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Exchange Flows in Lakes

By:

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MANAGEMENT PERSPECTIVE

As human activities impact increasingly on lakes, gradients in the quality of lake water between distinct basins of lakes, between interconnected lakes and between harbours and embayments have been of growing concern. The transfer of substances between these water bodies has been termed exchange flow. This timely topic is reviewed in this research article at the request of the organizers of the Internation Union of Applied and Theoretical Mechanics who have invited the author to present a plenary talk on the topic as well. Various examples are drawn from the scientific literature on the Great Lakes and from our numerous studies of Hamilton Harbour, in particular. On the latter, an example is given which for the first time shows the importance of water level fluctuations in the western end of Lake Ontario in quantitative terms on the flushing of Hamilton Harbour. The attention of the international limnological community is drawn to the key question of the summer exhange between the harbour and lake which due to its complexity requires further work.

Revised

Exchange Flows in Lakes

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Abstract

Concern for interbasin gradients in water quality in lakes has stimulated interest in exchange flows. Exchange flows in lakes have been mainly studied by field experiments on a site specific basis. Despite obvious differences in the nature of the forcing, much of their theoretical framework stems from oceanography. One reason that our theoretical understand is still at an elementary stage in lakes is their complexity arising due to the need to consider both advective and diffusive effects. In general, in lakes, circulatory aspects of their nature have been studied more than their mixing characteristics. This is especially important for stratified exchange flows where vertical mixing within the exchange flow itself can lead to shortcircuiting of the exchange of properies. A rapid improvement in the understanding of exchange flows is anticipated as their study becomes facilitated by the effective employment of advanced observational methods coupled with three-dimensional models. An example is presented on the use of mathematical models in obtaining insight into the influence of water level fluctuations on the flushing between a bay and a large lake.

Introduction

Owing to the increased use of lakes for recreational purposes, sources of water supply and repositories of municipal and industrial discharges gradients in water quality have developed in many lakes between distinct basins and between nearshore and offshore areas. When there is confinement of the general lake circulation by shoreline configuration or by bathymetry such as is the case of embayments or harbours then the mixing and circulation of water masses between these areas is often termed exchange flow. It is important to stress that exchange flows do not simply refer to the local circulation in these restricted water bodies but that the subject includes the combined effect of both advection and diffusion on the transport of water quality constituents. However, in many studies estimates of exchange flows have been based on measurements or modelling of flows alone when it was not possible to include diffusive effects. An outstanding characteristic of exchange flows is their complexity. Not only do they combine nearly all the physical processes known in lakes with irregular topography but due to the confinement of the geometry flows tend to be concentrated to levels seldom experienced in other regions of lakes. These flow concentrations result in unusually high Froude numbers and their gradients which means that simple linear theory is seldom applicable. While much of our current understanding of exchange flow processes in lakes stems from oceanography significant differences exist for lakes. In the flushing of marine coastal embayments, as for example, the Western Australian marina studied by Schwartz and Imberger (1988) is dominated by the single and highly regular frequency of the astronomical tide. On the other hand the forcing of exchange flows in lakes ranges from time scales of infragravity waves to meteorological disturbances of about 100 hr and lacks the regularity of tidal forcing. This episodic nature of exchange flow in lakes adds an element of complexity not generally found in the oceans.

In the present paper methods of observation of exchange flows are discussed, some examples from the limnological literature are cited illustrating the complexity and diversity of exchange flows, some theory is reviewed and finally an example of the use of numerical models in facilitating the understanding of exchange flow between a harbour and a lake is presented.

