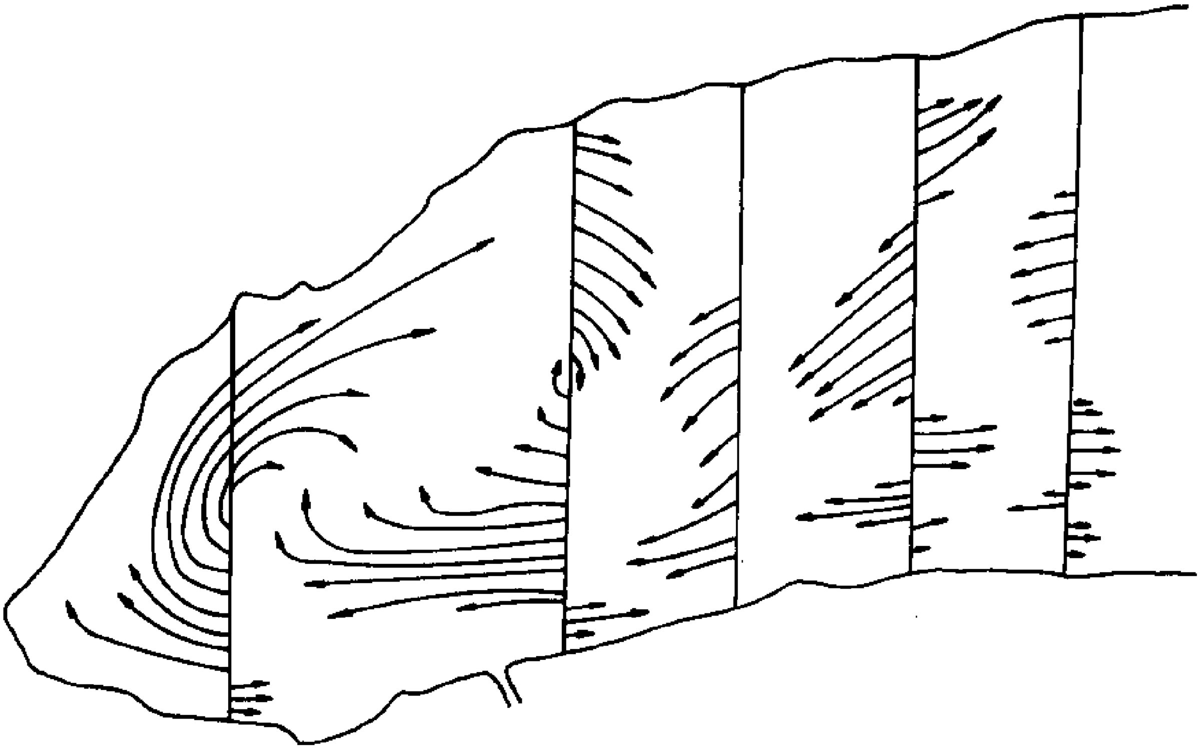


Figure 11 – Subsurface Circulation Observed in Model: Wind Velocity in Model, 2.94 fps (Western Basin)

