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HYDRAULIC RESIDENCE TIMES FOR THE LAURENTIAN GREAT LAKES

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ABSTRACT. The Laurentian Great Lakes comprise one of the major water resources of North America. For many water quality studies the hydraulic residence times or replacement times of the Great Lakes serve as measures of how quickly water quality will change in response to changes in contaminant loadings. The residence time for a conservative substance represents the average time a conservative substance which remains dissolved in the water spends in a lake. The hydraulic residence times of conservative substances for the Great Lakes are relatively long ranging, from close to 200 years for Lake Superior to a little over 2 years for Lake Erie. A major reduction of 38 years was found in the residence time for Lake Michigan (62 years as compared with the 100 year value previously reported) due to the consideration of flow exchange between Lakes Michigan and Huron. This indicates that Lake Michigan may respond much faster to reductions in contaminant loadings than previously expected. Because of their low ratio of volume to outflow, only Lakes Erie and Ontario are affected by normal climatic variations of less than 20 years in duration. Extreme lake level conditions over the period of 2 to 8 years can also significantly affect the residence times of Lakes Erie and Ontario. Thus high levels in the early 1970s may have contributed to the improvement of water quality in Lake Erie. Existing diversions and potential global warming appear to have no significant effect on residence times.

INDEX WORDS: Residence times, flushing rates, water quality, Great Lakes, climate change.

INTRODUCTION

The Laurentian Great Lakes system (Fig. 1) comprises one of the major water resources of North America. During the last 25 years there have been major efforts undertaken, and even more planned, to improve the water quality of these lakes (IJC 1988). For many water quality studies, the hydraulic residence times of the Great Lakes serve as a measure of how quickly water quality will change in response to increases or decreases in sources of contamination. The residence time for a non-volatile conservative substance represents the average time the substance spends in a lake. As will be shown later, this is equivalent to the length of time required to remove 63 percent of the substance through the lake's connecting channels and diversions. This will also be demonstrated to be equivalent to the time required to remove 63 percent of the water from a lake through its total outflow. The residence times are based upon the time required to drain a lake by its outflow, assuming its inflow is terminated. These are approximations to true residence times which are also functions of the complex circulation patterns within the lakes. The reciprocal of the residence time for water is the flushing rate, given as a percent of the lake volume replaced each year by the lake's inflow. Prior computed Great Lakes residence times (Winchester 1969) were based upon average lake volumes and average outflows through the connecting channels only.

This study updates those values based upon more extensive hydrologic data, determines the residence times for water taking into account all water losses from each lake, and examines the sensitivity of residence times to existing diversions, to high and low lake levels and outflows, and to the potential impacts of global warming. The application of residence times to Great Lakes studies is also illustrated.