Observations of Exchange Flows in Lakes

The complex nature of exchange processes necessitates the collection of site specific field observations as an essential component of their analysis and interpretation. One observational approach that may provide useful information on exchange is the budget method whereby differences in the concentrations of a conservative substance such as dissolved solids between two water bodies may be exploited to determine the exchange. Klapwicjk and Snodgrass(1985) inferred the seasonal exchanges between Hamilton Harbour and Lake Ontario based on the salt balance of the harbour. Unfortunately, errors associated with the subtraction of large numbers

common to budget methods meant that their method could not resolve variations in exchange having scales less than a month. On a qualitative basis exchange or the lack of if has been studied by microbiological concentrations by Palmer et al.(1993) between Georgian Bay and a small bay favoured as a weekend anchorage by recreational boaters. The authors measured the effluent concentrations of bacterial contamination and attempted to relate them to physical conditions by means of a simple exchange model as the levels in the bay built up and dissipated over the course of a number of weekends.

When exchange between connected lakes or basins of a lake is of concern frequently it is not possible to employ budget methods as inputs are too uncertain. In a number of cases interbasin exchanges have been observed by direct measurement of current based on moored current meters placed in the connecting passage. For example, Saylor and Sloss(1976) measured exchange between Lake Michigan and Lake Huron with an array of 11 recording current meters placed in the connecting passage and discovered what must be the largest lacustrine exchange ever recorded of 0.085 Sverdrup and associated current speeds of 1.1m/s. Similarly, Bennett(1976) observed the longterm exchange between Lake Huron and Georgian Bay. Both found eastward flow in the upper layer and westward flow below during the stratified season. Interbasin exchanges have been extensively measured with current meters and thermistor arrays in Lake Erie by a considerable number of investigators and have been thoroughly reviewed by Bartish(1987). The difficulty with these current meter observations while capable of resolving all the relevant time scales except for the turbulent ones, is that they do not account for the effect of mixing on the exchange. In a subsequent section on theory the importance of the excursion distance of a flow intruding from one water body to another is discussed, Consequently, it is noteworthy in the case of Lake Erie that Chiocchio(1981) found that hypolimnetic exchanges between the eastern and central basins had frequent flow reversals of 2-6 days and that the excursion distance is typically 9km, which is just sufficient to clear the connecting passage and enter the opposite basin. As will be shown later, the net exchange in this case will depend critically on the hypolimnetic circulations in the two basins. Recording thermistor profilers have served as a valuable complement to current meters. Okamoto and Endoh(1995) have inferred net exchange volume associated with both internal co-oscillations and extreme upwelling events driven by typhoons from such data and the hypsometric curve for a large deep bay connected to Lake Biwa. Finally, the interesting case of exchange flow further compicated by the effects of the temperature of maximum density has been studied experimentally by Roy(1983) between Black Bay and Lake Superior.

In some instances the measurement of longterm exchanges between harbours and lakes presents special difficulties. In the case of frequent ship traffic in the connecting waterway conventional moored current meters are not possible due to hazards to unattended instrumentation from commercial shipping. Simons and Schertzer(1983) addressed this problem in the case of the Burlington Ship Canal by deploying a differential pressure gauge designed to measure the water level difference between the two ends of the ship canal. Unfortunately, they were unable to establish the calibration of this potentially useful device on account of the operational failure of an array of standard current meters moored during a rare occasion when the canal was closed to ships. Since 1989 devices which remotely sense currents have been commercially available. An evaluation of the field performances of two types of ultrasonic current meters in Burlington Ship Canal has been reported by Hamblin(1991), one, a bottom mounted acoustic doppler current meter and the other, a time-of-flight current meter integrating across the channel at the level of the acoustic ray. Hamblin (1995) has provided a detailed analysis of the in situ calibration of the latter instrument based on a method developed by Spigel(1989) employing a conventional profiling current meter. His study indicated that this technique is limited to the unstratified season when refraction of the acoustic trajectories by the isopycnals is least.

The problem of the exchange due to the diurnal and seasonal cooling of sidearms recognized as mainly a theoretical problem since such exchange flows are usually masked by stronger wind forced circulations. However, there have been two notable field studies of this phenomenon. Monismith et al.(1990) have studied such convective motions diurnally while on a seasonal basis, Okubo(1995) found intermittent intrusions of more dense bottom water flowing into the northern basin of Lake Biwa formed in the shallow southern basin during episodes of intense autumnal cooling.

