A POLLUTION DISPLACEMENT MODEL

FOR THE GREAT LAKES SYSTEM

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ABSTRACT

A pollution displacement model of the Great Lakes system is presented, together with a brief review of previous Great Lakes water balance and pollution displacement models. The DYNAMO II language is utilized in a simulation of historical water balance relationships and a water pollution transport system for dissolved substances in each lake. The model enacts a continuous simulation of some hydrologic and water quality components of each subsystem, while making the concentration of pollutant in a downstream lake partially dependent upon the calculated inflow from the upstream lake. The concept of residence time or response time of a lake is developed. Due to the long residence time of pollution in the Great Lakes, especially in Lakes Superior and Michigan, the effects of water quality degradation or improvement may not be detectable for many decades.

INTRODUCTION

The Great Lakes system represents the largest open flowing system of fresh water in the world. The total drainage basin includes over 753,000 square kilometers and the total volume of water exceeds 20,800 cubic kilometers. Flowing eastward for 1,630 kilometers from northern Minnesota to the headwaters of the St. Lawrence River, this network of lakes and rivers comprises parts of eight states in the U.S. and one-third of the Canadian province of Ontario. (40) The 18 million people who now rely on water supplied by the lakes use over 152 billion liters per day. The present level of industrial water use is double that figure. It seems obvious that the capacity of the lakes for sustaining modification and use is immense; the lakes have remained essentially unchanged for over 10,000 years. However, man's impact on this system has already become quite evident.

In order to assess the response of any lake subsystem of the Great Lakes to further pollution, pollution abatement, or further modification of the lake flows, it is essential to consider both the behavior of the total Great Lakes system and the unique characteristics of each lake. This paper describes a hydrologic and water quality model of the Great Lakes system that integrates such complex concepts into a form which may be adopted as a tool in regional land and water use planning.

THE HYDROLOGIC SYSTEM

Flowing from west to east, the Great Lakes system includes the five principal lakes, their connecting channels and the peripheral lands of the drainage area. Lake Superior and Lake Michigan drain into Lake Huron via the St. Mary's River and the Straits of Mackinac, respectively. Lake Huron drains into the St. Clair River-Lake St. Clair-Detroit River system before flowing into Lake Erie. The Niagara River connects Lake Erie with Lake Ontario, and finally the St. Lawrence River drains the Great Lakes waters into the Atlantic Ocean. The water levels and outflows of Lake Superior and Lake Ontario are regulated by locks and dams in their downstream channels according to international agreement and supervision. (15) A general summary of the hydrology of each lake basin is presented in Table 1.

TABLE 1

General Hydrology of the Great Lakes Basins

Lake	Surface Areas(km^2) (1)		Volume (km) (2)	Mean Depth(m) (3)	Range in Stage(m) (4)
	Water	Land			
Superior	82,102	127,687	12,234	148	1.17
Michigan	57,757	118,104	4,918	84	2.00
Huron	59,829	133,903	3,539	59	2.00
Erie	25,667	58,767	483.5	17.7	1.61
Ontario	19,554	70,577	1,638	86	2.01

Parameters (1)-(4) taken from references:

    (1): 15, 29, 35, 39
    (2): 22, 29
    (3): 21, 22, 29
    (4): 21

A number of important comparative factors for the Great Lakes are indicated in the hydrologic data above. Due to the enormous storage capacity of the lakes (22,800 km^3 of water), the lake outflows are relatively uniform over time. For example, the lowest recorded flow in the St. Lawrence River is about one-half of the maximum. (39) The lake surfaces occupy nearly one-third of their drainage area--245,000 km^2 of the total 753,000 km^2. The lakeshores and the outer boundaries of their basins are never more than 200 km apart, and at one point the boundary lies within 3 km of the shore. (27) Consequently, few large rivers flow into the Great Lakes.

For purposes of this discussion the units of the water transport model are in cubic kilometers and the time units are in years. The long-term patterns of flow and volume are characterized by mean annual values upon which are superimposed random variations of a normal distribution. The water balance of each lake can be represented by a series of inflows and outflows, measured in cubic kilometers per year:

$$(TIFLOW) = (P) + (R) + (I) + (BI) \qquad (1)$$

where:

$(TIFLOW)$ = Total Inflow to lake (km^3/yr)
(P) = Precipitation on lake (km^3/yr)
(R) = Runoff in lake basin (km^3/yr)
(I) = Inflow from upstream lakes (km^3/yr)
(BI) = Balance for Total Inflow (km^3/yr)

$$(TOFLOW) = (O) + (E) + (BO) \qquad (2)$$

where:

$(TOFLOW)$ = Total Outflow from lake (km^3/yr)
(O) = Outflow to downstream lakes (km^3/yr)
(E) = Evaporation from lake (km^3/yr)
(BO) = Balance for Total Outflow (km^3/yr)

Slight discrepancies in the calculated water budget for each lake are due to differences among these various source data, and are taken into account by including the balance for total inflow (BI) and balance for total outflow (BO) terms. These terms amount to less than one percent of the total budget of each lake.

Mean annual rates of precipitation and evaporation vary according to calculations of the mean and standard deviation for the period 1900-1967. Precipitation data are taken from references (15,23,27,35, and 39). It is assumed that data from shoreline weather stations are representative of over-lake conditions for each yearly intervals. Runoff data, taken from references (17,26,35, and 39), include all surface water flows, overland flows, and direct discharges which flow directly into the lakes. It is assumed that runoff is constant for each lake over the yearly intervals. Lake volumes, found in

references (22 and 29), are assumed to vary according to the changing water balances in each lake as expressed in equations (1) and (2). The volume of the present year is calculated in equation (3) from the volume of the previous year, net of the factors described in equations (1) and (2):

$$(V_k) = (V_j) + (TIFLOW) - (TOFLOW) \qquad (3)$$

where:

(V_k) = Volume of lake at present time (k)
(V_j) = Volume of lake at previous time (j)

For the purposes of this study, lake outflows are assumed to change with changing volume, as expressed in equation (4):

$$(O) = (V_k) * (ORATE) \qquad (4)$$

where:

$(ORATE)$ = Outflow-to-Volume ratio, $(O)/(V_k)$

The upstream inflow (I) to each lake is equivalent to the sum of the outflow (O) from the upstream lake plus that portion of local runoff (R) which occurs along the connecting channel. A water balance of the hydrologic components for the entire Great Lakes system is shown in Figure 1, which indicates the mean annual values (km^3/yr) of all components for the period 1900-1967.

