HYDROLOGY MODELS

GLERL's AHPS consists of daily runoff models for each of the 121 watersheds, lake thermodynamic models for each of the seven water bodies, hydraulic models for the four connecting channels and five water body outflow points with operating plans encoded for Lakes Superior and Ontario, and simultaneous water balances on all the lakes. It is described in detailed overviews elsewhere (Croley 2003, 2005).

1.1 Runoff

GLERL's Large Basin Runoff Model (LBRM) consists of moisture storages arranged as a serial and parallel cascade of "tanks" coinciding with the upper and lower soil zones, a groundwater zone, and the surface channel system (Croley 2002). Water enters the snow pack, which supplies the basin surface (degree-day snowmelt). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Water percolates from the upper to the lower soil zone tank and from the lower to the groundwater zone tank (deep percolation). Water also flows from the upper, lower, and groundwater zone tanks into the surface channel system, as surface runoff, interflow, and groundwater flow respectively. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Evapotranspiration is proportional to available water and to sensible heat (a complementary concept in that evapotranspiration reduces available sensible heat). Mass conservation applies for the snow pack and tanks; energy conservation applies to evapotranspiration. Complete analytical solutions exist. The model has been calibrated to each of the 121 watersheds contributing to the Great Lakes by minimizing root mean square error between daily model outflows and adjusted outflow observations. Each calibration determined parameters for infiltration, snow melt, surface runoff, percolation, interflow, deep percolation, groundwater flow, surface storage, and evapotranspiration from all moisture storages by systematically searching the parameter space (with a gradient-search technique). The model agrees quite well with weekly and monthly observations (Croley 2002, 2003). These parameters represent present-day hydrology and are not changed in the simulations. All 121 model applications are used in the simulations.

1.2 Evaporation

GLERL's Lake Thermodynamic Model adjusts over-land data (original or adjusted as a changed-climate scenario) from the 40 over-land stations that are used to estimate over water meteorology for over-water or over-ice conditions based on empirical relationships between the two (Croley 1989, 1992a; Croley and Assel 1994). Surface flux processes are represented for reflection and short-wave radiation, net long-wave radiation, and advection. Aerodynamic equation bulk transfer coefficients for sensible and latent heat are formulated with atmospheric stability effects. Energy conservation accounts for heat storage; superposition of heat additions or losses determines temperature-depth profiles. Each addition is parameterized by age and mixes throughout the volume. Mass and energy conservation account for ice formation and decay. The model has been calibrated to each of the seven lake surfaces by minimizing root mean square error between daily model surface temperatures and observations. The model enables one-dimensional modeling throughout of spatially averaged water temperatures over the lake depth and can be used to follow thermal development and turnovers in the lake.

1.3 Lake Area Adjustment

For each lake, precipitation *p* is provided as a scenario-dependent boundary condition and runoff *r* and evaporation *e* are estimated with the runoff and evaporation models. They are expressed as depths over the lake surface, in m, for a given time interval (day), and are based on the lake area C as coordinated between the US and Canada (CCGLBHHD 1977). That is, no variation of lake area is actually considered in their determination in the runoff and evaporation models. However, we adjust to actual lake area A by converting these depth rates into volumetric flow rates,

$$P = \frac{pA}{\Delta} \tag{1}$$

$$R = r\frac{C}{B-C}\frac{B-A}{\Delta} \tag{2}$$

$$E = \frac{eA}{\Delta} \tag{3}$$

where P = volumetric precipitation rate in m^3s^{-1}, R = volumetric runoff rate in m^3s^{-1}, E = volumetric evaporation rate in m^3s^{-1}, B = basin area (including the lake), and Δ = number of seconds in the time interval. Note, B and C are constants for a lake while *p*, *r*, *e*, and *A* vary with time. Precipitation and evaporation are directly converted by simply multiplying the overlake rates by actual lake area. Runoff is first multiplied by the coordinated lake area (over which it was expressed) to calculate the modeled runoff volume, then divided by the coordinated land area (to express it as the equivalent yield per unit of land area), and then multiplied by the actual land area to calculate the adjusted runoff volume. Thus "*R*" gets bigger as "*A*" gets smaller. Of course, there is some error involved with this procedure since p, r, and e actually depend on actual lake area too and should have been computed from models considering actual lake area and volume changes. Also, exposed land areas would not have the same properties as the original basin. Consideration of the uncertainty associated with these errors is beyond the scope of this exploratory study.

1.4 Outflow Relations

Unmanaged lake outflow depends on lake level and outflow sill elevation for lakes not affected by backwater (such as Superior, Erie, and Ontario) or on these variables as well as downstream lake level for lakes affected by backwater (such as Michigan-Huron and St. Clair). In a study designed to assess the cumulative impact of all of Society's developments on Great Lakes water levels, Southam (1989) described a quantitative empirical relationship between water elevation and outflow for each lake that represents "natural" conditions, prior to the introduction of societal developments. For the

Laurentian Great Lakes watershed, these developments include regulation of outflows of Lakes Superior and Ontario, modification of connecting channels through dredging or shoreline changes, use of ice control measures, and diversion of water into and out of the lakes. Any impacts caused by land use modification, consumptive uses, and regulation of tributary rivers are viewed as reflected by changes in water supplies to the lakes and not by changes in elevation—outflow relationships, and were not considered in that study. We convert Southam's relationships from their original English units and IGLD'55 water level datum to metric units and IGLD'85 water level datum. We also transform his Lake Erie adjustment for channel project removals to one compatible with basic weir formulae and express Ontario outflows in terms of the 1985 sill elevation.