Returning to the previous discussion of the exchange flows of Lake Erie it worthy of mention that interbasin exchanges may now be studied based on archived numerical model output stored online by Schwab and Bedford(1994). At this stage of their model development as only vertically averaged and hourly modelled currents are available the exchange between the western and central basins would be appropriately studied which, as Bartish(1987) points out, is mainly unstratified.

Theoretical Considerations

Fischer et al.(1979) have formulated a meaningful concept for exchanges in estuaries, the tidal exchange ratio, which is defined as the ratio of the volume of new ocean water actually exchanged by advection and diffusion to the total water entering an estuary over a flood cycle. Unfortunately, it is usually not possible to predict the exchange ratio from theory. In a situation where the exchange is dominated by the longitudinal seiche Saylor and Miller(1987) have employed an analogous concept which they termed the tidal exchange prism length. They found that this length for exchanges between the western and central basins of Lake Erie ranged up to 5km.With a prism length of 2km, approximately 0.5km^3 of water would be exchanged during each seiche cycle(14hrs), and at this rate complete flushing of the western basin by seiche activity alone would occur in 20-30 days. This example illustrates the shortcoming of such concepts as the tidal exchange prism length and much of the theory to follow compared to the tidal exchange ratio. Without taking account of the mixing the actual flushing times will most likely be underestimated. The following theoretical considerations while not leading to such useful quantities as the exchange ratio at least shed some light on the pertinent temporal scales of interbasin exchange and the magnitude of exchanges excited by water level fluctuations and density gradients.

Resonant or Co-oscillations

Based on linear theory the equation of motion for the displacement, ζ, of a particle along the longitudinal axis, x,of the basin is

$$\frac{\partial^2\zeta}{\partial t^2}+\beta\frac{\partial\zeta}{\partial t}-gh\frac{\partial^2\zeta}{\partial x^2}=0 \qquad (1)$$

where g is the acceleration of gravity, h the depth and the damping coefficient,β_j may be expressed as μ/h_j^2 where where μ is the vertical eddy viscosity and j refers to basin j. For a lake consisting of two basins, 1 and 3, connected by another, 2, the boundary conditions require zero displacement at the ends of 1 and 3 and continuity of mass and pressure between 1 and 2 as well as between 2 and 3. The free solution in basin j has the form

$\zeta_j=A_j\sin(\alpha_j x)e^{\sigma t}+B_j\cos(\alpha_j x)e^{\sigma t}$ where i is the square root of minus one, σ is the complex frequency of oscillation and $\alpha_j=\sqrt{(\sigma^2-\beta_j\sigma)/gh_j}$. From the boundary conditions it is possible to eliminate A_j and B_j, leading to the characteristic equation, where b_j and L_j are the breadth and length of basin j respectively,

$$\sqrt{L_2}b_2^2\alpha_1\alpha_2\tan\alpha_2=b_1b_1\sqrt{L_1}\sqrt{L_2}\sqrt{L_3}\alpha_2^2\tan\alpha_1\tan\alpha_2\tan\alpha_3+b_2b_3\sqrt{L_3}\alpha_1\alpha_2\tan\alpha_3+b_1b_2\sqrt{L_1}\alpha_2\alpha_3\tan\alpha_1 \qquad (2)$$

By use of trignometric identities it is straightforward to show that (2) reduces to the Merian formula when $b_1=b_2=b_3$, $h_1=h_2=h_3$ and all β_j are zero. Secondly, if it is assumed that the frequency of co-oscillation is less than the the seiche frequency of any individual basin such that $\sigma<L_j/\sqrt{gh_j}$ and that there is no bottom friction then (2) reduces to

$$\sigma^2=\frac{gb_2h_2A_L}{L_2A_1A_3} \qquad (3)$$

where A_L is the surface area of the lake and A_j is area of basin j.