Underground infiltration and seepage are insignificant compared to the other hydrologic components, and are omitted from the water budget calculations. Man-made diversions are incorporated into the appropriate components.
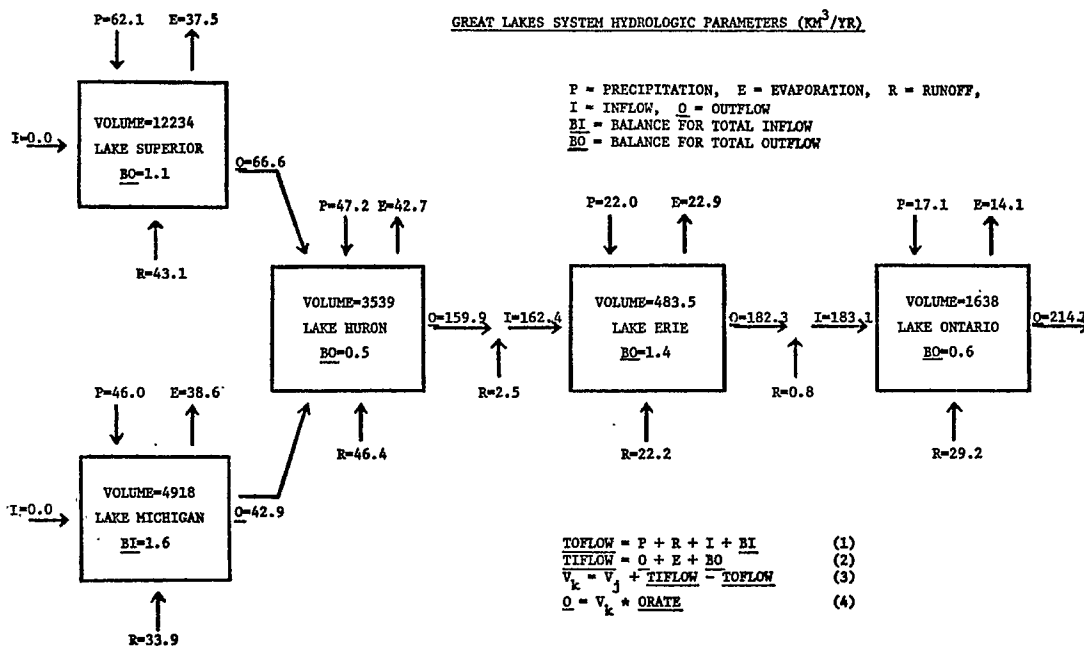
Precipitation is the most significant component of total inflow for both Lake Superior and Lake Michigan, and the water quality of these lakes is greatly influenced by this factor. However, in Lakes Huron, Erie, and Ontario, total inflow is dominated by outflow from the upstream lakes. Lake Huron receives about one-half of its total inflow from the upstream lakes. Upstream contributions to Lake Erie and Lake Ontario account for about 80% of their total inflow. Consequently, the water quality in the Upper Great Lakes is a principal determinant in the dilution or concentration of water quality constituents in the Lower Lakes.

DISSOLVED SOLIDS AS A MEASURE OF WATER QUALITY

Simulation of the displacement of water quality constituents requires an initial understanding of the nature of each constituent which is to be studied. In order to predict the rates of pollution displacement with reasonable accuracy over long time periods, one must distinguish between "conservative" and "non-conservative" constituents. In natural waters, conservative constituents are defined as those constituents which are known to remain stable, both in mass and in chemical

FIGURE 1.

GREAT LAKES SYSTEM HYDROLOGIC PARAMETERS (KM^3/YR)

P = PRECIPITATION, E = EVAPORATION, R = RUNOFF,
I = INFLOW, O = OUTFLOW
BI = BALANCE FOR TOTAL INFLOW
BO = BALANCE FOR TOTAL OUTFLOW

P=62.1 E=37.5

I=0.0

VOLUME=12234
LAKE SUPERIOR
BO=1.1

Q=66.6

R=43.1

P=47.2 E=42.7

VOLUME=3539
LAKE HURON
BO=0.5

Q=159.9 I=162.4

R=2.5

P=46.0 E=38.6

I=0.0

VOLUME=4918
LAKE MICHIGAN
BI=1.6

Q=42.9

R=46.4

R=33.9

P=22.0 E=22.9

VOLUME=483.5
LAKE ERIE
BO=1.4

Q=182.3 I=183.1

R=22.2

R=0.8

P=17.1 E=14.1

VOLUME=1638
LAKE ONTARIO
BO=0.6

Q=214.7

R=29.2

$$\text{TOFLOW} = P + R + I + BI \qquad (1)$$
$$\text{TIFLOW} = O + E + BO \qquad (2)$$
$$V_k = V_j + \text{TIFLOW} - \text{TOFLOW} \qquad (3)$$
$$O = V_k * \text{ORATE} \qquad (4)$$

composition, over extremely long time periods.
They are not readily incorporated into lake
sediments, evaporated, or biologically assimi-
lated as may be other water quality constituents.
This report will deal specifically with conserva-
tive constituents, namely dissolved solids, as
they exist and are displaced through the
Great Lakes system.

Non-conservative constituents are those which
change either in mass or chemical composition
over time. Nutrients, suspended solids, many
trace elements, and a number of other water
quality constituents are included in this
category. The extent to which non-conservative
constituents undergo changes from their original
state in a lake can be accounted for by removal
rates or "sink" functions. Although this report
does not include simulation of these non-
conservatives, the pollution displacement model
which is discussed below is designed to enact
such first-order removal rates.

Dissolved Solids

Dissolved solid concentrations, which include
chloride ions, sulfate ions, and many of the
other "conservative" dissolved ions in water,
have been monitored extensively throughout
the Great Lakes system. (1,3,5,9,18,37) Histori-
cal observation of these substances covers the
past 100 years. (3)

The dissolved solids concentration is considered
to be a collective indicator of water quality,
reflecting changes in the concentrations of major
mineral contaminants. The buildup of dissolved
solid concentrations in the Great Lakes is not,
in itself, a serious problem, but it indicates

large accumulations of materials. (16) In
Lake Erie, which is the most polluted of the
Great Lakes, the concentration has risen by
30 percent in the last 40 years. (16) Thus,
the International Joint Commission has established
objectives for dissolved solid concentrations
which are considerably more stringent than
levels which would merely impair domestic and
industrial water supplies. (3) It is assumed
that changes in the lake concentrations in the
Great Lakes are indicative of the external
loading of pollution. A comparison of the
average concentrations of dissolved substances
in each Great Lake is presented in Table 2.