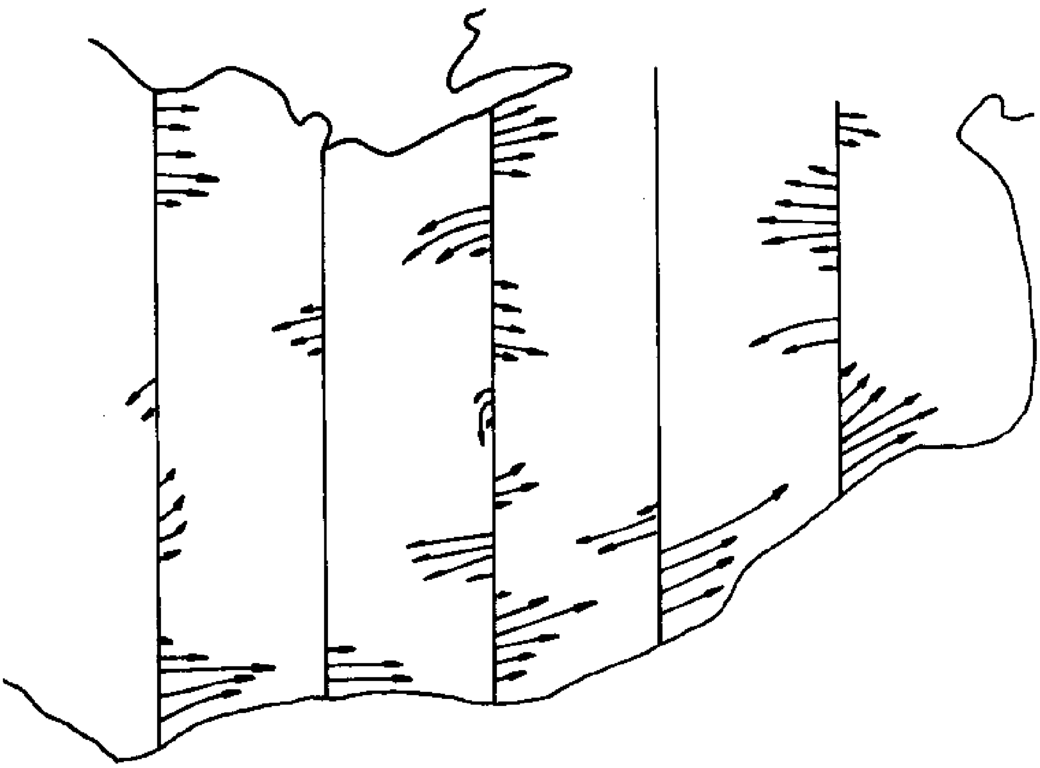


Figure 12 – Subsurface Circulation Observed in Model: Wind Velocity in Model, 2.94 fps (Eastern Basin)

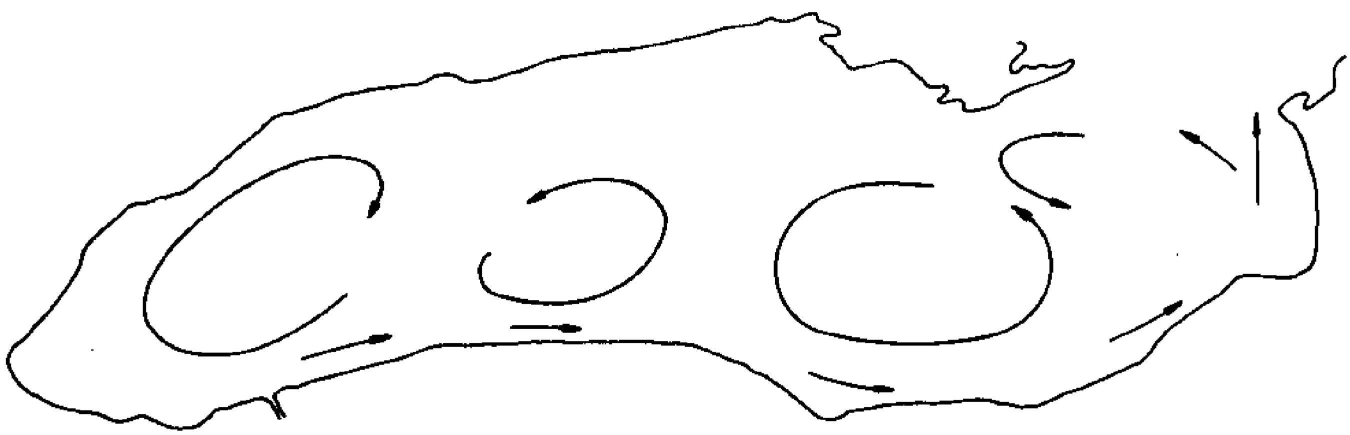


Figure 13 – Synthesized Observed Subsurface Circulation in Model: Wind Velocity in Model, 2.94 fps

