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AN EVALUATION OF GREAT LAKES HYDRAULIC ROUTING MODELS

Holly C. Hartmann

Great Lakes Environmental Research Laboratory
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Anthony J. Calio,
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AN EVALUATION OF GREAT LAKES HYDRAULIC ROUTING MODELS[1]

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ABSTRACT. Water resource studies require hydraulic routing models for simulating water levels of the non-regulated Great Lakes. This report compares the U.S. Army Corps of Engineer's hydraulic routing model and the Great Lakes Environmental Research Laboratory's Hydrologic Response Model (HRM). Although the model solution techniques produce equivalent results, the HRM reduces cpu requirements by 94%. The HRM also uses discharge equations that better reflect present channel conditions and a more appropriate conversion of lake storage changes to lake level fluctuations.

1. INTRODUCTION

A continued high rate of precipitation throughout the Great Lakes region since 1970 has created important water management problems associated with high lake levels (Croley, 1986; Quinn, 1986). Lakes Michigan, Huron, and St. Clair experienced record monthly levels from October 1985 through January 1987; during that period, Lake Erie levels set records every month except April 1986 (U.S. Army Corps of Engineers, 1986d, 1987). In 1986, each of those lakes reached their highest recorded levels of this century (U.S. Army Corps of Engineers, 1986a,b,c). In response to widespread public concern, on 1 August 1986 the U.S. and Canadian governments requested that the International Joint Commission (IJC) conduct a 3-year study on ways to reduce the negative effects of fluctuating Great Lakes water levels (Medas, 1986). As part of this IJC reference, studies are being conducted that require hydraulic routing models for simulating water levels of the nonregulated Great Lakes.

The hydraulic routing model of the U.S. Army Corps of Engineers (USACE) has been used in several previous IJC studies, including the development of Lake Superior's regulation plan (International Great Lakes Levels Board, 1973), an assessment of Lake Erie regulation alternatives (International Lake Erie Regulation Study Board, 1981), and evaluation of the effects of Great Lakes diversions and consumptive uses (International Great Lakes Diversions and Consumptive Uses Study Board, 1981a). The Great Lakes Environmental Research Laboratory (GLERL) developed the Hydrologic Response Model (HRM) as an efficient implementation of the basic reservoir routing procedure (Quinn, 1978a); the HRM also has been used in studies concerned with Great Lakes levels (Hartmann, 1987; Quinn, 1978b, 1985).

This report compares the USACE hydraulic routing model with the GLERL HRM. Model simulations over 1962-1980 are used to determine to what extent the model solution techniques and discharge equations affect estimation of water levels and connecting channel flows. Differences in hydrometeorologic data

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maintained by the USACE and GLERL preclude simply comparing the two models as they are used by the two agencies. All comparisons here are based on use of GLERL's hydrometeorologic data (Quinn and Kelley, 1983).

2. THE USACE HYDRAULIC ROUTING MODEL

The USACE hydraulic routing model considers net basin supplies, diversions, St. Marys River flows, and ice retardation of flows in the determination of water levels on Lakes Michigan-Huron, St. Clair, and Erie (Lakes Michigan and Huron are considered one lake hydraulically). It also determines flows through the St. Clair, Detroit, and Niagara Rivers. The International Great Lakes Diversions and Consumptive Uses Study Board (1981b) documented the FORTRAN implementation of the model. Briefly, the USACE model uses an iterative approach to solve a series of stage-fall-discharge equations for each of the connecting channels and, for each lake, an expression of the standard reservoir routing equation:

$$0.5(I_1 + I_2)\Delta t - 0.5(O_1 + O_2)\Delta t = S_2 - S_1 \qquad (1)$$

where I = the rate of all inflows to a lake, O = the rate of all outflows from a lake, S = the storage volume of a lake, Δt = a specified time interval, and subscripts 1 and 2 = the beginning and end of the time interval, respectively. Each month is divided into 40 equal time intervals, with 5 iterations of end-of-period lake levels. Thus, for each month, there are 200 iterations to determine monthly flows, mean monthly levels, and end-of-month levels.