TABLE 2

Comparison of Average Concentrations of Dissolved Substances in the Great Lakes (ppm)

	Chloride	Sulfate	Total Dissolved Solids
Superior	1.9 (a)	1.9 (a)	60 (f)
Michigan	6.5 (d)	20.0 (e)	150 (g)
Huron	5.9 (a)	13.0 (g)	134 (f)
Erie	23.4 (d)	21.1 (d)	198 (g)
Ontario	26.7 (c)	27.1 (c)	194 (g)

(a) Beeton, 1971
(b) Canada Centre for Inland Waters, 1972
(c) Dobson, 1967
(d) FWPCA, 1968
(e) FWPCA, 1968b
(f) Sutherland, et al., 1968
(g) Weiler and Chawla, 1969

Chlorides

The chloride ion is one of the major conservative
ions which are found in natural and waste waters.
In natural waters there is no observed saturation
level or upper limit for the chloride ion con-
centration—the maximum amount is that added by

human activity and the minimum is that which is residual in precipitation. (18) The principal sources for the Great Lakes are the outfalls of municipal and industrial waste treatment facilities and runoff from urbanized areas where salt (sodium chloride) is employed in the de-icing of roads. Although chlorides are relatively non-toxic constituents of water systems, they are indicators of the cumulative effects of population growth on water pollution. Yearly estimates of chlorides added to each lake basin are largely incomplete, and little historical data is available. However, over the past 50 years the chloride concentration has remained relatively close to the background level in Lake Superior (3) while increasing approximately three-fold in Lake Erie and Lake Ontario. (16)

Sulfates

The sulfate ion is another widely distributed dissolved substance which is naturally found in low concentrations in fresh water. Although an upper limit to the concentration of sulfate in the Great Lakes is presumed to exist, this upper limit is well above the present level of concentration. (18) Consequently, it is also considered as a conservative ion. The concentration in Lake Superior is close to the background level, (3) although in Lake Erie and Lake Ontario it has doubled over the past 50 years. (16)

Sources of sulfates for the Great Lakes include the natural drainage of streams which overlie sulfide-bearing bedrock materials, stream drainage from sulfide ore mines where sulfides are oxidized into sulfate, industrial waste discharges, and airborne emissions from such industrial sources as copper-nickel smelters. Sulfide concentrations in lakes can be oxidized into the conservative sulfate form, thereby increasing the activity of sulfur-reducing bacteria and depleting the concentration of dissolved oxygen in lakes. (18) Consequently, sulfates have been considered as a possible index of lake eutrophication.

The chemical alteration of the Great Lakes is prone to cause severe modifications in their natural biota and in their natural rates of aging. It is important to develop a water quality model valid for long time periods which will also take into consideration the individual characteristics of each lake subsystem.

MODELING POLLUTION DISPLACEMENT

Hydrologic Flushing Time as a Basis for the Model

One measure of the rate of displacement of water and its constituents through a lake system is the hydrologic flushing time, which is the time required to displace the total lake volume through its outflow. It is simply calculated as:

$$\text{FLUSHING TIME} \quad (\underline{FT}) = (V_k) / (O) \quad (5)$$

The calculated flushing time for each Great Lake is presented in Table 3. It has been considered as a minimum estimate of the time required to significantly change the composition of lake water. In fact, pollution displacement can be a slower process than the flushing time implies.

Rainey (1967) has presented a model which implies that differences between the inflowing concentration and lake concentration would cause changes to occur in the lake concentration at a rate which is inversely proportional to the flushing time of the lake. He calculated that a constant rate of loading of pollution into Lake Superior would cause a maximum, or equilibrium buildup of pollutant concentration to occur in no less than 500 years. A theoretical formulation for this concept of pollution displacement can be expressed as:

$$(dC) / (dt) = (C_{In} - C_L) / (\underline{FT}) \quad (6)$$

where:

(dC) = Increment in concentration in lake (ppm)
(dt) = Increment in time (yrs)
(C_{In}) = Inflowing concentration (ppm)
(C_L) = Concentration in lake (ppm)

The inflowing concentration (C_{In}) is assumed to be held constant over time. This generalized formulation is only applicable for conservative water quality constituents, since non-conservatives are likely to change in composition or be displaced more rapidly than the calculation above would predict.

TABLE 3	
HYDROLOGIC FLUSHING TIMES FOR THE GREAT LAKES (YRS)	
LAKE SUPERIOR	184
LAKE MICHIGAN	115
LAKE HURON	22
LAKE ERIE	2.7
LAKE ONTARIO	7.6

Other models of pollution displacement for the Great Lakes have either intuitively or directly used flushing time as a premise in their calculations. (14,25,29,34) Rainey has described such models as compromising between a fast, purging displacement rate such as that found in a river system, and a slow diffusion rate which is the controlling mechanism in the case of a channelized, stratified fluid system. The basis for the model presented in this report is similar to that described by Rainey. This model is also based on several assumptions which need to be clearly

expressed.

Basis for Considering Pollution Displacement

The model presented here is based on the assumption that each Great Lake is a completely mixed system. That is, the entire volume of each lake is presumed to be available for dilution and flow within a yearly period. Vertical and horizontal stratification, surface currents and nearshore diffusion patterns tend to limit the degree of mixing within short time periods. However, there is evidence to support the assumption that a unit interval of one year, which is the time unit used for simulation of this model, is a valid interval for the mixing assumption.

Vertical stratification takes place during the summer in each Great Lake, when the warmer surface waters develop into an independent, stratified layer (called the epilimnion). The epilimnion diminishes during autumnal cooling until a time is reached in early winter when the water in the lake approaches uniform temperature and density at all depths, and the lake is well mixed by wind-induced currents. The effect of five months of stratification in Lake Ontario was analyzed for its effects on the hydrologic flushing time. (34) The outflow of the lake was assumed to leave only from the epilimnion during this stratification period. The calculated flushing time was shown to increase from 19 to 20 years, or by five percent. As long as the volume of the epilimnion is large with respect to the annual rate of outflow, the effect of stratification will be negligible. Although Lake Erie does not have the large volume-to-outflow ratio that is characteristic of the other Great Lakes, its shallow depth (mean depth = 18m) causes it to be vertically mixed by wave action.