For Lake Superior,

$$Q_S' = 4901\left(Z_S' - 593.99\right)^{1.5} - H_S' \qquad (4)$$

where Q_S' = Lake Superior outflow in ft^3s^{-1}, Z_S' = Lake Superior water elevation (at Point Iroquois) with respect to the IGLD'55 water level datum (CCGLBHHD 1979) in ft, and

Table 1. Great Lake Outflow Ice and Weed Retardation[a] (Southam 1989).

	Superior		Michigan-Huron		St. Clair		Erie	
Month	$10^3ft^3s^{-1}$	m^3s^{-1}	$10^3ft^3s^{-1}$	m^3s^{-1}	$10^3ft^3s^{-1}$	m^3s^{-1}	$10^3ft^3s^{-1}$	m^3s^{-1}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
January	4	113	36	1020	15	425	4	113
February	4	113	48	136	15	425	5	142
March	4	113	23	651	8	227	3	85
April	4	113	6	170	2	57	5	142
May								
June							2	57
July							5	142
August							4	113
September							3	85
October							2	57
November								
December			4	113	5	142		

[a]No values for Ontario are given in the reference.

Table 2. Selected Location Datum Elevation Differences, IGLD'85 – IGLD'55, m (CCGLBHHD 1995).

Pt. Iroquois	Harbor Beach	Gross Pointe	Cleveland, Buffalo	Oswego
(1)	(2)	(3)	(4)	(5)
0.377	0.214	0.200[a]	0.180[a]	0.158

[a]Lake-wide average of all water level gages is used.

H'_S = ice retardation, in ft^{3}s^{-1}, as given in Table 1. Converting units (1 ft = 0.3048 m),

$$\begin{aligned} Q_S &= \left[\frac{4901}{(0.3048)^{1.5}} \left(Z''_S - 181.048 \right)^{1.5} - H'_S \right] (0.3048)^3 \\ &= 824.721 \left(Z''_S - 181.048 \right)^{1.5} - H_S \end{aligned} \tag{5}$$

where Q_S = outflow in m^{3}s^{-1}, Z''_S = IGLD'55 elevation in m, and H_S = ice retardation, in m^{3}s^{-1}, in Table 1. Lake levels relative to Point Iroquois in 1985 are equivalent to lake levels relative to Point Iroquois in 1955 plus 0.377 m, as shown in Table 2, because of upward crustal movement caused by isostatic rebound since the retreat of the glaciers. Converting to the current IGLD'85 datum (CCGLBHHD 1995) by using this adjustment,

$$Q_S = 824.721 \left(Z_S - 181.425 \right)^{1.5} - H_S, \qquad Z_S \geq 181.425 \tag{6}$$

where Z_S = IGLD'85 elevation in m and Q_S = 0 when elevation is below the "sill" elevation of 181.425 m; the sill is the lowest elevation for which flow from the lake is still possible.

Southam (1989) gave relations for the other lakes as:

$$Q'_T = 84.1168 \left(\frac{1}{2} Z'_T + \frac{1}{2} Z'_C - 545.74 \right)^2 \left(Z'_T - Z'_C \right)^{\frac{1}{2}} - H'_T \tag{7}$$

$$Q'_C = 128.0849 \left(Z'_C - 543.81 \right)^2 \left(Z'_C - Z'_E \right)^{\frac{1}{2}} - H'_C \tag{8}$$

$$Q'_E = 4058 \left(Z'_E - 556.95 \right)^{1.5} - H'_E + 5600 \tag{9}$$

$$Q'_O = 3430 \left(Z'_O - 0.0055 \left(Y - 1903 \right) - 227.45 \right)^{1.5} - H'_O \tag{10}$$

where Q'_T, Q'_C, Q'_E, and Q'_O = outflows from Lakes Michigan-Huron, St. Clair, Erie, and Ontario, respectively, in ft^{3}s^{-1}, Z'_T, Z'_C, Z'_E, and Z'_O = water elevations with respect to the IGLD'55 water level datum on Lakes Michigan-Huron (at Harbor Beach), St. Clair (at Grosse Pte.), Erie (at Cleveland or Buffalo, regarded here as the same), and Ontario (at Oswego), respectively, in ft, Y = year, and H'_T, H'_C, H'_E, H'_O, = ice retardations for Lakes Michigan-Huron, St. Clair, Erie, and Ontario, respectively, in ft^{3}s^{-1}; ice retardation values are given in Table 1. The 5,600 ft^{3}s^{-1} in (9) was added to adjust for channel project removals (Southam 1989). Here, it is presumed that the added 5,600 ft^{3}s^{-1} represents an average flow adjustment for average flow conditions and should be zero for zero flow. Taking the average flow as 208,000 ft^{3}s^{-1} [from the study outlined by

