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DESCRIPTION OF THE METHOD USED BY THE GREAT LAKES ENVIRONMENTAL RESEARCH LABORATORY TO DETERMINE FLOWS IN THE ST. CLAIR AND DETROIT RIVERS FOR THE RIVER FLOW SUBCOMMITTEE

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1. INTRODUCTION

Prior to international coordination, the U.S. monthly flows of the St. Clair and Detroit Rivers for the 1959-76 period were coordinated by the U.S. Army Corps of Engineers, Detroit District, (COE) and the Great Lakes Environmental Research Laboratory (GLERL). The methods used by the two agencies to determine the Great Lakes connecting channel flows are basically different. The method used by the COE consisted of the traditional stage-fall-discharge equations. GLERL employed hydraulic transient models developed to simulate unsteady flow rates in the rivers. These models can be operated at hourly, daily, or monthly time intervals. Calibration of both methods is based on recorded water levels and periodic river flow measurements.

2. THE MODELS

The hydraulic transient models for the St. Clair and Detroit Rivers are based on complete partial differential equations of continuity and motion, expressed in terms of flow Q and stage Z above a fixed datum as follows:

$$\frac{\partial Z}{\partial t} + \frac{1}{T}\frac{\partial Q}{\partial X} = 0 \tag{1}$$

$$\frac{1}{A}\frac{\partial Q}{\partial t} - \frac{2QT}{A^2}\frac{\partial Z}{\partial t} + \left(g - \frac{Q^2T}{A^3}\right)\frac{\partial Z}{\partial X} + \frac{gn^2Q|Q|}{2.208\ A^2R^{4/3}} = 0, \tag{2}$$

where

X = distance in the positive flow direction,

t = time,

A = channel cross-sectional area,

T = water surface top width of the channel,

g = acceleration due to gravity,

R = hydraulic radius,

n = Manning's roughness coefficient.

Equations (1) and (2) were placed in finite difference form at point M in the X-t grid (Figure 1) to yield respectively

$$\frac{Zu' + Zd' - Zu - Zd}{2\Delta t} - \frac{\theta(Qd' - Qu') + (1-\theta)(Qd - Qu)}{T\Delta X} = 0 \qquad (3)$$

$$\frac{Qu' + Qd' - Qu - Qd}{2\bar{A}\,\Delta t} - \frac{\bar{Q}T}{\bar{A}^2\,\Delta t}\cdot(Zu' + Zd' - Zu - Zd)$$

$$+ \left(g - \frac{\bar{Q}^2 T}{\bar{A}^3}\right)\cdot\left[\frac{\theta(Zd' - Zu') + (1-\theta)(Zd - Zu)}{\Delta X}\right]$$

$$+ \frac{gn^2\bar{Q}|\bar{Q}|}{2.08\,\bar{A}^2\bar{R}^{4/3}} = 0, \qquad (4)$$

where prime indicates location and overbars indicate mean, such that

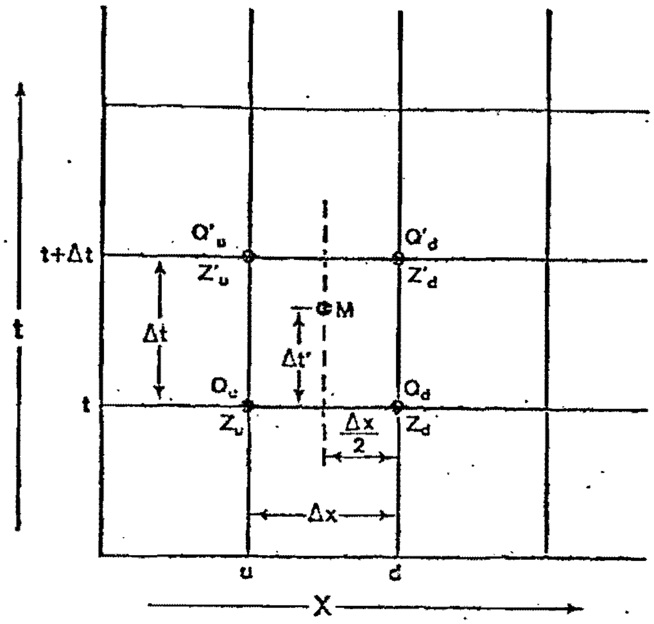

Figure 1. X-t grid for the implicit method.