Horizontal mixing in each lake is primarily enacted by a counterclockwise circulation pattern which prevails during much of the year. Although the nearshore surface currents are thought to inhibit the dispersion of land-derived pollutants over the period of one season, it appears that on an annual basis the composition of outflowing waters is representative of average lake conditions. The analyses of thousands of lake samples from Lake Erie and Lake Ontario have shown that chloride ion concentrations are remarkably uniform across the entire surfaces of these lakes. (34)

The connecting river channels are assumed to act as thoroughly mixed subsystems, since their lengths are not excessive and their velocities are usually greater than one-half meter per second. (18) Consequently, assumptions regarding vertical and horizontal mixing in and between each Great Lake are justifiable over the long time periods which are of interest in this discussion.

Most of the water balance models of the Great Lakes have made some simplifying assumptions about the balance between the total inflow and total outflow of each lake basin. It has been indicated by Kohler (1959) that a one percent miscalculation of the inflow and outflow of Lake Ontario would incorrectly represent an annual change in depth of about 20 centimeters over the lake surface. This would be equivalent to a 25 percent miscalculation of the total annual precipitation on the lake basin. (17) The components of flow and volume which are being used in the simulation of the model presented in this report are allowed to oscillate around mean annual values, but remain within the assigned standard deviations. Consequently, the potential for misrepresentation of the water balance over long time periods should not be significant.

Another assumption which has frequently been made regarding Great Lakes water balances is that annual rates of precipitation (P) and evaporation (E) are equal over each of the lake surfaces. If the relative magnitudes of these components are not equivalent $[(P)/(E) \neq 1]$, the concentration of chemical constituents in the lake should either be diluted or further concentrated before flowing out of the lake. If their ratio $(P)/(E)$ is greater than one, and if the chemical composition of precipitation is more pure than that of the lake, then the net effect is to dilute the lake concentration. If $(P)/(E)$ is less than one, then the lake concentration will be further concentrated before flowing out of the lake. Lake Superior has a $(P)/(E)$ ratio of 1.7/1; consequently, its waters should undergo considerable dilution by the atmosphere. The $(P)/(E)$ ratio for Lake Erie is 0.95/1, so its waters should actually become more concentrated before passing into Lake Ontario. However, it has recently been indicated that precipitation is a major source of several pollutants in the Great Lakes. (20) The assumption that higher rates of precipitation should dilute the pollutant concentrations of lakes may therefore be more misleading than useful. The need for considering the unique characteristics of each Great Lake, however, is made all the more important by considering this type of discontinuity.

Hydrologic Residence Time

The calculation of flushing time which was presented in equation (5) can be modified by considering mean annual evaporation as a factor in the displacement of water and pollutants. Since evaporated water is practically distilled in nature, evaporation tends to further concentrate the chemical composition of a lake. In other words, lakes which have relatively high rates of evaporation tend to have more rapid rates of response to changes in water quality, and lakes having lower evaporation rates generally have slower response times for water quality changes. This modified formulation of flushing time is used in this model and will be called hydrologic "residence time":

$$\text{RESIDENCE TIME} \quad (\underline{RT}) = (V_k) / (\underline{O} + E) \qquad (7)$$

By dividing the lake volume (V_k) both by the annual rate of outflow $(\underline{O})$ and evaporation (E), the residence time calculation takes into account the natural purging rate of lake water (as it passes through the outflow) as well as the concentrating effect of evaporation (as pure water

is evaporated from the lake surface). The resi-
dence time calculation is presented as a calcula-
tion which is more reasonable than flushing time
for estimating the rate of response of a lake
to a change in water quality.

A hypothetical example can be used to explain
the advantage of using residence time instead of
flushing time for a model of pollution displace-
ment. Consider two lakes with identical volumes
and rates of outflow (i.e., identical flushing
times). One of the lakes is situated in a lower
latitude than the other, and consequently, it has
a higher rate of evaporation. (41) If both lakes
have the same initial conditions of water quality,
it should be expected that the lake which has a
higher evaporation rate will also have a more
rapid rate of response to changes in the quality
of inflowing waters. In other words, the lake
with greater evaporation should have a shorter
water quality response time, and consequently,
a shorter residence time.

The calculated residence time for each Great Lake
is presented in Table 4. Significant portions of
the total outflows of Lake Superior and
Lake Michigan are incorporated in their evapora-
tion rates (see Figure 1). Their residence times
are therefore considerably less than their flush-
ing times. The total outflows of the Lower Lakes
are dominated by the downstream flows, and as
a result their residence time and flushing time
calculations are quite similar.

TABLE 4
HYDROLOGIC RESIDENCE TIMES AND FLUSHING TIMES FOR THE GREAT LAKES (YRS)

	RESIDENCE TIME	FLUSHING TIME
LAKE SUPERIOR	117	184
LAKE MICHIGAN	60	115
LAKE HURON	17.5	22
LAKE ERIE	2.4	2.7
LAKE ONTARIO	7.2	7.6

The residence time calculation in equation (7)
can be substituted for flushing time in the
formulation of pollution displacement which was
described in equation (6).

$$(dC) / (dt) = (C_{In} - C_L) / (RT) \qquad (8)$$

The amount of time which is required for the
concentration in a lake to change with respect
to a constant level of input can be calculated
by using a probabilistic function of the ex-
ponential number, e. A theoretical formulation
for this exponential function can either be used
to calculate the rate of removal of pollution
from a lake, or to calculate the rate of
pollution buildup:

$$(a): \quad C * e^{-t/RT} \quad ; \text{ OR} \qquad (9)$$
$$(b): \quad C(1 - e^{-t/RT})$$

where:

C = Concentration in lake (ppm)
e = Exponential number ~ 2.71
t = Time (yrs)

These functions are only valid for water quality
constituents which are conservative over time and
space. The first function (9a) describes the rate
of removal of pollution, and the second (9b) des-
cribes the rate of pollution buildup. These time-
dependent displacement rates are illustrated in
Figure 2.