The large spread between the fundamental periods of oscillation reported for Lake Biwa(240 min) and the next higher modes of 70 and 30 mins (Imasato, 1971) suggests that the fundamental seiche is in fact a co-oscillation between the north and south basins. Based on the lake geometry published by Okuda and Kumagai(1995) and an assumed connecting channel length,L_2 of 4km, breadth 1.4km and mean depth of 3.5m expression (3) yields a free period of 214 min. A similar application of this expression to the northern and southern basins of Lake Winnepeg results in inviscid periods of 31 and 45.5 hr when the extreme lengths of the connecting channel of 20 and 50km respectively are assumed. These periods may be compared to that computed by means of a finite element model of 39.1hr (Hamblin,1976). In what is probably the longest exchange period found in any lake Saylor and Sloss(1976) observed a period of co-oscillation between Lakes Huron and Michigan from 44 to 76hr. which may be compared to that of (3) of 29 hr based on L_2=7km and the geometrical data of Saylor and Sloss(1974).

Helmholtz Period

When one of the basins, say 3, has a much larger area than the other then (3) reduces further to give the Helmholtz period P for an embayment,

$$P=2\pi\sqrt{\frac{L_2A_1}{gb_2h_2}} \qquad (4)$$

Applications of this flushing mode to three Great Lakes harbours have been provided by Freeman et al.(1974) as well as its extension to harbours with multiple inlets such as Toronto Harbour. Expression (4) in cases where the density field may be represented by two layers, ρ_1 and ρ_2, and the bathymetry is not too complex may provide the period of internal co-oscillations when g is replaced by reduced gravity, g'. The reduced gravitational acceleration $g'=g(\rho_2-\rho_1)/\rho_2$ and ranges from 10^{-2} - 10^{-4} m/s^2 in lakes. Okamoto and Endoh(1995) found that the summer flushing period of Lake Biwa's Shiozu Bay of 24hrs was often energized due to resonance with the daily wind. One practical implication of (4) in small harbours is that infilling reduces A_1, thereby decreasing the length of time for flushing or the excursion of the inflow.

Forced Oscillations

(a) Water level

The topic of tidally forced inflows into harbours and inlets is a well developed field with two excellent review articles providing sources of useful information to lakes as well, namely, Mehta and Joshi(1988) and van de Kreeke(1988). The approach is to predict the water level in the bay and the flow in the connecting channel forced by the ocean tide based on a one-dimensional momentum equation nearly identical to a forced version of (1) except for the retention of full nonlinearity spatially integrated along the channel and a continuity equation equating the flux through the channel to the rise of water level in the bay. Both authors stress that in most cases it is important to retain the inertia term and various techniques have been developed to obtain analytical solutions for sinusoidally forced motion. In an early application of these equations except that local acceleration of the flow was neglected Dick and Marsalek(1973) found that inertia was significant in the case of exchange flow between Hamilton Harbour and Lake Ontario. Hamblin and He(1995) showed that integration of the complete one-dimensional equations in time can account for about 60% of the variance of 15-min observations of the channel flow over a period of a month. Despite the great success of these simple equations in simulating the flow they provide little insight into the actual exchange itself. This question will be examined in a subsequent section on higher dimensional modelling.