Southam (1989)], using an average Erie ice retardation from Table 1 (2,750 ft^{3}s^{-1}), and solving (9) gives a corresponding water level elevation of 570.62 ft. Solving for an alternate formula, like (9) but without the flow adjustment, that gives the same values,

$$Q'_E = 4168.77\left(Z'_E - 556.95\right)^{1.5} - H'_E \tag{11}$$

Converting (7), (8), (10), and (11) to metric units and to the current IGLD'85 datum (datum differences are given in Table 2) and using the 1985 version of (10),

$$\begin{aligned} Q_T &= 46.440\left(\frac{1}{2}Z_T + \frac{1}{2}Z_C - 166.549\right)^2 \left(Z_T - Z_C\right)^{\frac{1}{2}} - H_T, && Z_T \geq Z_C \geq 166.549 \\ &= 46.440\left(\frac{1}{2}Z_T - \frac{1}{2}166.549\right)^2 \left(Z_T - 166.549\right)^{\frac{1}{2}} - H_T, && Z_T \geq 166.549 > Z_C \end{aligned} \tag{12}$$

$$\begin{aligned} Q_C &= 70.714\left(Z_C - 165.953\right)^2 \left(Z_C - Z_E\right)^{\frac{1}{2}} - H_C, && Z_C \geq Z_E \geq 165.953 \\ &= 70.714\left(Z_C - 165.953\right)^2 \left(Z_C - 165.953\right)^{\frac{1}{2}} - H_C, && Z_C \geq 165.953 > Z_E \end{aligned} \tag{13}$$

$$Q_E = 701.504\left(Z_E - 169.938\right)^{1.5} - H_E, \qquad Z_E \geq 169.938 \tag{14}$$

$$Q_O = 577.187\left(Z_O - 69.622\right)^{1.5} - H_O, \qquad Z_O \geq 69.622 \tag{15}$$

where Q_T, Q_C, Q_E, and Q_O = outflows from Lakes Michigan-Huron, St. Clair, Erie, and Ontario, respectively, in m^{3}s^{-1}, Z_T, Z_C, Z_E, and Z_O = respective water elevations with respect to the IGLD'85 water level datum in m, and H_T, H_C, H_E, H_O, = respective ice retardations in m^{3}s^{-1}. We ignore the small elevation differences, introduced by the datum change, between Michigan-Huron and St. Clair levels and between St. Clair and Erie levels to keep the equations physically meaningful; i.e., when Lakes Michigan-Huron and St. Clair are at the same level ($Z_T = Z_C$) or Lakes St. Clair and Erie are at the same level ($Z_C = Z_E$), there should be no flow between the respective pair of lakes (Q_T = 0 or Q_C = 0). However, backflow is possible from Lake Erie to Lake St. Clair and from Lake St. Clair to Lake Michigan-Huron. This backflow is not described by these equations (but is addressed subsequently).

Note that when St. Clair water level is below the Michigan-Huron sill, the sill elevation is controlling in (12); likewise when Erie water level is below the St. Clair sill, the sill elevation is controlling in (13). These are reasonable extensions, made here to allow flow computations as lake levels drop below those historically experienced. Note that Q_T = 0 when the Michigan-Huron water level is below the sill of 166.549 m, Q_C = 0 when St.

Clair is below the sill of 165.953 m, Q_E = 0 when Erie is below the sill of 169.938 m, and Q_O = 0 when Ontario is below the sill of 69.622 m.

Since (6) and (12)—(15) were derived from semi-empirical stage-fall-discharge or rating curves that were fit to a range of flows and elevations not necessarily close to the sill, the sill elevations estimated here are in error. Sill heights on all lakes but St. Clair are well above the bottom of the lake. On Lake St. Clair, the bottom of the lake is 168.4 m (subtract maximum coordinated depth from chart datum in column 6 of Table 3); this is above the Michigan-Huron and St. Clair sills. This corresponds to a channel running along the bottom of Lake St. Clair; i. e., the lake bottom is at the top of this channel and we can have flow from the Lake St. Clair basin without lake storage. Since the lake bottom is below the Erie sill of 169.938 m, we see that St. Clair will never be empty as long as Lake Erie is not terminal (water line above its sill). Lake outflows in (6) and (12) —(15) are set to zero when negative values would be computed (ice retardation would drop to equal flow rate).

1.5 Hypsometric Relations

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD, 1977) provided graphical relations, for each lake, between depth and volume; inspection reveals that simple power relations are a very good fit,

$$\begin{aligned} V &= a\left(M-D\right)^{b} \\ A &= -\frac{d}{dD}V = ab\left(M-D\right)^{b-1} \end{aligned} \tag{16}$$

where A = area of horizontal surface at depth D below a reference elevation, M = maximum depth, V = lake volume beneath horizontal surface at depth D, and a and b are empirical parameters. By requiring that the coordinated values of area, C, and volume, S, (CCGLBHHD, 1977) exist at the reference elevation (chart datum), where D = 0, for each lake, as in Table 3, the parameters are

Table 3. Coordinated Values of Great Lake Parameters (CCGLBHHD 1977).