FIGURE 2

DISPLACEMENT RATES FOR REMOVAL AND BUILDUP OF POLLUTION IN LAKES

2a) POLLUTION REMOVAL   2b) POLLUTION BUILDUP
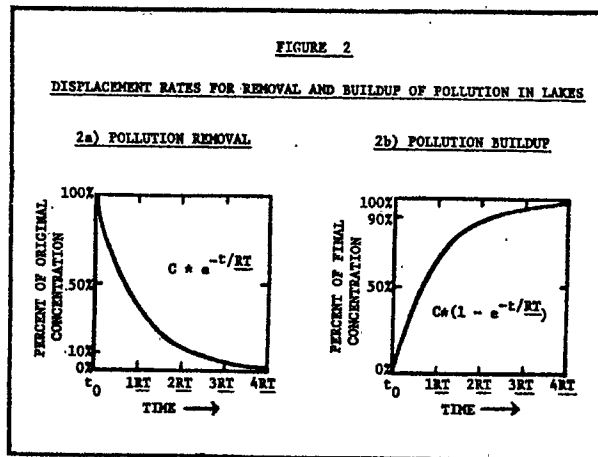
It is seen that the initial concentration in a lake
will change exponentially with respect to an in-
flowing concentration which is more or less con-
centrated than the lake. An equilibrium lake con-
centration is eventually reached after many resi-
dence times are passed. This is based on the
assumptions that the inflowing concentration is
constant over time, and that the outflowing con-
centration is characteristic of the lake concentra-
tion for each year.

It is interesting to compare the amounts of time
required for the displacement of some fraction of
the original pollutant concentration in each
Great Lake. For example, one might wish to calcu-
late the time required for displacement of
90 percent of the pollution in each Great Lake.
The calculation of these displacement times can
be performed with the use of equation (9) in two
different ways. First, each lake can be considered
as a system which is independent of the other lake
systems. In other words, the lakes can be assumed
to have no connecting channels, and the upstream
inflow of each basin would not be affected by
conditions in the lakes upstream. Second, the
five lakes can be considered as a linked series of
lake subsystems, whereby the concentration in each
lake is determined both by the unique hydrology in
its own basin and by the dynamic conditions in up-
stream basins. The time which is required for

the displacement of 90 percent of the original pollutant concentrations in each Great Lake under both of the above conditions is presented in Table 5.

TABLE 5

DISPLACEMENT TIMES FOR 90% CHANGE IN POLLUTANT CONCENTRATIONS (YRS)

	INDEPENDENT LAKE SYSTEMS	INTERCONNECTED LAKE SYSTEMS
LAKE SUPERIOR	420-425	420-425
LAKE MICHIGAN	260-265	260-265
LAKE HURON	50-52	210-215
LAKE ERIE	6.0-6.2	145-150
LAKE ONTARIO	17-18	100-105

The displacement times for Lake Superior and Lake Huron are equivalent in the "independent lake" and "interconnected lake" formulations, because these lakes have no upstream inflows. The displacement times in the Lower Lakes are significantly longer in the "interconnected lake" formulations because the cumulative effects of the long residence times of the Upper Lakes are allowed to act upon the total Great Lakes system. Some of the previous pollution displacement models have considered each of the Great Lakes as an independent lake system. However, it is obvious that changes in the water quality of the Upper Lakes will also cause changes in downstream lakes. At the present time, Lake Superior and Lake Michigan represent significant sources of clear water--their effect is to dilute the concentration of pollutants which are being discharged downstream. However, if the Upper Lakes become increasingly polluted, they will gradually become significant sources of pollution for the Lower Lakes.

Inflowing Concentration

The total inflowing concentration of each lake is derived from the concentration of the hydrologic components which comprise total inflow [see equation (1)]. It can be expressed as:

$$C_{In} = [C_P(P) + C_R(R) + C_I(I)] / [(P) + (R) + (I)] \quad (10)$$

where:

C_{In} = Inflowing concentration (ppm)

C_P = Concentration in precipitation (ppm)

C_R = Concentration in runoff (ppm)

C_I = Concentration in upstream inflow (ppm)

Equation (10) is applicable to the theoretical calculation of pollution displacement which was presented in equation (8). It was assumed in those displacement calculations that the inflowing concentration (C_{In}) was held constant over time. However, in the model which is presented in this report, the total amount of pollution entering a lake can be made to vary in two ways. First, the concentration of one or more flows (C_P, C_R, C_I) may vary with assigned trends or oscillations, thereby changing the inflowing concentration (C_{In}). Second, the annual rate of one or more hydrologic

flows [(P),(R),(I)] may vary in accordance with their means and standard deviations, as described above in the section on hydrology. This would change the total mass of pollution entering the lake. It is assumed that the formulation in equation (10) is only valid for conservative water quality constituents.

Equilibrium Concentration

It is shown in equation (9) that, if the inflowing concentration is assumed to be constant over time, and many residence times are allowed to pass, the lake concentration will approach an equilibrium condition. This concept is assumed to be valid only for conservative constituents. It is applicable to pollution buildup or removal, depending on the relative concentrations of inflow and initial lake conditions. The equilibrium concentration of a lake with respect to specific inputs can be described as:

$$C_{Eq} = [C_P(P) + C_R(R) + C_I(I)] / [(P) + (R) + (I) - (E)] \quad (11)$$

This calculation is similar to the residence time calculation in equation (7), in that it considers the concentrating effects of evaporation. It is identical to the total inflow concentration in equation (9), except that evaporation can only affect the concentration of pollutants after they have entered the lake basin.

This calculation of equilibrium concentration has been used by Dingman and Johnson (1971) in describing the "pollution potential" of several New Hampshire lakes. Although the calculation is independent of time, it has been used to estimate the final concentration in a lake for any known level of input. For example, if accurate data existed for the rate of pollution entering each Great Lake through each hydrologic source, then it would be possible to calculate the maximum (equilibrium) buildup of concentrations in the lakes. However, all of the hydrologic flows are changing from year to year as a result of natural variations, and the total loading of pollution in the lakes has been steadily increasing over the past several decades. (11,16) Consequently, the final equilibrium concentration in each Great Lake may actually never be realized. When the increasing rates of pollution are incorporated into the calculations of displacement time which were discussed above, the equilibrium concentration will tend to lag continuously with respect to the changing inputs.