$$\Theta = \frac{\Delta t'}{\Delta t} ,$$

$$\bar{Q} = 0.5\ [\Theta(Qu' + Qd') + (1 - \Theta)\ (Qu + Qd)],$$

$$\bar{A} = 0.5\ [\Theta(Au' + Ad') + (1 - \Theta)\ (Au + Ad)].$$

Solution of equations (3) and (4) by the implicit method forms the basis of the transient models. A stable solution for equations (3) and (4) is provided by the weighting coefficient Θ, which was determined empirically to be 0.75. Application of these equations at sections of predetermined reaches produces a set of nonlinear equations solved simultaneously with linear approximations by the Newton-Raphson numerical iteration procedure. Descriptions of the St. Clair and Detroit River transient models, along with their calibration, sensitivity analysis, program listings, and output samples are beyond the scope of this report, but are given by Quinn and Hagman (1977).

2.1 Calibration

Calibration of the models consisted of adjusting the Manning's roughness coefficient, n, the unknown in the flow equations, for each selected reach. Determination of the roughness coefficients is based on recorded water levels and river flow measurements conducted by the COE during 1959-73 and 1962-73 on the St. Clair and Detroit Rivers, respectively. The downstream reaches of the St. Clair River were affected by the regimen changes caused by shipping lane dredging between 1959 and 1963. For these reaches a separate roughness coefficient was computed for each regimen, representing 1959-63 and 1964-76 (present) periods, respectively. The roughness coefficients were computed by the following equation:

$$n + \frac{1.486\ AR^{2/3}}{Q} \cdot \left(\frac{(Zu - Zd)}{L} + \frac{Q^2 \Delta A}{32.2\ LA^3} \right)^{1/2}, \tag{5}$$

where

n = Manning roughness coefficient,

A = mean channel area,

R = hydraulic radius,

Q = flow through the channel,

Zu = water surface at upstream gage,

Zd = water surface at downstream gage,

L = length of reach from upstream to downstream gage,

ΔA = change in area of river from upstream to downstream gage.

The unsteady flow of the rivers between selected water level gages can be computed after calibration with the input of known hydraulic parameters for the mean base area, reference area elevation, length of reach between gages, and average channel width. The accuracy of developed models for both rivers was determined to be 2% of total flow or 4,000 cubic feet per second (4 TCFS). This accuracy represents the sensitivity of computed flows to changes in water levels or roughness coefficients during open-water conditions. Computed flow changes by 1% for a corresponding 2% change in water level data, which are generally accepted to be $\pm$ 2%. Computed flow also changes by 1-1.5% for a corresponding change of 2% in the channel roughness coefficient.

2.2 Transfer Factors

Monthly hydrologic transfer factors were developed for Lake St. Clair for the period 1950–76 to aid in the comparison and coordination of St. Clair and Detroit River monthly flows. The transfer factor represents the hydrologic water balance between the St. Clair and Detroit Rivers. Ignoring the groundwater flux into the lake, which is assumed to be negligible, the transfer factor, T, is defined by the equation

$$T = P + R - E - \Delta S, \tag{6}$$

where

P = over-lake precipitation,

R = drainage basin runoff,

E = lake evaporation,

ΔS = change in lake storage.

The above input parameters were determined independently from available data, as described by Quinn (1976a). Resulting GLERL transfer factors are listed in Table 1. Applying the transfer factor to Lake St. Clair hydrologic balance gives the flow comparison equation

$$Q_{sc} + T = Q_D, \tag{7}$$

where

Q_{sc} = inflow into the lake from the St. Clair River,

Q_D = outflow from the lake into the Detroit River.