(1)	SUP (2)	MIC (3)	HUR (4)	GEO (5)	STC (6)	ERI (7)	ONT (8)
chart datum, m	183.2	176.0	176.0	176.0	174.4	173.5	74.2
maximum depth, m	405	281	229	164	6	64	244
coordinated area, km^2	82100	57800	40640	18960	1114	25700	18960
coordinated volume, km^3	12100	4920	2761	779	3.4	484	1640

$$
\begin{aligned}
a &= M\frac{C}{S} \\
b &= \frac{S}{M^a}
\end{aligned} \tag{17}
$$

Writing (16) in terms of elevation instead of depth,

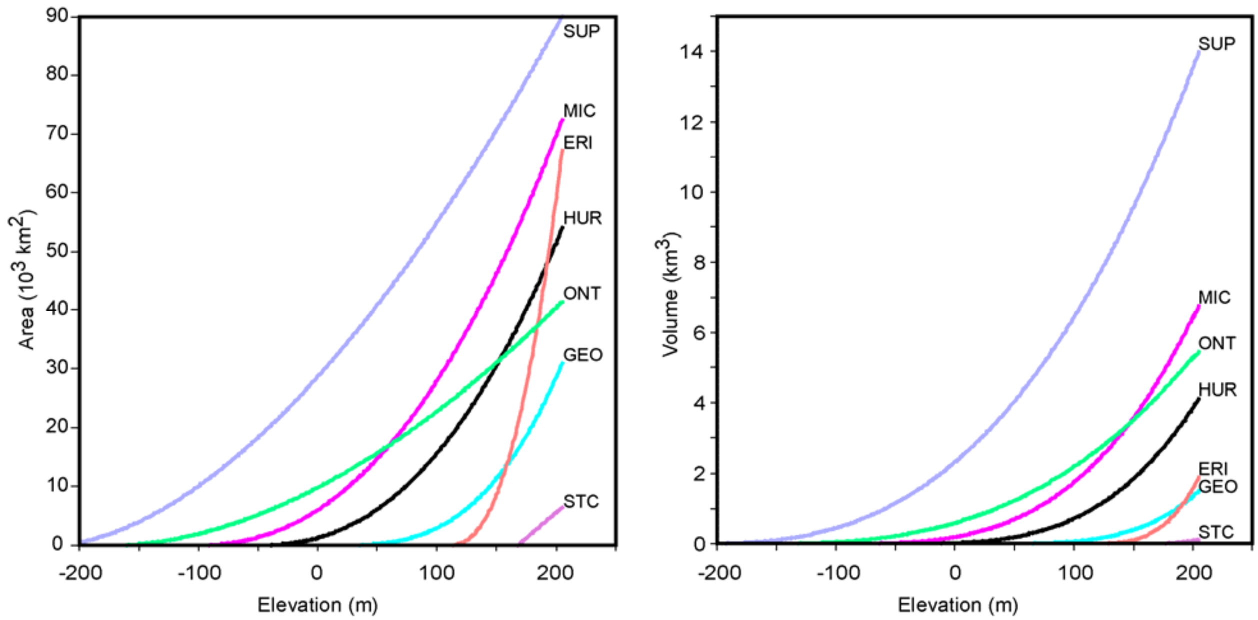

Figure 1. Great Lakes hypsometric relationships

$$
\begin{aligned}
V &= a\left(Z - Z_B\right)^b \\
A &= ab\left(Z - Z_B\right)^{b-1}
\end{aligned} \tag{18}
$$

where Z = elevation at depth D, in m, and Z_B = elevation of lake bottom, in m, given from Table 3 by subtracting maximum depth from chart datum. Figure 1 shows (18) for all lakes; note Michigan, Huron, and Georgian Bay are separate in (18).

3.6 Water Balance

The adjusted over-lake precipitation, runoff to the lake, and lake evaporation are used in a water balance, based on the arrangement of the Great Lakes and their connection channels, depicted in Figure 2.

$$\frac{dV}{dt} = I - Q + P + R - E \tag{19}$$

where t = time, I = volumetric water body inflow rate (outflow from the upstream lake) , and Q = volumetric water body outflow rate. Equations (1)—(3) and (19) are applied over time interval Δ to each water body based on the lakes and connecting channels arrangement,

$$\Delta V_S \cong \left(I_S - Q_S\right)\Delta + p_S A_S + R_S \frac{C_S}{B_S - C_S}\left(B_S - A_S\right) - e_S A_S \tag{20}$$

$$\begin{aligned}\Delta\left(V_M + V_H + V_G\right) \cong \left(I_T - Q_T\right)\Delta + p_M A_M + R_M \frac{C_M}{B_M - C_M}\left(B_M - A_M\right) - e_M A_M \\ + p_H A_H + R_H \frac{C_H}{B_H - C_H}\left(B_H - A_H\right) - e_H A_H \\ + p_G A_G + R_G \frac{C_G}{B_G - C_G}\left(B_G - A_G\right) - e_G A_G\end{aligned} \tag{21}$$

$$\Delta V_C \cong \left(I_C - Q_C\right)\Delta + p_C A_C + R_C \frac{C_C}{B_C - C_C}\left(B_C - A_C\right) - e_C A_C \tag{22}$$

$$\Delta V_E \cong \left(I_E - Q_E\right)\Delta + p_E A_E + R_E \frac{C_E}{B_E - C_E}\left(B_E - A_E\right) - e_E A_E \tag{23}$$

$$\Delta V_O \cong \left(I_O - Q_O\right)\Delta + p_O A_O + R_O \frac{C_O}{B_O - C_O}\left(B_O - A_O\right) - e_O A_O \tag{24}$$