Concentration of Non-Conservative Constituents

Non-conservative constituents include most of the nutrients, major ions and suspended materials which are found in the Great Lakes. These constituents are not considered in the formulations which are described above, because their masses or chemical compositions tend to be removed from solution more rapidly than the displacement rates which are calculated from hydrologic residence times. Some of the previous pollution displacement models have considered non-conservatives such as nutrients by assuming that the ultimate "sink" for the nutrients is the bottom sediment of the lake. (8,32,36) These models used both a first-order function for calculating the rate of sedimentation

of non-conservatives and the hydrologic flushing time for calculating the displacement of the constituent through the lake outflow. The equilibrium concentration of a lake, which was presented in equation (11), can be modified in order to consider the displacement of non-conservatives:

$$C_{Eq} = [C_P(P) + C_R(R) + C_I(I) - (S)] / [(P) + (R) + (I) - (E)] \quad (12)$$

where:

(S) = Rate of sedimentation of non-conservatives

This formulation was used by Dingman and Johnson (1971), and (S) was considered as a mass rate (concentration x volume/unit of time) of removal from the lake system. Sonzogni, Uttormark and Lee (1973) have also considered (S) to be a mass rate variable, by describing it as a rate which is directly proportional both to the mean concentration of the lake and to the lake volume:

$$(S) = C(K) * (V_k) \quad (13)$$

where:

(K) = Rate loss constant $(0 \geqslant (K) \geqslant 1)$
C = Concentration in lake (ppm)

This calculation can be illustrated with a hypothetical example. If one-half of all the non-conservative constituents in a lake were lost to the sediments over the period of one year, then (K) would equal 0.5, and (S) would equal one-half of the constituent concentration in the lake volume. This first-order calculation of the displacement of non-conservatives is supported by the "critical loading" model of Vollenweider (1969), who described the net sedimentation rate of phosphorus as proportional to the mean concentration of the lake, and by Dobson (1973), who discussed a "pollution susceptibility index" for phosphorus which was based on sedimentation rates, lake surface area, and the external loading of pollution. Thus, if (S) and the annual rate of inflow of a non-conservative entering a lake are known, then it is possible to derive an approximation of the displacement time for the nutrient as it enters the lake, passes through the outflow and undergoes sedimentation. (32)

The calculations of the exponential rates of removal and buildup of constituents which were presented in equation (9) were only assumed to be valid for constituents which were conservative over time and space. These can now be modified in order to calculate the displacement rates of non-conservatives in a lake:

$$(a): \quad C * e^{-(t/\underline{RT}) * (C_{In}/C_{Eq})} \quad ; OR$$
$$(b): \quad C(1 - e^{-[t/\underline{RT}] * [C_{In}/C_{Eq}]}) \quad (14)$$

In these calculations the exponential functions for pollution removal and buildup are made to be dependent upon the relative change in concentration of a constituent $(C_{In} \rightarrow C_{Eq})$ as it passes through the lake system. In other words, at any instant in time, the concentration of a water quality constituent is proportional to the potential difference between the inflowing concentrations (C_{In}) and the equilibrium buildup of concentrations (C_{Eq}) in the lake system. In the case of the displacement of conservative constituents, the ratio of inflowing concentrations to equilibrium concentrations (C_{In}/C_{Eq}) is dependent upon the relative magnitudes of the hydrologic parameters of the lake, because these parameters may tend to concentrate or dilute the constituents as they pass through the lake. One would expect that this ratio is approximately equal to one for conservatives. However, in the case of non-conservative constituents, this ratio is dependent on both the hydrologic parameters of the lake and the sedimentation rate of the constituents; therefore, the magnitude of this ratio would be considerably less than one. Consequently, the displacement times for non-conservatives are usually shorter than those for conservatives.

Concentrations in Lakes

The formulations which are presented in this model can be classified into two groups. First, there are equations which only describe the response times of lake systems for the displacement of pollution [see equations (7),(8),(9)]. These equations are independent of the concentrations of constituents in the lakes--they are only based on the hydrologic and geomorphic characteristics of the basins. Second, there are equations in this model which describe the different concentrations of water quality constituents as they pass through the lake systems [see equations (10),(12),(13)]. Unlike the first group of equations, these equations are based on the assumption that the various concentrations are constant with respect to time. It is possible, however, to combine these formulations into one pollution displacement equation. The new equation for pollution displacement is presented as:

$$C_L = C_{Eq} + (C_o - C_{Eq}) * e^{-(t/\underline{RT}) * (C_{In}/C_{Eq})} \quad (15)$$

where:

C_L = Concentration in lake (ppm)
C_o = Initial concentration in lake (ppm) when t = 0 years

In this equation, the concentration in a lake can be determined for any point in time by evaluating the equation for different values of (t). It is assumed in the equation above that the equilibrium and inflowing concentrations are constant through time. Similar lake equations have been used by others in modeling pollution displacement. They have been used to calculate both the buildup and removal of water quality constituents in the Great Lakes. (14,25,29) They have also been used

to calculate the displacement of constituents be-tween connected basins or reservoirs. (25,38)

However, this formulation is different from pre-vious models of pollution displacement in three respects. First, the exponential function in this equation is proportional to the ratio of the in-flowing concentration to the final equilibrium concentration. This ratio should work equally well for conservative and non-conservative con-stituents. The second departure that is·made from previous models is that evaporation from a lake is considered as a factor in concentrating a constituent once it enters the lake system. This concept was first discussed by Kramer (1964), who described the importance of the ratio of precipitation to evaporation for ·the Great Lakes. It is used in equation (15) for both the residence time calculation [equation (7)], and equilibrium lake concentration [equation (12)]. The third distinction between this formulation and those in previous models is that all of the hydrologic and water quality relationships described above are incorporated into a computer simulation model of pollution displacement for the Great Lakes. With the use of computer simulation, it is pos-sible to predict the response of the entire Great Lakes system to any combination of the unique hydrologic and water quality relationships which are included in this model.

COMPUTER SIMULATIONS

The Great Lakes pollution displacement model is written in DYNAMO II language and is executed on a UNIVAC 1108 computer. The results which are presented below are both preliminary and hypo-thetical in nature; however, they do show the range of potential questions which can be con-sidered with the model. Although the model is capable of simulating the displacement of non-conservative water quality constituents, the re-sults below will only describe conservative con-stituents in the Great Lakes. A description of the DYNAMO computer program is included in the Appendix of this report. (42)

Pollution Buildup

The first results of the model are based on the assumption that certain concentrations of pollu-tants are known to flow into each Great Lake over extended periods of time. It is possible to calculate from these inflowing concentrations both the yearly buildup and equilibrium level of pollution in each Great Lake. If the time span for these conditions is long with respect to the residence time of each lake, then the concentra-tion in each lake will continue to increase until an equilibrium condition is reached.