Table 1. St. Clair River Transfer Factors (in HCFS)*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1950	147	115	130	144	28	6	13	11	20	25	48	117
1951	125	98	105	108	20	11	14	5	7	16	42	13
1952	187	52	139	104	29	-12	11	5	9	14	14	24
1953	35	34	102	40	46	47	13	16	7	2	14	25
1954	75	116	143	117	33	4	0	1	1	86	40	52
1955	100	40	160	65	7	6	12	14	12	24	51	28
1956	128	-10	134	57	223	26	16	31	42	24	31	53
1957	91	12	90	90	45	8	41	10	26	29	69	116
1958	121	-34	60	13	-22	2	1	1	9	-3	29	13
1959	40	38	125	104	36	6	6	14	7	38	53	79
1960	126	16	-2	236	50	54	3	6	0	20	25	-8
1961	23	-4	57	64	41	11	8	32	26	15	16	11
1962	85	-13	104	54	2	11	6	11	-1	16	39	4
1963	52	-6	63	87	33	9	-1	-6	0	-6	4	-3
1964	68	24	15	57	14	8	0	18	12	8	5	26
1965	89	106	87	118	15	-7	8	3	8	10	20	63
1966	39	69	63	46	22	16	7	11	8	9	20	99
1967	48	50	79	147	13	38	44	13	13	47	63	118
1968	54	165	104	59	13	56	43	27	11	18	9	79
1969	62	143	45	102	68	35	25	18	3	10	44	74
1970	-14	25	41	109	18	10	16	-1	-6	16	26	53
1971	64	40	128	59	-17	0	-5	-11	15	13	1	35
1972	29	36	113	125	11	1	20	25	4	12	82	78
1973	98	46	219	83	34	28	25	13	-5	21	27	70
1974	148	111	156	100	90	11	11	11	10	12	1	53
1975	70	89	127	116	18	27	12	28	73	26	46	30
1976	65	153	232	68	76	9	57	40	16	28	42	24

* HCFS--Hundreds of cubic feet per second

3. RESULTS

3.1 St. Clair River--Open-Water Flows

Four operational St. Clair River models have been developed, based on the one-dimensional equations for continuity and motion described earlier. These models span the upper portion of the river from its outflow at Port Huron, Mich., to St. Clair, Mich., nearly midway down the river. Four U.S. water level gages located along this reach of the river are used in the models. In downstream sequential order, the location of these gages include Fort Gratiot (FG), the mouth of the Black River (MBR), and Dry Dock in Grant Place (DD), all located in Port Huron, and St. Clair (SC). Gage locations are shown in Figure 2. Three gages are used in each model, with the midstream gage used primarily for checking flow values by comparing computed and measured water levels. Using the three-gage designation for river reaches involved yields the following models for the St. Clair river:

FG-MBR-DD,

FG-MBR-SC,

FG-DD-SC,

MBR-DD-SC.

Each model privides three sets of flows corresponding to the river profile indicated by the water level records of the employed gages. The hydraulic parameters (average width, length, reference elevation, and base area) and roughness coefficients required for the flow computations are listed in Tables 2 and 3, respectively. As mentioned previously, two sets of roughness coefficients (1959-63 and 1964-76) are used for the lower river reaches because of regimen changes caused by channel dredging. Another adjustment contained in the models is for the Fort Gratiot and St. Clair gage relocations. The movement of these gages in 1970 caused changes in the apparent hydraulic regimens due to the different river velocities at the new gage locations (Quinn, 1976b). All the hydraulic computations for discharge equations and transient model calibrations are based on the original gage locations; thus, the relocated gages require corrections to make them equivalent to the original gages. A comparison study indicated that the water levels from the new Fort Gratiot gage must be reduced by 0.18 ft, while those from the new St. Clair gage are increased by 0.09 ft to agree with the measurements taken prior to 1970.

The models can be operated on hourly, daily, or monthly time increments, depending on the requirements. For coordinating monthly flows, the monthly time intervals were generally used because the short-term unsteady flow effects are normally averaged out during these longer