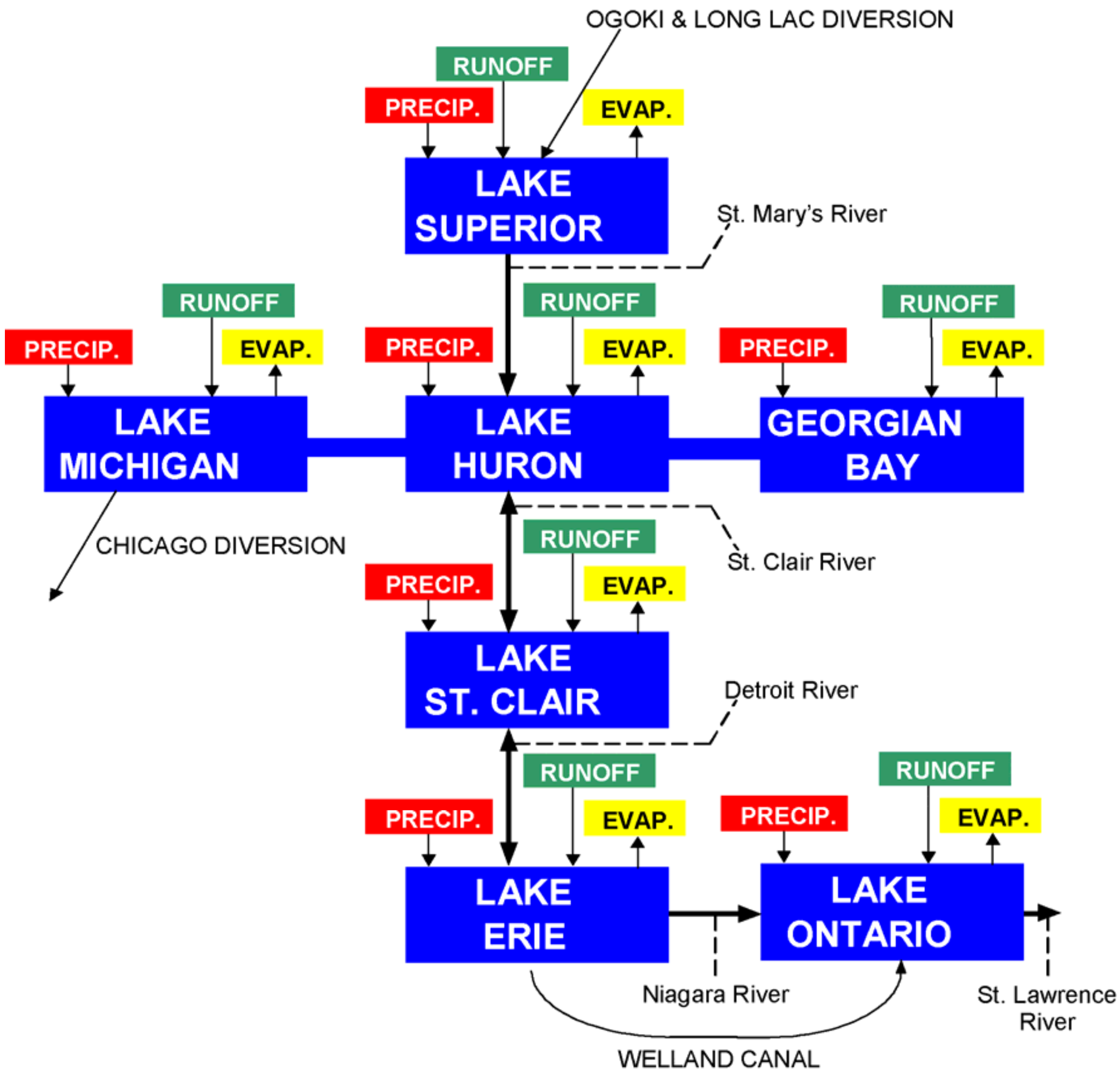

Figure 2. Arrangement schematic of Great Lakes, connecting channels, and all water flows.