(b) Densimetric forcing

As a result of unequal heat capture between the shallower confined water body and the open lake as well as upwelling of colder bottom water in the lake there may be a contrast in density at the level of the connecting passage which drives a densimetric exchange flow. This concept of a summer exchange between Lake Ontario and Hamilton Harbour that has emerged from the studies of Dick and Marselek(1973), Klapwijk and Snodgrass(1985) and Spigel(1989) is illustrated schematically in Figure 1. Cold Lake Ontario water enters the harbour along the bottom while warmer and lighter harbour water exits as a surface layer. To model the two-layer densimetric exchange for exchanges where both friction and inertia are important internal hydraulic theory may be applied as developed for an exchange problem in the Great Salt Lake by Holley and Waddell(1977). If it is assumed that exchange flows are sufficiently strong to develop internal hydraulic controls at or near the two ends of the joining passage then at these points the composite Froude number G^2 is unity where $G^2= F_1^2+F_2^2$ and the densimetric Froude numbers $F_i^2=u_i2/g'h_i$, i=1,2. The subscript 1 refers to the upper layer(outflow) while 2 denotes the lower layer(inflow). The thickness and average velocity of each layer are symbolized by h_i and u_i respectively. In accordance with internal hydraulic theory the slope of the interface along the channel, dh_1/dx, is given by the internal resistance equation,

$$\frac{dh_1}{dx}=-\frac{K_bF_2^2+K_I\dfrac{(h_1+h_2)\,(|u_1|+|u_2|)^2}{h_1h_2g'}}{1-G^2} \qquad (5)$$

Of course, this equation cannot apply at the control points where $G^2=1$. Apart from uncertainties in the specification of the frictional coefficients of K_b for bottom friction and K_i for internal friction the internal hydraulic equations do not form a closed set. Hamblin(1989) and Hamblin and Lawrence(1990) have predicted the inflow based on the observed value of the outflow and compared the modelled inflows to Hamilton Harbour with generally good correspondence to the field observations of Spigel(1989). Further work on developing a time

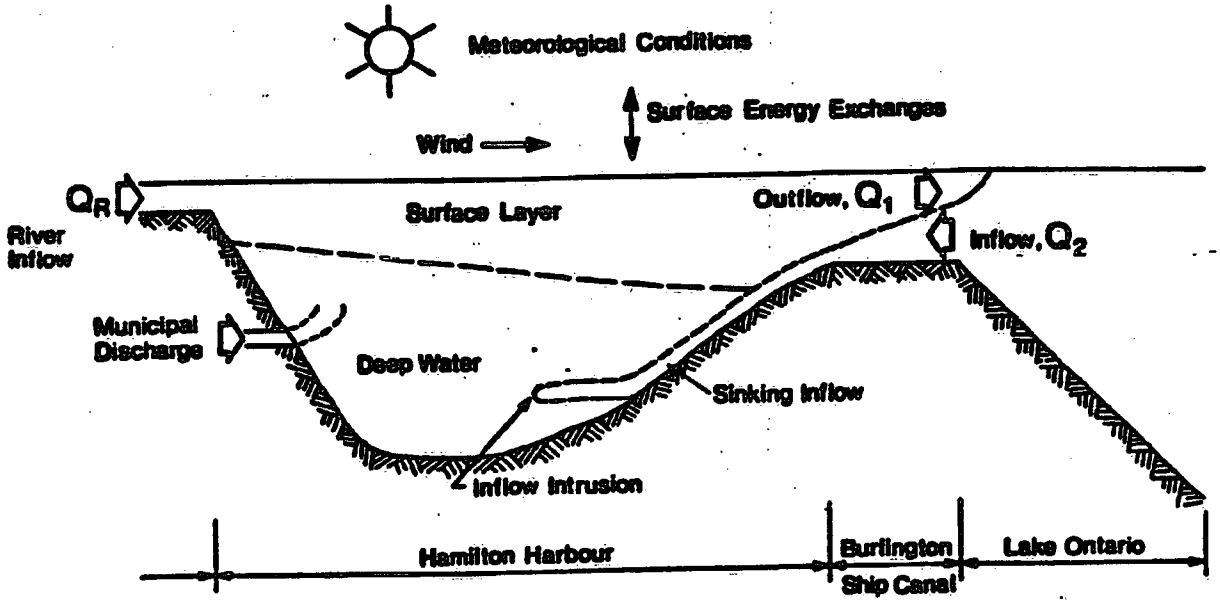

Figure 1. Schematic of the two-layer exchange flow between Hamilton Harbour and Lake Ontario, applicable on occasions from May to October.

dependent model of the internal exchange flow has been sparked by this limitation of the internal hydraulic equations and by more recent observations of current profiles in the Burlington Ship Canal with an acoustic doppler current profiler which indicate a highly transient flow regime alternating between the vertically uniform barotropically forced exchange and a two layer densimetrically dominated condition.