METHODOLOGY

The hydrologic water balance for any of the Great Lakes can be expressed as

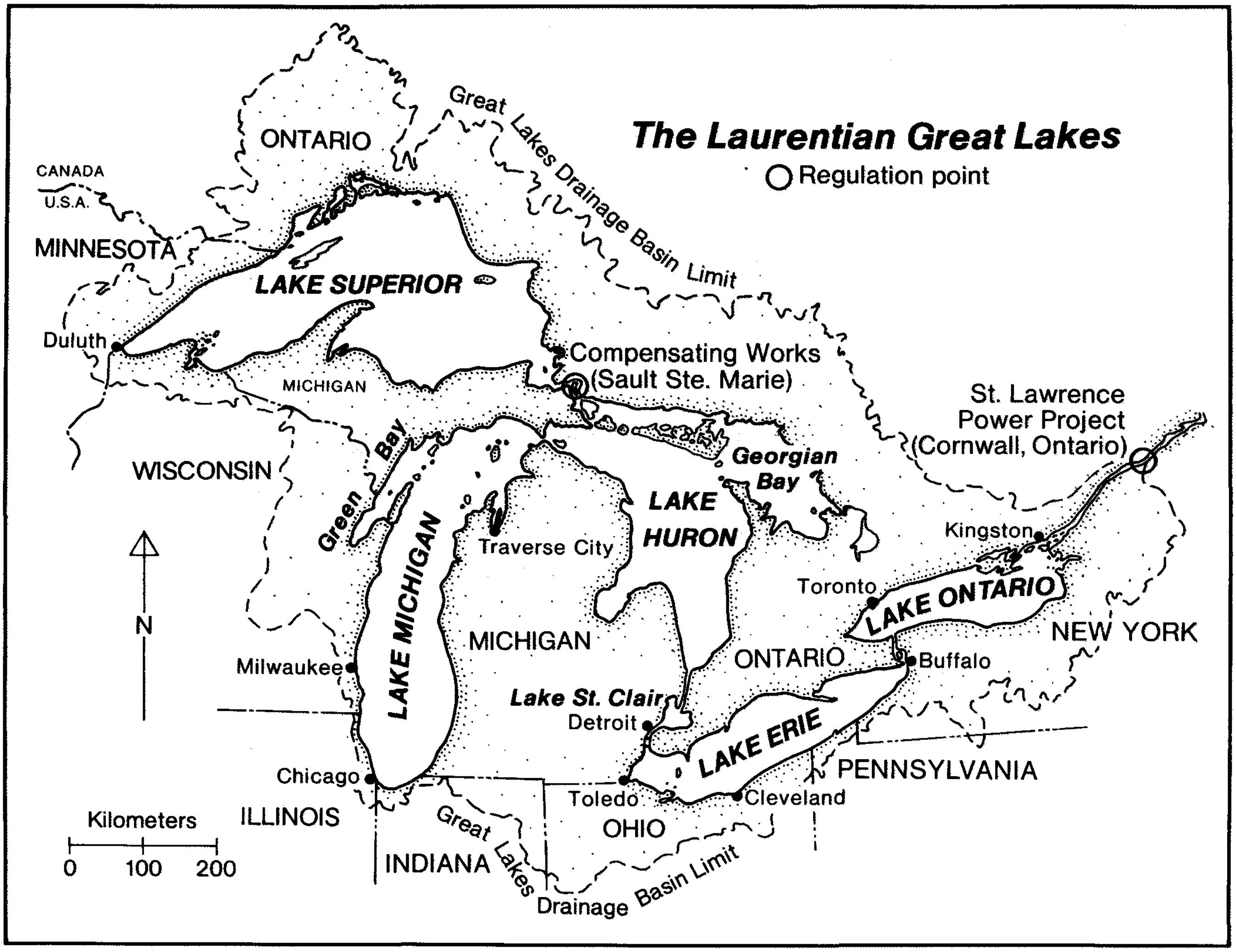

FIG. 1. The Great Lakes basin.

Inflow = Outflow + Change in Storage

or

$$P + R + Qi + Di = Qo + Do + E + dV/dT \quad (1)$$

where: P is the precipitation over a lake surface
R is the runoff to a lake from its drainage basin
Di and Do are the diversions into or out of a lake respectively
Qi is the connecting channel inflow into a lake
Qo is the connecting channel outflow from a lake
E is the evaporation from a lake water surface
V is the lake volume
T is the time interval under consideration.

The hydraulic residence time for a conservative substance, T_r, useful for considering the removal of contaminants from a lake, is obtained by setting the inflow terms to zero and calculating how long it would take to drain a lake through its connecting channel and diversions. The calculation of T_r does not include lake evaporation. Lake evaporation,

TABLE 1. Basic Great Lakes data (Coordinating Committee 1977). Base volume and area are referred to chart datums on IGLD 1955. Average elevation is for the period 1900–1985.

Lake	Area km² (1)	Base Volume km³ (1)	Datum m	Ave. Elev. m (2)	Volume km³ (3)
Superior	82,100	12,100	182.88	183.06	12,115
Michigan	57,800	4,920	175.81	176.27	4,947
Huron	59,600	3,540	175.81	176.27	3,567
St. Clair	1,114	6	174.25	174.76	6.6
Erie	25,700	484	173.31	173.88	499
Ontario	18,960	1,640	74.01	74.59	1,651

TABLE 2. Basic hydrologic data.

Lake	Connecting Channel	Qo m^3s^{-1}	Diversion Location	Diversion m^3s^{-1}
Superior	St. Marys R.	2,218	Ogoki/LL	154
Michigan	St. of Mackinac	2,520	Chicago	-91
Huron	St. Clair R.	5,289		
St. Clair	Detroit R.	5,408		
Erie	Niagara R.	5,812	Welland	-260
Ontario	St. Lawrence R.	6,962	Welland	260

while an outflow term, is not appropriate as it does not remove conservative substances dissolved in the water from a lake. This results in

$$O = Qo + Do + V/T_r$$

$$T_r = V/(Qo + Do). \qquad (2)$$

Prior estimates of residence time (Winchester 1969) were based on setting the net inflow, defined as (P + R - E), equal to zero and ignoring diversions which yields

$$T_r = V/Qo. \qquad (3)$$

COMPUTATION OF RESIDENCE TIMES

The basic physical and hydrologic data required for equations (2) and (3) are summarized in Tables 1 and 2. These data consist of the annual mean Great Lakes connecting channels flows adjusted for current diversions, the current diversion rates, and the average evaporation rates for each of the lakes. The connecting channel flows were first adjusted by subtracting or adding the appropriate recorded diversions to the recorded connecting channel outflows. They were then expressed in terms of the present diversion rates by adding or subtracting the current diversion rates. The connecting channel flows and historical diversion data are for the period 1900–1985 (Quinn and Kelley 1983, updated through 1985).