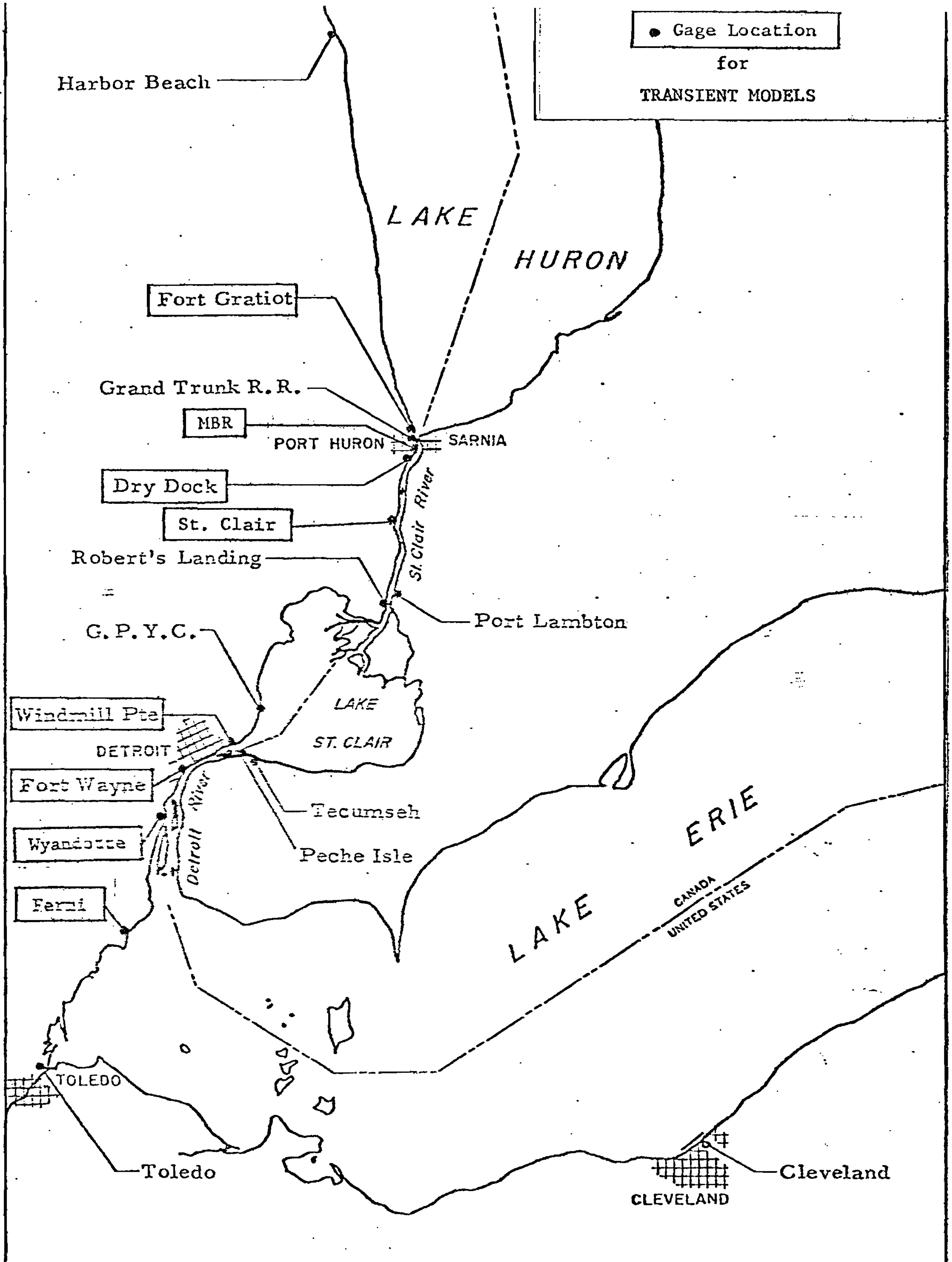

Figure 2. St. Clair-Detroit River system.

Table 2. St. Clair River Hydraulic Parameters

Reach from-to	Average width (ft)	Length (ft)	Reference elevation IGLD*(1955)	Base area (ft^2)
Fort Gratiot-MBR	1550	12,560	576.3	51,140
Fort Gratiot-Dry Dock	1760	25,490	576.1	54,800
MBR-Dry Dock	2108	12,930	575.6	60,900
MBR-St. Clair	1930	60,410	574.5	51,205
Dry Dock-St. Clair	2490	47,150	574.8	64,600

*IGLD--International Great Lakes Datum

Table 3. St. Clair River Roughness Coefficients

Reach	Roughness coefficient, n
Fort Gratiot-MBR	0.000570 FG - 0.2940
Fort Gratiot-Dry Dock	0.000306 FG - (-0.1476)
MBR-Dry Dock	0.0235
MBR-St. Clair	0.0205 current regime; 0.0214 '59 - '63 regime
Dry Dock-St. Clair	0.0250 current regime; 0.0261 '59 - '63 regime

periods. The open-water flows (May-November) computed by different models generally agree within 2% or 4 TCFS, which is considered to be the accuracy of the models. The GLERL open-water flows selected for the coordination of monthly St. Clair River flows by the River Flow Subcommittee for the 1959-76 period are listed in Table 4. The selection of flows was based on the completeness of water level data, relative accuracy as indicated by the midstream gage, and agreement by more than one model. Some consideration was also given to the transferred Detroit River flows. This consideration was relatively minor, since preservation of continuity between the two rivers did not present any serious problems during the open-water season.