Discharge equations for the St. Clair and Detroit Rivers reflect channel conditions over 1962-1968; dredging of the St. Clair River for an 8.2-m (27-ft) navigation channel was completed in 1962. The St. Clair River discharge equation is

$$Q_{SCR} = C_{SCR}[(Z_{MH} + Z_{SC})/2 - ym_{SCR}]^2 (Z_{MH} - Z_{SC})^{0.5} \qquad (2)$$

where Q = the connecting channel discharge, C = a constant based on the application of Manning's equation to the connecting channel (Quinn, 1979), Z = a lake's water level, ym = the mean bottom elevation of the connecting channel, SCR = the St. Clair River, MH = Lake Michigan-Huron, and SC = Lake St. Clair. The Detroit River discharge equation is

$$Q_{DR} = C_{DR} (Z_{SC} - ym_{DR})^2 (Z_{SC} - Z_{ER})^{0.5} \qquad (3)$$

where DR = the Detroit River and ER = Lake Erie. No modifications in equation constants or form are incorporated to reflect changes in channel conditions during different seasons of the year.

The Niagara discharge equation reflects channel conditions over 1948-1952; it was derived by matching flows computed by a discharge equation that considered water levels at both Buffalo and Black Rock (Schutze, 1953). The Niagara River discharge equation is

$$Q_{NR} = C_{NR} (Z_{ER} - ym_{NR})^{1.5} \qquad (4)$$

where NR = the Niagara River. However, since 1961, power diversion operations and methods for estimating actual Niagara River outflows have changed considerably, and are not reflected in the USACE model. As for the St. Clair and Detroit Rivers, seasonal changes in channel conditions are not considered in the USACE Niagara River discharge equations.

Several other assumptions and conditions are used in the USACE hydraulic routing model :

(1) The model is implemented in English units. During each of the 200 iterations to determine monthly levels and flows, levels are rounded to the nearest 0.01 ft (3 mm) and flows are rounded to the nearest thousand cubic feet per second (28.3 m^3/s). This rounding at each iteration introduces numeric error that is negligible for 200 iterations/month (3-6 mm/month [0.01- 0.02 ft/month] for levels and 2.8 cms [100 ft^3/s] for flows), but as the number of iterations is increased the numeric rounding error grows rapidly.

(2) Conversion of a change in storage volume to a change in lake levels requires lake areas. The USACE model uses coordinated lake areas (Coordinating Committee on Great Lake Basic Hydraulic and Hydrologic Data, 1977) for Lakes Michigan-Huron and Erie, but not for Lake St. Clair; the USACE model's Lake St. Clair area is equivalent to 1123 million square meters (433 square miles); the coordinated area is 1114 million square meters (430 square miles).

(3) Conversion of a rate of change in storage volume to a change in lake levels requires a time factor, reflecting the number of seconds per month. The USACE routing model uses a constant 30.4 days/month in this conversion (equivalent to 364.8 days/year).

(4) The USACE routing model considers actual diversions from Lake Michigan-Huron at Chicago, but uses a constant Welland Canal diversion from Lake Erie equivalent to 198.2 m^3/s (7000 ft^3/s).

3. THE GLERL HYDROLOGIC RESPONSE MODEL

The GLERL Hydrologic Response Model (HRM) considers overlake precipitation, basin runoff, lake evaporation, diversions, St. Marys River flows, and ice retardation of flows in the determination of water levels and connecting channel flows for the unregulated portion of the Great Lakes system. Quinn (1978a) described the model and its calibration in detail. Like the USACE routing model, the HRM uses the standard reservoir routing equation for each lake, and stage-fall-discharge equations for each connecting channel. However, the HRM solves the equations using a second-order finite-difference technique that requires only four intervals/month, with no iterations. The HRM is implemented in metric units. It uses the actual number of days/month and coordinated surface areas for each lake in determining changes in lake levels. Actual diversions at Chicago and through the Welland Canal are considered as well. Additionally, the HRM includes a constant 57 m^3/s (2013 ft^3/s) loss of water from Lake Erie due to consumptive use, based on estimates by the International Great Lakes Diversions and Consumptive Uses Study Board (1981a). Consumptive use estimates for Lake St. Clair are not available, and because lake evaporation for Lake Michigan-Huron is determined as a water balance residual, consumptive uses for that lake are considered implicitly.