Numerical and Physical Modelling

To date little physical modelling of exchange flows in lakes has taken been published. As the importance of exchange flows in lakes is more widely recognized this will hopefully change. G.A. Lawrence (pers. com.) is planning to conduct laboratory experiments on the exchange between Hamilton Harbour and Lake Ontario. Laboratory experiments could provide potentially valuable insight provided mixing processes can be accurately represented in the model.

Mathematical modelling of exchange processes is a particularly valuable tool for facilitating their understanding and providing practical input to other limnological studies. For example, ecologists modelling the ecosystems in lakes often require specification of fluxes between physical boundaries of the cells of their models and turn to the physical limnologist for assistance. Recently, advanced three dimensional lake circulation models have been used to assist in the interpretation of exchange phenomena in lakes. For example, Oonishi(1995) has demonstrated by means of a three-dimensional model the blocking effect of the earth's rotation on the weak convectively driven exchange between the south and north basins of Lake Biwa. Moreover, he showed that with rotation average cooling rates were insufficient to drive a density current but at four times the average rate a strong intermittent exchange was evident. In the next section another example of the use of two dimensional circulation and transport model will be presented in detail. On the subject of the exchange between the principal basins of Lake Biwa it is mentioned parenthetically that shortly our knowledge will be greatly enhanced as the results of the co-ordinated international field experiment conducted in 1993 appear in the literature.

Seiche and Wind Driven Flushing of Hamilton Harbour

there has been a notable lack of attention devoted the question of mixing in exchange flows both on the experimental and theoretical sides. Mixing processes are especially critical in stratified exchange problems since vertical mixing between the counter flowing layers acts as a short circuit for the transfer of substance through the exchange zone. This remains as one of the most challenging problems confronting physical limnologists at present.