TABLE 3. Hydraulic residence times based on present diversion rates.

Lake	T_r years	T_r* years
Superior	173	190
Michigan	62	100
Huron	21	20
St. Clair	.04	
Erie	2.7	3
Ontario	7.5	8

*(Winchester 1969: does not include diversions or flow exchange between Lakes Michigan and Huron).

The Lake Michigan outflow calculations through the Straits of Mackinac are based on measurements by Saylor and Sloss (1976). They measured a significant inflow into Lake Michigan through the Straits of Mackinac during the summer stratification. The outflow is computed as a water balance residual as per Quinn (1977), and updated with Lake Michigan precipitation and runoff data for 1948–1985 (Croley 1990).

The residence times for each lake computed by equation (2) are given in Table 3.

The residence times for conservative substances agree closely with those computed by Winchester (1969) for Lakes Huron, Erie, and Ontario. The 16-year difference for Lake Superior is a decrease of 10 percent. The major significant difference is a reduction of 38 years, 38 percent, in the residence time for Lake Michigan. The difference is due to Winchester not considering inflow of water into Lake Michigan through the Straits of Mackinac.

IMPACT OF EXISTING DIVERSIONS ON RESIDENCE TIMES

The impacts of the existing diversions are determined by subtracting or adding the current diversion rates (Do) from the diversion adjusted outflows (Qo) and substituting into equation (2). Only the Long Lac-Ogoki and Lake Michigan at Chicago interbasin diversions affect the residence time. The Long Lac-Ogoki diversion brings water from the Hudson Bay watershed into Lake Superior east of Thunder Bay, Ontario, while water is diverted from Lake Michigan into the Mississippi River basin at Chicago. The water currently flow-

TABLE 4. Impact of existing diversions on residence times.

Lake	Long-Lac-Ogoki m^3s^{-1}	Chicago m^3s^{-1}	T_r years	ΔT_r years
Superior	-154	—	186	-13
Michigan	—	—	62	- 0
Huron	-154	91	22	- 1
Erie	-154	91	2.7	0
Ontario	-154	91	7.6	- .1

TABLE 5. The effects of lake level and outflow changes on residence times.

Lake	Condition	Period (years)	Elevation (meters)	Qo (m^3s^{-1})	T_r years
Erie	High	1985–1986	174.62	7,196	2.3
Erie	Low	1934–1936	173.18	4,500	3.4
Ontario	High	1972–1977	74.82	8,196	6.4
Ontario	Low	1931–1938	74.15	5,786	9.0

ing through the Welland Diversion between Lakes Erie and Ontario would flow at the same rate through the Niagara River if the diversion was halted. This would result in Lake Erie being at a higher water level for the same total outflow. For a similar reason, the Lake Michigan diversion at Chicago does not appreciably impact the Lake Michigan residence time as the outflow through the diversion would otherwise flow through the Straits of Mackinac. The Long Lac-Ogoki diversion affects the residence times of Lakes Superior, Huron, Erie, and Ontario, while the Chicago diversion effects the residence times of Lakes Huron, Erie, and Ontario. Table 4 gives the residence times without the current diversions. The net effect of the current diversions are a 13-year reduction in the residence time of Lake Superior and no significant change to the other lakes. This is because the Long-Lac and Ogoki diversion, and the Chicago diversion, represent only 3 and 2 percent of the St. Clair, Niagara, and St. Lawrence River flows, respectively.

IMPACTS OF EXTREME LAKE LEVELS ON RESIDENCE TIMES

Only Lakes Erie and Ontario have significant changes in levels and flows over averaging periods corresponding to their residence times. As the natural outflows are a function of the lake levels, the period of record from 1900–1986 was examined to select the highest and lowest average lake levels corresponding to the appropriate residence times for Lakes Erie and Ontario. The average outflows for these periods were then determined and the residence times computed as given in Table 5.

The results show a dramatic decrease, about 30 percent, in the residence time for both Lakes Erie and Ontario between the low and high flow periods. A similar decrease in residence times during the early 1970s may have contributed to the rapid improvement in water quality between the mid 1960s and the mid 1970s. This is illustrated by Figure 2 which shows the percent of the lake volume replaced each year. During the early 1970s close to 50 percent of the lake's volume was replaced by its inflow each year compared with about 35 percent in the mid 1960s.