where ΔV = change in volume and the subscripts refer to individual Great Lakes or extended water bodies: Superior (S), Michigan (M), Huron (H), Georgian Bay (G), Michigan-Huron (T), St. Clair (C), Erie (E), and Ontario (O). Equation (21) considers Lakes Michigan and Huron, including Georgian Bay, as one water body. Boundary conditions are

$$I_S = 0 \tag{25}$$

$$I_T = Q_S \tag{26}$$

$$I_C = Q_T, \quad \text{for upper Great Lakes flowing into lower}$$
$$\quad = 0, \quad \text{for upper Great Lakes flowing into the Mattawa and Ottawa basins} \tag{27}$$

$$I_E = Q_C \tag{28}$$

$$I_O = Q_E \tag{29}$$

For each water body, it is necessary to compute the inflow as outflow from the upstream lake, the lake(s) area, and the adjusted net basin supplies as part of the solution. This requires calculating lake levels as part of the water balance. We solve (6), (12)—(15), (18) for each lake, (20)—(24), and (25)—(29) simultaneously at each time step. Our numerical procedure at each time step is: ***i***) given p, r, e, and Z_0 (water elevation at beginning of time step) for all lakes, ***ii***) calculate A_0 (lake area at beginning of time step) and V_0 (lake volume at beginning of time step) for all lakes from (18) and Q_0 (outflow rate at beginning of time step) for all water bodies from (6) and (12)—(15), ***iii***) approximate Z_1 (end-of-time-step water elevation) as Z_0 for all lakes, ***iv***) calculate A_1 (end-of-time-step lake area) for all lakes from (18) and Q_1 (end-of-time-step water body outflow rate) for all water bodies from (6) and (12)—(15), ***v***) approximate outflow rates and lake areas over the time increment as linear, $Q = (Q_0 + Q_1)/2$ and $A = (A_0 + A_1)/2$, ***vi***) calculate the changes in storage for all water bodies over the time interval by using these approximate outflow rates and lake areas in (20)—(24) and (25)—(29), and ***vii***) calculate $V_1 = V_0 + \Delta V$ for each lake and then find Z_1 by using V_1 with (18) for each water body (for Lake Michigan-Huron, interpolate for Z_1 by using V_1 with (18) applied to Lakes Michigan, Huron, and Georgian Bay and summed). Repeat steps ***iv—vii*** until successive values of Z_1 for all lakes change negligibly. Repeat steps ***i—vii*** for the next time step, and so forth.

When solving (6), (12)—(15), (18), (20)—(24), and (25)—(29), we check and correct for backflow between lakes. This could occur if water levels on Lake Erie are above those on St. Clair (and above the St. Clair sill) or those on St. Clair are above those on Lake Michigan-Huron (and above the Michigan-Huron sill). For those times when backflow would occur between two lakes, we simply balance the lakes involved so that water levels on both are equal and the flow between them is zero. Furthermore, we consider sill heights in this adjustment and do not let backflow reduce a lake's level below the upstream sill. Note that backflow does not occur when simulating the existing system with the existing climate. It also does not occur when simulating the upper lake system (Superior, Michigan, and Huron) with any climate since (12) is replaced with a relation that is a function of Michigan-Huron levels only (discussed subsequently). Backflow corrections are only required when simulating the existing system or the lower lake system (St. Clair, Erie, and Ontario) with warmer or dryer climates. The equations solution converges to an insignificant difference within 2-15 iterations (the difference between water elevations in successive iterations, summed over all lakes, is less than one thousandth of a millimeter).

2. VALIDATION

To check the models and water balance approximations, we simulated the entire interconnected Great Lakes for the historical meteorological record. First, we compared simulated net basin supplies (precipitation + runoff – lake evaporation) resulting from the model, applied to the historical meteorological record with actual initial conditions, directly to historical net basin supplies (computed as a water balance residual from historical lake levels and flows). Figure 3 compares our estimates with historical NBS and shows good agreement, as expected since historical meteorology data are used in the simulation. Differences can be ascribed to water balance errors in the computation of residual NBS and to modeling errors in the computation of the NBS components. The biggest differences occur on Lake Ontario, suggesting they arise from water balance errors in computing the historical residual NBS.

Next, we compared simulated lake levels resulting from the model, applied to the historical meteorological record with actual initial conditions, directly to historical levels. For this comparison, we included all diversions but used the natural outflow and channel relationships. Figure 4 is a plot of daily simulated levels and monthly historical levels; it shows fair agreement, but has expected deviations. On Superior, levels match well with historical data after about 1965 but differ before; this could be due to sparse water level station networks prior to 1965 (hard to evaluate), poorer meteorological estimates prior to 1965 (when station densities are lowest on Superior and areal estimates are often underestimated), and differences in the outflow and channel relationships (water was released on Superior in 1965 to alleviate low water levels downstream; there were also changes in the Superior regulation plan between 1970-77; the model simulation uses an unchanging outflow and channel relationship). On Michigan-Huron, it appears that the historical water levels are lower than the simulated; this lowering probably results from the historical changes in Lake Superior operations and in the St. Clair River channel which has been dredged over time. It also may be related to variation in crustal rebound occurring after retreat of the last ice sheet; crustal rebound results in relative tilting of Lake Michigan-Huron towards its outlet suggesting higher outflows and lower levels in the historical record than simulated (Quinn and Sellinger 1990). Lakes St. Clair and Erie are very similar to the simulation but Ontario shows lower water levels historically, probably as a result of the difference between regulated Niagara flows and the natural outflow and channel conditions. The model appears to simulate the system reasonably well when all sources of differences between the simulations and historical flows are considered. Connecting channel flow differences (not shown here) also match well.