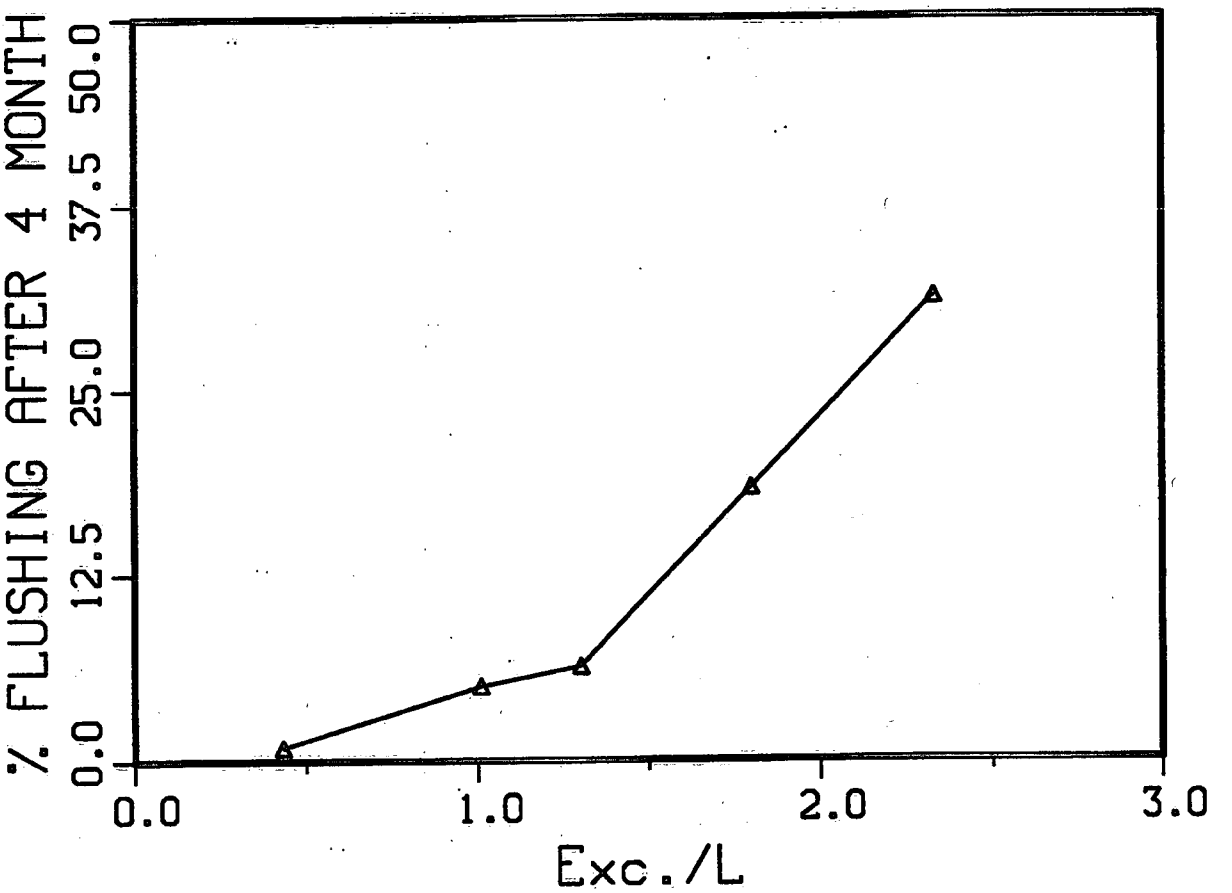

Figure 2. Percentage of Lake Ontario water mixed with Hamilton Harbour after a four month period as a function of the non dimensional excursion length for the case of no wind and water level forcing at the Helmholtz period of 2.6hr.

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References

Bartish, T., 1987: A review of exchange processes among the three basins of Lake Erie. *J. Great Lakes Res.* 13,607-618.

Bennett,E. B., 1976: Aspects of the physical limnology of Georgian Bay, Ontario. *Unpublished Report.* Canada Centre Inland Waters. 1-33.

Chiocchio,F., 1981: Lake Erie hypolimnion and mesolimnion flow exchange between the central and eastern basins during 1978. *National Water Research Institute* ,CCIW, Internal Report. APSD 009.

Dick, T.M. and J.Marsalek, 1973: Exchange flow between Lake Ontario and Hamilton Harbour. *Unpublished Report* Sci. *Ser.* No.36 Canada Centre for Inland Waters, Burlington, Canada.

Fischer,H.B.,E.J.List,R.C.Y.Koh, J.Imberger and N.H.Brooks,1979: Mixing in inland and coastal waters. *Academic Press.*

Freeman, N.G., P.F.Hamblin and T.S.Murthy, 1974: Helmholtz resonance in harbours in the Great Lakes. *Proc. 17th Conf.*