Discharge equations used in the HRM differ from those used in the USACE routing model. All HRM discharge equations reflect connecting channel conditions over 1962-1980. Two discharge equations are used for the St. Clair River. The standard equation is

$$Q_{SCR} = C_{SCR} (Z_{MH} - ym_{SCR})^2 (Z_{MH} - Z_{SC})^{0.5} \tag{5}$$

However, during the winter months ice jams often occur. For the months of December through February, a single gage equation better matches actual channel flows:

$$Q_{SCR} = C_{SCR} (Z_{MH} - ym_{SCR})^2 \tag{6}$$

The values of CSCR and ym_{SCR} differ between Eqs. 5 and 6, reflecting channel conditions during March-November and December-February, respectively. A single discharge equation is used throughout the year for the Detroit River. It is like that used in the USACE routing model (Eq. 3), but the equation constants are different, reflecting calibration over a longer period (1962-1980 vs. 1962-1968).

Finally, the Niagara River discharge equation is

$$Q_{NR} = C_{NR} (Z_{ER} - ym_{NR})^2 \tag{7}$$

During much of the year, weeds significantly affect channel conditions. Thus, two values of CNR are used, one based on channel conditions during June-October (weed period) and the other based on conditions during November-May (weed-free period).

4. MODEL COMPARISON

Although based on the same general reservoir routing concepts, the USACE hydraulic routing model and the GLERL HRM differ in many respects. The USACE's use of its model cannot simply be contrasted with GLERL's use of the HRM; too many differences exist in the model implementations and the agencies' data for the comparison to be meaningful. Data provided by the USACE for 1964, 1973, and 1977 (C. Thieme-Janish, USACE, personal communication, 1986) are compared with GLERL's hydrometeorologic data (Quinn and Kelley, 1983) in Table 1. There are notable differences between the agencies' data for the net basin supplies to each of the lakes and for flow retardations in the connecting channels. The large difference in flow retardations for the Niagara River results because the USACE values reflect consideration of ice in the winter and weeds in the summer, while the HRM uses a retardation factor for ice but not for weeds. The HRM accounts for weed effects by using modified discharge equation parameters. Net basin supply differences result from different methods of derivation. The USACE net basin supplies are based on a water balance; beginning-of-month levels are derived using an arithmetic average of station observations. In contrast, GLERL net basin supplies are based on estimates of overlake precipitation, basin runoff, and lake evaporation. Lake evaporation for Lakes St. Clair and Erie are derived using a mass transfer approach. Evaporation for Lake Michigan-Huron is derived as a residual from a water balance; beginning-of-month levels are based on a Thiessen-weighting of station observations. Because the lake is so huge, even small differences in beginning-of-month levels result in large differences in the water balance residuals. To eliminate differences in model results due to data, our simulations use GLERL's hydrometeorologic data in both models.

Table 1. --Comparison of selected USACE and GLERL hydrometeorologic data over 1964, 1973, 1977[1]

Data type	GLERL Mean	GLERL Std. dev.	USACE Mean	USACE Std. dev.	Root-mean square error	Corr.
Michigan-Huron net basin supply	3314	3162	3082	3213	486	0.99
St. Clair net basin supply	143	168	178	205	131	0.79
Erie net basin supply	853	1103	730	1165	261	0.98
St. Marys River flow	2174	560	2178	559	8	1.00
St. Clair River flow	5210	830	5209	830	2	1.00
Detroit River flow	5351	852	5386	831	128	0.99
Niagara River flow	5871	1065	5871	1065	2	1.00
St. Clair River flow retardation	115	268	119	272	92	0.94
Detroit River flow retardation	124	422	107	306	136	0.98
Niagara River flow retardation	28	117	77	52	127	0.22
Chicago diversion	89	22	88	22	5	0.97
Welland diversion	203	61	214	67	15	0.99
Michigan-Huron BOM level[2]	176.23	0.60	176.23	0.60	0.01	1.00
St. Clair BOM level[2]	174.88	0.56	174.88	0.56	0.01	1.00
Erie BOM level[2]	174.03	0.50	174.03	0.49	0.01	1.00
Michigan-Huron mean monthly level	176.22	0.60	176.22	0.60	0.00	1.00
St. Clair mean monthly level	174.88	0.54	174.88	0.54	0.00	1.00
Erie mean monthly level	174.03	0.50	174.03	0.50	0.00	1.00