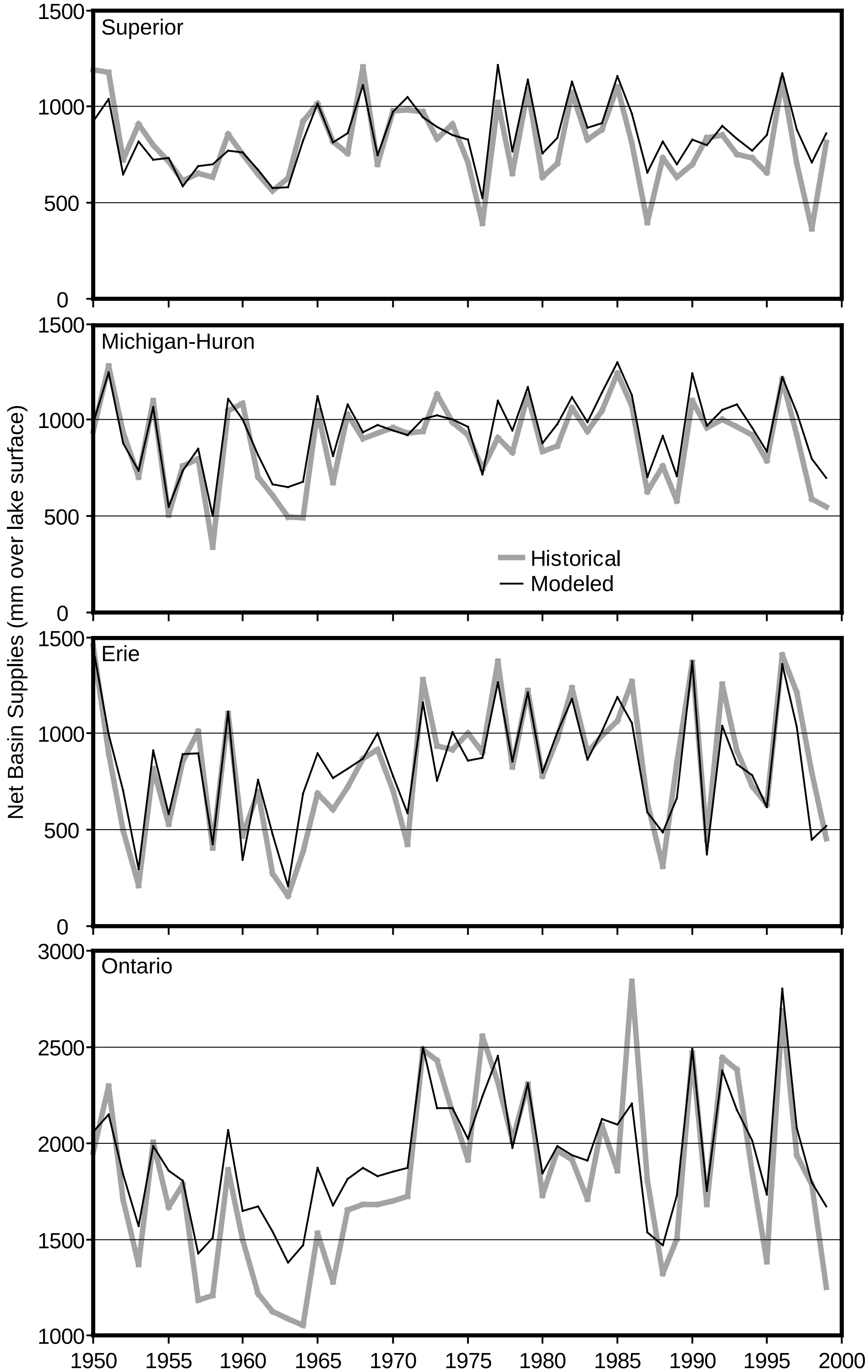

Figure 3. Net basin supply comparison for 1950-1999 of observed (historical) and simulated (modeled) supplies.