POTENTIAL EFFECTS OF CLIMATE CHANGE ON RESIDENCE TIMES

The potential impact of global warming was analyzed by taking the hydrologic data and lake levels computed under three General Circulation Model scenarios (Croley 1990, Hartmann 1990) and applying equation (2) to compute the residence times. It is assumed that the current diversion rates would be in effect during the warming scenarios. The most severe scenario for each lake is shown in Table 6. Lake Michigan is not reported as the flow through the Straits was not determined under the scenarios. Likewise Lake Ontario results are not given because the existing regulation plan failed under the climate scenarios. The small increases in

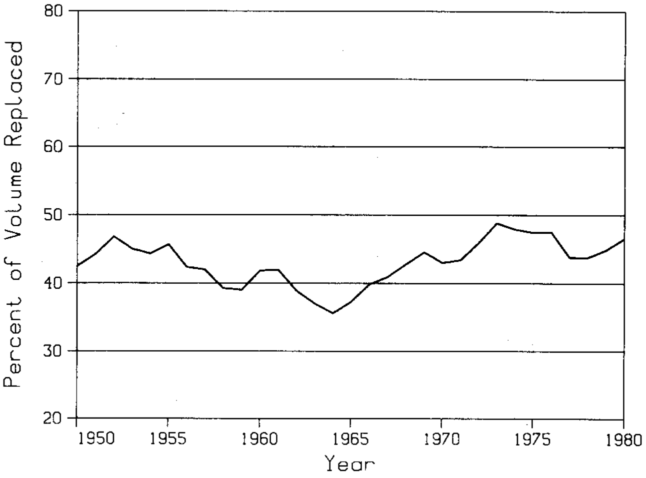

FIG. 2. Percent of Lake Erie volume replaced on an annual basis.

TABLE 6. Residence time under climate change scenarios.

Lake	Water Level meters	Volume km^3	Qo m^{3}s^{-1}	T_r years
Superior	182.66	12,086	2,181	176
Huron	175.32	3,511	4,306	26
Erie	173.17	480	4,975	3.1

residence times are about what one would expect with the decreased volume being offset by reduced flows in the connecting channels.

The most important impact of climate change on the residence time is unable to be quantified at the present time It is the decrease in residence time for Lake Michigan due to increased westward flow into the lake through the Straits of Mackinac. The flow is driven by the thermal gradient through the Straits. This gradient would be established earlier, perhaps be more intense, and would break up later under global warming. This could dramatically decrease the residence time for Lake Michigan.

APPLICATIONS

The residence time can be used to form simplified lake response models for simulating first order system responses to changes in loadings of conservative substances (O'Conner and Mueller 1970, Eadie and Robbins 1987). Consider a hypothetical fully mixed lake of volume V with an outflow Q. Denote the volume of water containing dissolved conservative substances in the lake at time = 0 as v, and the volume of the original water mass remaining in the lake at any time T as v_r. Assuming a fully mixed lake, the change in volume of the original water mass remaining in the lake v_r is given by

$$\frac{dv_r}{dt} = -Q\frac{v_r}{V} \qquad (4)$$

or alternately

$$\frac{dv_r}{v_r} = -\frac{dt}{T_r} \qquad (5)$$

The volume of original water remaining at any given time T can be determined by integrating equation (5) between time 0 and time T. The corresponding volumes are V and v_r. This yields

$$\Big[\ln(v_r)\Big]_{v_r}^{V} = -\frac{1}{T_r}\Big[\,t\,\Big]_{0}^{T} \qquad (6)$$

$$\frac{v_r}{V} = e^{-(T/T_r)} \qquad (7)$$

As the term v_r/V is equivalent to the relative concentration (C_r) of a conservative substance in a lake, equation (7) can be written

$$C_r = e^{-(T/T_r)} \qquad (8)$$

Equation (7) forms the basis for the modeling framework.

For example, at T equal to the residence time T_r, equation (7) yields

$$\frac{v_r}{V} = e^{-1} = 0.37 \qquad (9)$$

Thus, 37 percent of the original volume remains in the lake after one residence time. Particular caution must be taken, especially in dealing with the media, to emphasize that the residence time is not the length of time to replace all of the water in a given lake. Likewise, the time required to remove 99.9 percent of the contaminants from a lake, assuming no additional inputs, can be computed by setting the left side of equation (7) to .001 and solving for T. The result is 6.91 T_r. In the case of Lake Superior this is 1,195 years.