1 Units are m^3/s for flow rates and meters for levels (m^3/s = 35.31 ft^3/s; m = 3.28 ft).
2 BOM = Beginning-of-Month

4.1 Comparison of Solution Techniques

The USACE model was implemented on GLERL's VAX 11/780 and tested by using USACE input data for 1964, 1973, 1977, 1981, and 1985; model results matched output provided by the USACE. To assess the effects of the solution technique on model results, the USACE model was modified to use

GLERL discharge equations, lake surface areas, time factors, consumptive use rates, and Welland Canal diversion rates. Thus, the modified USACE model and the HRM were logically equivalent except for the solution technique. Each model was used with GLERL data in a continuous simulation over 1962-1980. Equivalent simulation results indicate that, although the HRM solution technique uses 50 times fewer computations, it produces the same lake levels and connecting channel flows as the USACE solution technique. Although the effect of the solution technique on execution speed is moderated by other considerations (e.g., testing for the use of winter or weed-free connecting-channel equations), the HRM produces a cpu time savings of 94% in the solution of the stage-fall-discharge and reservoir routing equations. The HRM requires less than 3 cpu seconds (on a VAX 11/780) to determine end-of-month and mean monthly lake levels and mean monthly connecting-channel flows over a 19-year period (exclusive of data input and output); only about 12K storage is needed for the 19-year simulation.

4.2 Comparison of Discharge Equations

Table 2 presents a comparison between the USACE and GLERL discharge equations for the St. Clair and Detroit Rivers. The Niagara River equations were not compared, since the USACE version is invalid for channel conditions after 1961. The USACE and GLERL discharge equations were applied for each month over 1962-1980, independent of the routing models and using actual monthly mean levels for Lakes Michigan-Huron, St. Clair, and Erie. Modeled flows were adjusted for ice effects as well. The root-mean-square error between actual and modeled St. Clair River flows is 22% lower when the GLERL discharge equations are used. The USACE and GLERL Detroit River discharge equations are essentially equivalent.

Table 2. --Comparison of USACE and GLERL discharge equations[1]

	Actual		Model		Root mean	
	Mean	Std. dev.	Mean	Std. dev.	square error	Correlation
St. Clair River						
USACE	5392	642	5403	626	103	0.99
GLERL	5392	642	5369	645	80	0.99
Detroit River						
USACE	5527	634	5515	635	77	0.99
GLERL	5527	634	5513	638	77	0.99

[1] Units are m^3/s (m^3/s = 35.31 ft^3/s).

5. SUMMARY AND RECOMMENDATIONS

Hydraulic routing models of the USACE and GLERL can simulate levels and flows in the unregulated section of the Great Lakes system. Although the USACE hydraulic routing model and the GLERL Hydrologic Response Model employ the same reservoir routing concepts, they use different data, model solution techniques, discharge equations, and ancillary assumptions. Simple comparisons of simulation results from each agency's implementation are not sufficient; each disparate element of the model applications should be evaluated independently. The data differences and the appropriateness of a Lake Erie consumptive use rate of 57 m^3/s (2013 ft^3/s) are not eva I uated here i n; however, the following recommendations are made:

(1) The HRM solution algorithm should be used. It requires 50 times fewer computations, thus offering significant advantages for studies requiring many simulations or for implementation on small computers.

(2) GLERL discharge equations should be used for the St. Clair and Detroit Rivers. Although the USACE and GLERL Detroit River equations produce almost identical results, the GLERL version is based on a longer calibration period. Use of GLERL's St. Clair River discharge equation reduces the root mean square error between actual and model flows by more than 20%.

(3) Further evaluation is required to determine the appropriate outflow relationship for the Niagara River. The USACE discharge equation, derived in 1953, does not reflect present channel conditions, power diversion operations, or methods of estimating actual flows. Although the derivation of the GLERL equation was based on 1962-1980 flow conditions, concerns that using the actual Niagara River flows over that period does not provide a water balance that satisfies continuity must be addressed (F. Quinn, GLERL, personal communication, 1987).