*on Great Lakes Res.*399-411.
Hamblin, P.F., 1995: Remote flow sensing in the Burligton Ship Canal. *Manuscript submitted for publication.*
Hamblin,P.F., 1991: Acoustical remote sensing of exchange flows in lales. *Proc. 10th Hydrotechnical Conference, Can. Soc. Civil Eng.*, 1,11-15.
Hamblin, P.F., 1989: Notes on the hydraulics of Hamilton Harbour. *Unpublished Report, National Water Research Institute Contr. No. 89-36*
Hamblin, P.F., 1976: Seiches, circulation and storm surges on an ice-free Lake Winnepeg. *J. Fish, Res. Bd. Can.* 33, 2377-2391.
Hamblin,P.F. and C. He, 1995: Unstratified harbour exchange hydraulics in lakes. *Manuscript in preparation.*
Hamblin, P.F. and G.A. Lawrence: 1990. Exchange flows between Hamilton Harbour and Lake Ontario.Proc. 1990 *An. Conf. Can. Soc. Civil Eng.* 1, 140-148.
Holley, E.R. and K.M. Waddell, 1976: Stratified flow in Great Salt Lake culvert.*J. Hydr. Div.ASCE,* 102,969-985.
Klapwijk,A. and W.J.Snodgrass, 1985: Model for lake-bay exchange flow. *J. Great Lakes Res.* 11, 43-52.
Imasato, N., 1971: Study of seiches in Lake Biwa-ko(II) *Contribution Geophys. Inst., Kyoto Univ.* 11, 77-90.
Mehta,A.J. and P.B.Joshi, 1988: Tidal inlet hydraulics. *J.Hydr. Engr.* 114, 1321-1338.
Monismith, S., J.Imberger and M.L.Morison, 1990: Convective motions in the sidarm of a small reservoir. 1 *J.Limno. Oceangr.*. 35,1676-1702.
Okamoto, I. and S.Endoh, 1995: Water mass exchange between the main basin and Shiozu Bay.In:*Physical Processes in a Large Lake: Lake Biwa, Japan.* Coastal and Estuarine Studies, Vol. 48, 31-42, American Geophysical Union.
Okubo,K., 1995: Field observations of the dense bottom water current between the north and south basins..In:*Physical Processes in a Large Lake: Lake Biwa,* Japan. Coastal and Estuarine Studies, Vol. 48, 43-51 ,American Geophysical Union.
Okuda, S. and M. Kumagai, 1995: Introduction.In:*Physical Processes in a Large Lake: Lake Biwa, Japan.* Coastal and Estuarine Studies, Vol. 48, 1-6 ,American Geophysical Union.
Oonishi,Y., 1995: Numerical simulation of density-induced currents beween the north and south basins of Lake Biwa. In:*Physical Processes in a Large Lake: Lake Biwa, Japan.* Coastal and Estuarine Studies, Vol. 48, 53-64, American Geophysical Union .
Palmer,M.D., M.F.Hollaran and M.J.Robert, 1993: The effect of indicator organisms in the waste water disposal on mooring embayments. *J. Great Lakes Res.* 19, 352-360.
Roy, F.E., 1983: Spring exchange flows Black Bay, Lake Superior.*Unpublished Manuscript, National Water Research Institute, Burlington,*ES-547.
Saylor,J.H. and G.S. Miller, 1987: Studies of large scale currents of Lake Erie. *J.Great Lakes Res.* 13, 487-515.
Saylor,J.H. and P.W. Sloss, 1976: Water volume transport and oscillatory current flow through the Straits of Mackinac.J. *Phys. Oceanogr.*, 6, 229-237.
Schwab, D.W. and K.W. Bedford, 1994. Initial implementation of the Great Lakes forecasting system: a real time system for predicting lake circulation and thermal structure. *Water Poll. Res. J. Canada* 29,203-220.
Schwartz, R.A. and J. Imberger, 1988: Flushing behaviour of a coastal marina, *Proc. 21 Internat. Conf. on Coastal* Engineering. Torremolinas, Spain, 2626-2640.
Simons, T.J. and W.M. Schertzer, 1983: Analysis of simultaneous current and pressure observations in the Burlington Ship Canal. *Unpublished Report , National Water Research Institute* Contr. No. 83-20.
Spigel, R.H., 1989: Some aspects on the physical limnology of Hamilton Harbour. *Unpublished Report , National Water Research Institute* Contr. No. 89-08.
van de Kreeke, J., 1988: Hydrodynamics of tidal inlets. In:*Hydrodynamics and seiment dynamics of tidal inlets* Vol. 29 Lecture Notes on Coastal and Estuarine Studies, Edited by M.J.Bowman, 1-21.

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