Another time constant of interest, the average length of time a conservative substance spends in the system. T_{ave}, can be determined by integrating equation (7) between time T = 0 and T = infinity, yielding

$$T_{ave} = \int_0^{\infty} e^{-(T/T_r)}\,dT$$

$$Ta = -T_r(0 - 1) = T_r.$$

Thus, the average length of time a conservative substance remains in the lake is the residence time. It should be noted that in most of the lakes, sedimentation, not outflow, is the most important removal mechanism for persistent contaminants (Eadie and Robbins 1987).

Figure 3 shows the system response to the cessation of loading of a conservative substance to Lake Superior. For illustration it is assumed that the initial concentration of the substance in Lake Superior is 100 ppm and 0 ppm initial concentration in the lower lakes. The removal process as the contaminant passes through the system is readily observable. It takes several hundred years for the

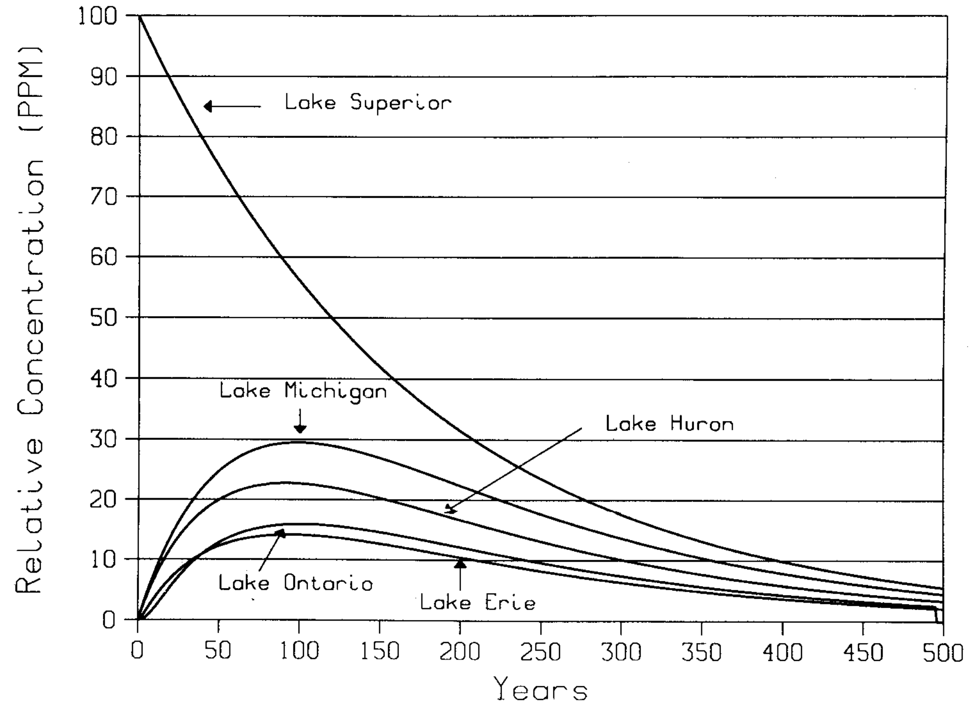

FIG. 3. ***Coupled lakes model. System response to ending conservative contaminant loading in Lake Superior (100 ppm initial concentration in Lake Superior and 0 ppm initial concentration in the lower lakes).***

contaminant to finally leave the system through Lake Ontario.

CONCLUSIONS

Hydraulic residence times are very useful in providing a system perspective on the impact of potential changes in contaminant loadings to the Great Lakes. The hydraulic residence times of conservative substances for the Great Lakes are relatively long ranging, from close to 200 years for Lake Superior to a little over 2 years for Lake Erie. A major reduction of 38 years was found in the residence time for Lake Michigan, 62 years as compared with the 100-year value previously reported. This indicates that Lake Michigan may respond much faster to reductions in contaminant loadings than previously expected. Because of the long residence times, only Lakes Erie and Ontario are affected by normal climatic variations of less than 20 years in duration. The existing diversions were found to have no appreciable effect on residence times. As diversions constitute a relatively small percentage of the total outflow, they would have to be significantly increased to affect residence times. Extreme lake level conditions over the period of 2 to 8 years can significantly affect the residence times of Lakes Erie and Ontario. The high levels in the early 1970s may have contributed to the improvement of water quality in Lake Erie. Surprisingly, potential climate change appears to have a relatively small impact on residence times This is due to higher evaporation rates being balanced by small connecting channel outflows.

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