(4) Actual Wel land Canal diversion rates should be used, where appropriate. Where simulations warrant use of an average Wel land Canal diversion (e. ., outlooks), the diversion rate should not be 198.2 m^3/s (7000 ft^3/s); present Wel land Canal diversions average 260.5 m^3/s (9200 ft^3/s).

(5) For the conversion of rates of change in lake storage to monthly changes in lake levels, the coordinated area of Lake St. Clair and the actual number of days/month should be used.

6. REFERENCES

Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data, 1977. Coordinated Great Lakes physical data. U.S. Army Corps of Engineers, Detroit, Michigan, 12 pp.

Croley, T.E., II, 1986. Understanding recent high Great Lakes water levels. Proceedings of the Great Lakes Symposium, pp. 60-70. Columbus, OH: Ohio State University.

Hartmann, H.C., 1987. Potential variation of Great Lakes levels: a hydrologic response analysis. NOAA Technical Memorandum ERL GLERL-XXX, NOAA Environmental Research Laboratories, Boulder, Colorado (in prep.).

International Great Lakes Diversions and Consumptive Uses Study Board, 1981a. Great Lakes Diversions and Consumptive Uses. International Joint Commission, Washington, D.C.

International Great Lakes Diversions and Consumptive Uses Study Board, 1981b. Great Lakes Diversions and Consumptive Uses, Appendix B: Computer Models-Great Lakes. International Joint Commission, Washington, D.C., 203 pp.

International Great Lakes Levels Board, 1973. Regulation of Great Lakes water levels. International Joint Commission, Washington, D.C., 294 pp.

International Lake Erie Regulation Study Board, 1981. Lake Erie water level study: main report. International Joint Commission, Washington, D.C., 231 pp.

Medas, J.M., 1986. Letter from the Deputy Assistant Secretary for Canada to the International Joint Commission, August 1, 1986, 3 pp.

Quinn, F.H., 1978a. Hydrologic response model of the North American Great Lakes. J. Hydrol. 37:295-307.

Quinn, F.H., 1978b. Lake Superior regulation effects. Water Resour. Bull. 14(5):1129-1142.

Quinn, F.H., 1979. Derivation and calibration of stage-fall-discharge equations for the Great Lakes connecting channels. GLERL Open File Report, Contribution No. 134, Great Lakes Environmental Research Laboratory, Ann Arbor, Michigan, 4 pp.

Quinn, F.H., 1985. Temporal effects of St. Clair River dredging on Lakes St. Clair and Erie water levels and connecting channel flow. J. Great Lakes Res. 11(3):400-403.

Quinn, F.H., 1986. Causes and consequences of the record high 1985 Great Lakes water levels. Preprint Volume of the Conference on the Human Consequences of 1985's Climate, pp. 281-284. Boston, MA: American Meteorological Society.

Quinn, F.H. and Kelley, R.N., 1983. Great Lakes monthly hydrologic data. NOAA Data Report ERL GLERL-26, NOAA Environmental Research Laboratories, Boulder, Colorado, 79 pp.

Schutze, L.T., 1953. Buffalo equation for Niagara River flow under present conditions. U.S. Army Corps of Engineers, Detroit, Michigan, 2 pp.

U.S. Army Corps of Engineers, 1986a. Monthly bulletin of lake levels for the Great Lakes, January 1986. U.S. Army Corps of Engineers, Detroit, Michigan, 5 pp.

U.S. Army Corps of Engineers, 1986b. Monthly bulletin of lake levels for the Great Lakes, July 1986. U.S. Army Corps of Engineers, Detroit, Michigan, 5 pp.

U.S. Army Corps of Engineers, 1986c. Monthly bulletin of lake levels for the Great Lakes, November 1986. U.S. Army Corps of Engineers, Detroit, Michigan, 5 pp.

U.S. Army Corps of Engineers, 1986d. Monthly bulletin of lake levels for the Great Lakes, December 1986. U.S. Army Corps of Engineers, Detroit, Michigan, 5 pp.

U.S. Army Corps of Engineers, 1987. Monthly bulletin of lake levels for the Great Lakes, February 1987. U.S. Army Corps of Engineers, Detroit, Michigan, 5 pp.