Table 6 contains two equilibrium concentrations for each Great Lake, which are computed for ·the buildup of pollution. The first concentration which is presented for each lake is based on the assumption that the chloride ion enters the lake systems through runoff at a steady concentration of 100 parts per million (ppm). Precipitation is not assumed to contribute any chloride concentra-tions to the lakes. The outflows and upstream inflows of the lakes· are allowed to transport the

average lake concentrations downstream. The second concentration which is presented for each Great Lake is also based on the assumption that 100 ppm of chloride enters each system, but 50 ppm enters through runoff and 50 ppm enters through precipita-tion.

TABLE 6

EQUILIBRIUM CONCENTRATIONS OF CHLORIDES IN THE GREAT LAKES (PPM)

	FOR: 100 PPM IN RUNOFF,	FOR: 50 PPM IN RUNOFF, 50 PPM IN PRECIPITATION
LAKE SUPERIOR	64	78
LAKE MICHIGAN	82	97
LAKE HURON	77	87
LAKE ERIE	81	89
LAKE ONTARIO	82	86

The relative importance of precipitation as a di-luting or concentrating factor in each Great Lake can be measured in the differences between the first and second equilibrium concentrations. It can be· seen from these hypothetical calculations that if accurate data for the inflowing rates of pollution exist for each lake, then it is possible to calculate the rate of buildup and the final equilibrium concentration for each Great Lake.

Pollution Removal--Sulfates

It is interesting to consider the minimum amount of time required for removing the present concentra-tions of pollutants from the Great Lakes. If all inflowing sources of pollution were to be abated, then the natural rates of displacement would cause the lake concentrations to approach equilibrium levels of zero ppm. A simulation of the model was performed for the removal of sulfates, using the considerations which are described above. Recently measured sulfate ion concentrations, which are found in Table 2, are presented in Table 7 along with simulated future concentrations. In this simulation, sulfates are transported downstream through the lake outflows and upstream inflows. However, no new sulfate concentrations are allowed to enter the lakes.

TABLE 7

DISPLACEMENT OF SULFATE CONCENTRATIONS FROM THE GREAT LAKES

DISPLACEMENT TIMES	SULFATE CONCENTRATIONS IN GREAT LAKES (PPM)				
	SUPERIOR	MICHIGAN	HURON	ERIE	ONTARIO
PRESENT	1.9	20.0	13.0	21.1	27.1
50 YEARS	1.5	12.8	5.6	5.3	5.0
100 YEARS	1.1	8.3	3.4	3.1	2.8
200 YEARS	0.6	3.5	1.5	1.3	1.2
400 YEARS	0.2	0.6	0.3	0.3	0.7

The long residence times of the Upper Lakes cause much of their sulfate concentrations to remain for several hundred years. Although the displacement rates of the Lower Lakes would be much faster if they were considered as separate lake systems, the cumulative effects of the upstream lakes tend to prolong the displacement of pollution throughout the entire Great Lakes system.

Test of Policy for Water Quality Regulation

The two simulations which are described above demonstrate that the model can be used to simulate both the buildup and removal of constituents according to specified conditions. It is also possible to perform more dynamic simulations so that the concentrations of pollutants in each lake may undergo buildup or removal, depending on the various policies which might be implemented. In the next simulation, some tests of specific policies are performed for the longer term regulation of water quality standards for dissolved solids in the Great Lakes. A complex arrangement of inflowing concentrations and lake concentrations will be considered. These concentrations will be allowed to change dynamically through time according to specified trends, and the effects of certain policies for pollution control will be analyzed for each Great Lake.

In the initial conditions of this simulation it is assumed that the components of runoff and precipitation carry equal concentrations of dissolved solids into the lakes. The recently measured dissolved solids concentrations which are listed in Table 2 are considered as the present concentrations. The duration of the simulation is 1,000 years. The inflowing concentrations for Lake Superior and Lake Michigan are set to increase at a linear rate for the first 500 years. After the first 500 years, these inflowing concentrations will remain stable at magnitudes which should cause the concentrations in the lakes to reach equilibrium levels of 200 ppm—the maximum water quality standard established by the International Joint Commission. (16) The inflowing concentrations for Lake Huron will remain at the present conditions throughout the entire simulation. The inflowing concentrations for Lake Erie and Lake Ontario will remain stable at the present concentrations for the first 500 years. After the first 500 years, a policy is implemented whereby the concentration in the runoff of these two basins will be reduced to one-half of the original concentration. The concentration in precipitation on these basins will be assumed to remain constant for the entire 1,000-year period. The results of this simulation are plotted in Figure 3.

Many important relationships can be observed in this simulation. The increase in the concentration in Lake Superior and Lake Michigan lagged behind the increasing inflowing concentrations for the first 500 years. While the inflowing concentrations remained stable during the second 500 years, the concentrations within these lakes still continued to rise for several hundred more

FIGURE 3.