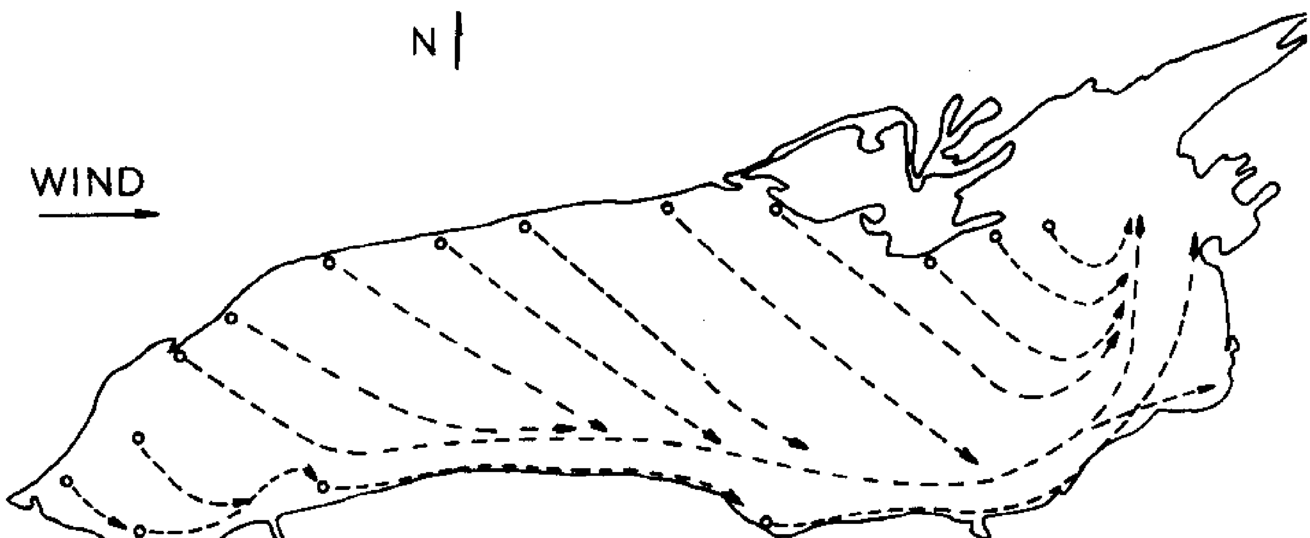


Figure 14 – Observed Surface Circulation in Model: Wind Velocity in Model, 2.94 fps

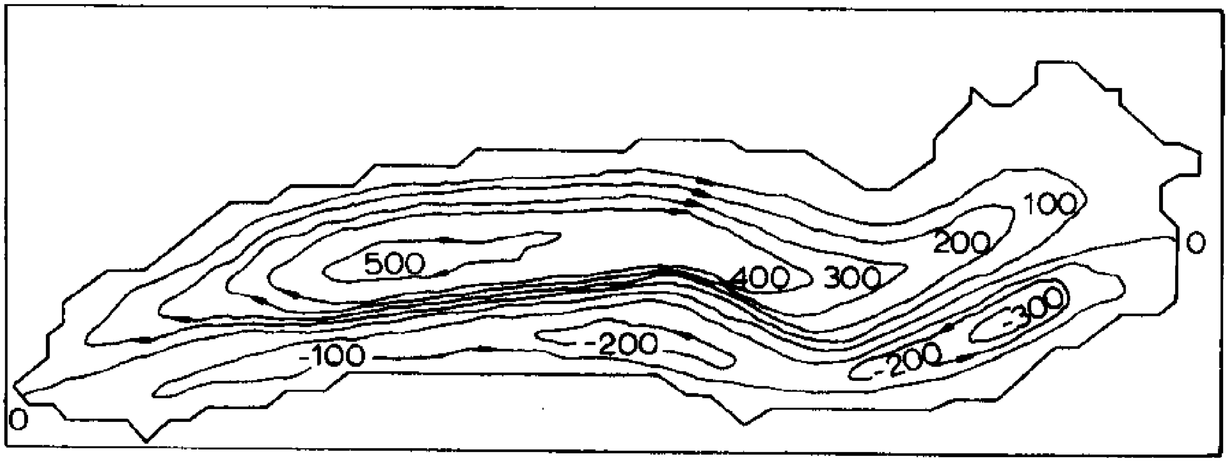


Figure 15 – Numerical Model for Transport Stream Function for Uniform Westerly Wind of Velocity 16.4 fps (after Rao and Murty, 1970)