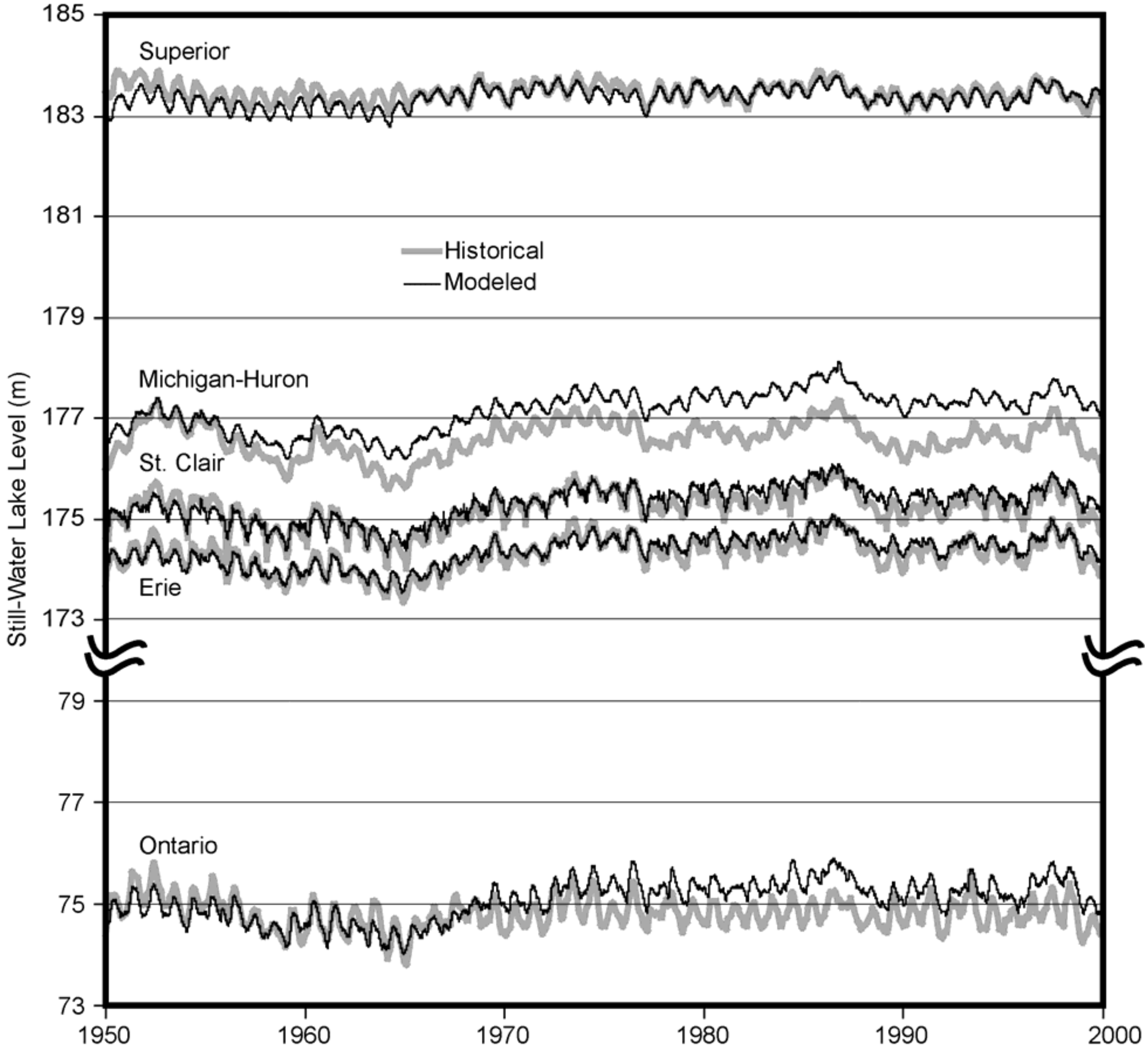

Figure 4. Great Lake levels comparison for 1950-1999 of observed (historical) and simulated (modeled) levels.

References

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD) 1977. *Coordinated Great Lakes physical data*. Physical Data Subcommittee, Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, US Army Corps of Engineers, Detroit District, Detroit, Michigan.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD) 1979. *Establishment of international Great Lakes datum (1955), 2nd Edition*. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, US Army Corps of Engineers, Detroit District, Detroit, Michigan.

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD) 1995. *Establishment of international Great Lakes datum (1985). Appendix A - Tabulation of primary bench mark elevations at gauge sites*. Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, US Army Corps of Engineers, Detroit District, Detroit, Michigan.

Croley, T.E., II 1989. Verifiable evaporation modeling on the Laurentian Great Lakes. *Water Resources Research* 25(5):781-792.

Croley, T.E., II 1990. Laurentian Great Lakes double-CO_2 climate change hydrological impacts. *Climatic Change* 17:27-47.

Croley, T.E., II 1992a. Long-term heat storage in the Great Lakes. *Water Resources Research* 28(1):69-81.

Croley, T.E., II 2002. Large basin runoff model. In *Mathematical Models in Watershed Hydrology* eds. V. Singh, D. Frevert, and S. Meyer, pp. 717-770. Littleton, Colorado: Water Resources Publications.

Croley, T.E., II 2003. *Great Lakes Climate Change Hydrological Impact Assessment, IJC Lake Ontario—St. Lawrence River Regulation Study*. Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, NOAA Tech. Memo. GLERL-126.

Croley, T.E., II 2005. Using Climate Predictions in Great Lakes Hydrologic Forecasts. In *Climatic Variability, Climate Change, and Water Resources Management*, eds. J. Garbrecht and T. Piechota, pp. 166-187. Arlington, Virginia: American Society of Civil Engineers.

Croley, T.E., II, and Assel, R.A. 1994. One-dimensional ice model for the Laurentian Great Lakes, *Water Resources Research* 30(3):625-639.

Quinn, F.H., and Sellinger, C.E. 1990. Lake Michigan record levels of 1838, a present perspective. Journal of Great Lakes Research 16(1):133-138.

Southam, C. 1989. *Procedure for developing the Great Lakes level and flow regime for pre-project conditions*. Functional Group 1, Hydrology, Hydraulics, and Climate, IJC Great Lakes Water Levels Reference Study, Environment Canada, Burlington, Ontario.