SIMULATED DISPLACEMENT OF DISSOLVED SOLIDS IN THE GREAT LAKES

SUPERIOR	0	100	200	300	400
HURON	130	150	170	190	210
ONTARIO	190	200	210	220	230
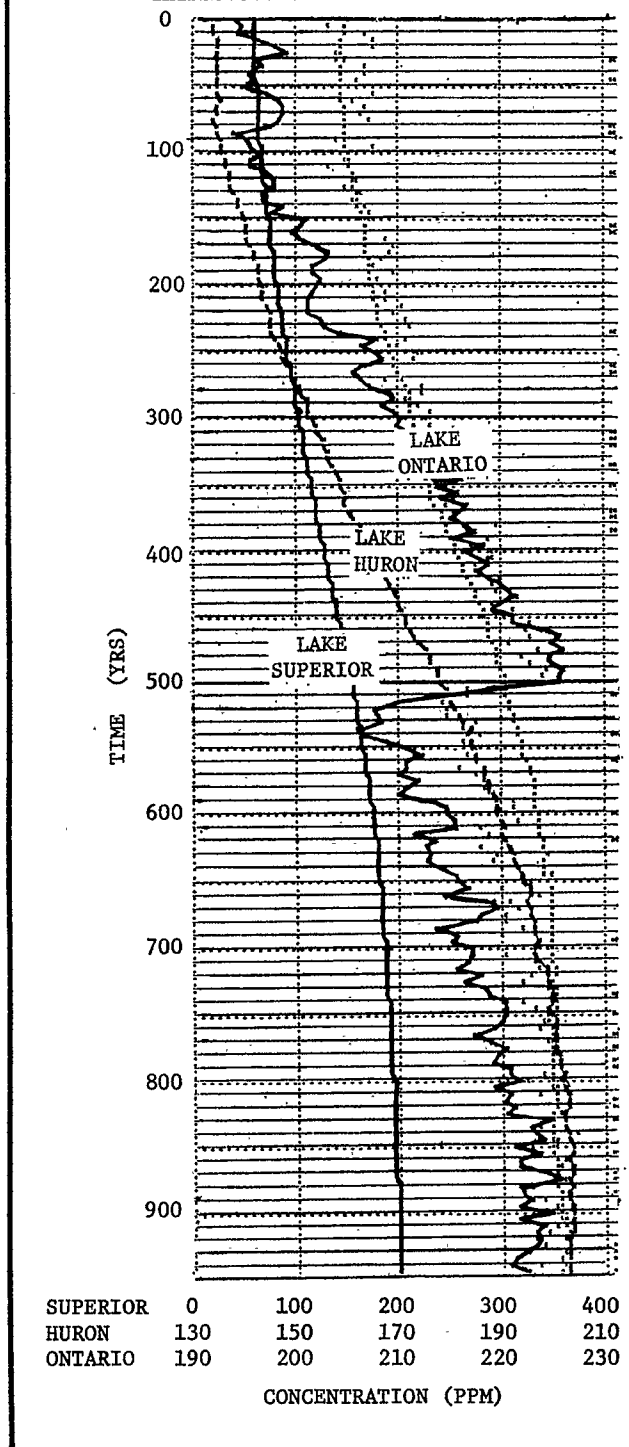
CONCENTRATION (PPM)

years until the equilibrium concentration of 200 ppm was reached.

Although the inflowing concentrations for Lake Huron were constant throughout the entire simulation, the lake concentration was so affected by the increases in Lake Superior and Lake Michigan that it rose above the maximum allowable standard. In the first 500 years the cumulative effects of pollution buildup in the Upper Lakes caused the concentrations in Lake Erie and Lake Ontario to rise well above the water quality standards. Most important, however, was the lag effect during the second 500 years, in which the implementation of pollution control in Lake Erie and Lake Ontario was counterbalanced by the long-term buildup in the concentrations of the Upper Lakes. Even though there were no increases in the inflowing concentrations during the second 500 years, the dissolved solids concentrations in Lake Erie and Lake Ontario exceeded the maximum levels which were attained in the first 500 years, when their runoff concentrations were twice as large.

The 1,000-year duration of this simulation is a very hypothetical time frame to use in considering pollution control. And yet, the cumulative effects of pollution buildup in all of the Great Lakes are only realized in such a length of time. It is evident from observing this simulation that the control of pollution can only be successful if the total Great Lakes system is taken into consideration. Although Lake Erie and Lake Ontario would seem to have rapid response times for the removal of pollution if the proper policies were implemented, the Upper Lakes are keystones in the preservation of water quality throughout the Great Lakes system.

CONCLUSIONS

This report has attempted to associate the hydrologic water balance relationships of the Great Lakes with various water quality constituents as the constituents are displaced through time. The pollution displacement model defines the "hydrologic residence time" of each lake, taking into account the dynamic balances between the hydrologic components as they concentrate or dilute the constituents which are passing through the lake systems. Several portions of the model are predicated on previous studies of pollution displacement and water balance in the Great Lakes. These studies and their assumptions are reviewed in this report, and certain departures are taken from these considerations.

Computer simulation is used as a tool for observing the dynamic behavior of water quality in the Great Lakes through time. The computer program is versatile because it is capable of associating different concentrations of water quality constituents with each of the hydrologic inflows of the lakes. It is also dynamic, because unlike the previous equations in which certain variables were assumed to be held constant, continuous simulation allows the user to evaluate the effects of changing concentrations in all the parameters through time. The model is only valid for long time periods; however, it is essential to consider that the natural rates of pollution displacement in these lakes are of magnitudes which would dwarf the effects of short-term water quality controls.

A logical extension of these preliminary efforts is the application of the model to empirical data and existing trends. Further development of the model may include the incorporation of discrete spatial sub-components within each lake system. It may also be possible to examine the displacement rates for monthly intervals, provided that adequate formulations and data are available over shorter time periods.

The potential for using such a model in regional land-use planning has yet to be explored. The realization of the long displacement times for some of the Great Lakes and the consequences of the cumulative interactions between them should no longer allow decisions to be based on entirely local considerations. At the present time, such models seem to provide the only method for incorporating complex, long-term elements into the decisionmaking process.

APPENDIX

The Great Lakes pollution displacement model is written in DYNAMO II simulation language and is executed on a UNIVAC 1108 computer. The reader is referred to DYNAMO II User's Manual by Pugh III (1970), which gives a full reference to the simulation language. The model is organized with the use of MACRO functions, which define once, in the beginning of the model, the relationships of major parameters which are used repeatedly throughout the model. Four MACRO functions are defined in the beginning of the model; they are Total Inflow, Total Outflow, Residence Time, and Dissolved Solids. Next, the equations of hydrologic flow are organized into five groups, with each group representing one of the Great Lakes. These equations invoke the MACRO functions in order to calculate total inflow, total outflow, and volume for each lake. Mean and standard deviations are specified for the hydrologic flow parameters in these equations.

After the equations are defined, the model specifies the relationships of these flows with the concentrations of water quality constituents which are being considered in the model. In each time interval, new changes in the concentration of water quality constituents are calculated for each lake. The unit concentration of each lake (in ppm) is multiplied by the rate of outflow for the lake, and the outflowing "mass" of constituents for the upstream lake becomes the inflowing "mass" for the downstream lake. Thus, the unit concentration of each lake is dynamically dependent upon the changing conditions upstream. The flexibility of the model stems from the ability to assign different levels and trends to the changing concentrations of water quality constituents in each hydrologic flow over different intervals of time.

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40. There are 35 million people living within the Great Lakes basin, 80 percent of whom live on the United States side.

41. The difference between the latitudes of Lake Superior and Lake Erie might be considered in this case. Lake Superior extends northward to 49°N., while Lake Erie extends southward to 41.5° N., making for an extreme difference of 7.5°

42. Copies of the computer program are available on request from the authors.