3.2 St. Clair River--Winter Flows

The same four open channel St. Clair River models are used to compute winter flows. However, during winter there is generally less agreement between different St. Clair models and there are relatively frequent discrepancies between St. Clair and Detroit River flows. The deterioration of the transient models during winter is caused by ice retardation of flows, which frequently occurs, especially at the lower St. Clair River. Resolution of the ice retardation problem requires winter flow measurements for model calibration during periods when ice retardation causes significant changes in the normal open-water river profile.

Winter flows were selected for the St. Clair River by basically the same procedure as used for the open-water season. Although some consideration was given to the transferred Detroit River flows, the flows indicated by the St. Clair River models were normally assumed to be more representative of actual flow conditions. This assumption was based on the minimum flow criteria established during previous flow coordination efforts (Regulation Subcommittee, International Great Lakes Levels Board, 1969). The criteria specify determination of winter flows with the open-water equations from ice-free reaches with maximum fall, where the relative error in slope measurement due to ice effect is minimized. Both rivers are normally ice free in the upper reaches, where most of the falls occur. Preference for the St. Clair River winter flows is based on greater fall in this river. The GLERL St. Clair winter flows selected under this criteria are given in Table 4.

Justification for the minimum flow criteria was derived from examination of ice-retardation-induced changes in the river profile. When ice moves upstream of the lower gage of a particular reach, the water level at the gage falls, producing steeper slope and artificially high computed discharge. Above the ice, backwater effects cause the river to have a flatter slope and, consequently, lower discharge. The error is reduced by selecting ice-free reaches with greatest fall. Because ice retardation normally occurs in the lower St. Clair River, the lower winter flows are obtained most frequently for this river. However, recent examination of several St. Clair-Detroit River system profiles during severe ice jams indicated that reductions in winter flow deduced

Table 4. St. Clair River Flows Recommended by GLERL (in TCFS)*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1959	111	116	151	159	164	169	168	169	171	170	172	174
1960	163	145	163	172	189	194	199	202	201	199	193	185
1961	174	182	190	187	182	181	186	186	186	188	189	183
1962	146	136	175	183	186	188	189	183	185	179	175	169
1963	137	124	157	166	167	171	171	172	169	168	164	155
1964	122	127	147	150	158	159	161	162	162	161	159	158
1965	131	137	148	159	168	173	176	178	177	182	179	179
1966	171	158	178	181	184	186	187	183	183	178	174	176
1967	172	154	171	180	185	193	196	193	192	187	190	183
1968	161	163	178	181	187	188	192	196	198	199	199	190
1969	164	185	192	192	193	202	209	211	211	207	205	197
1970	143	167	198	191	201	203	207	207	207	205	203	204
1971	180	171	196	207	214	217	218	219	216	212	211	207
1972	197	185	195	196	209	217	215	218	224	222	217	209
1973	206	184	196	207	218	220	223	226	225	222	222	213
1974	198	199	205	207	215	225	230	226	223	219	216	210
1975	200	195	190	204	216	217	221	219	215	211	204	206
1976	157	167	193	213	221	224	223	223	212	208	200	178

*TCFS--Thousand cubic feet per second

from the St. Clair River computations may be too severe, and that flows from the Detroit River computations might be more indicative of actual conditions. In the cases examined, despite severe reduction of flow in the St. Clair River, there was relatively little change in the total head between Lakes Huron and St. Clair. The Detroit River flows were more credible, showing better agreement with the total head between Lakes St. Clair and Erie. It is therefore recommended that flows coordinated for the winter problem months be withdrawn from Table 4 or designated as preliminary pending reevaluation.

3.3 Detroit River--Open-Water Flows

Two different Detroit River transient models have been developed. The upper river model is similar to the St. Clair River models. It spans the upper portion of the river from its outflow at Windmill Point (WP) in Detroit, Mich., to Wyandotte (WY), Mich., located above Grosse Ile, with an intermediate section at Fort Wayne (FW) in Detroit. The total river model spans the whole length of the river from its head at Windmill Point to its mouth at Fermi (FE), Mich., on Lake Erie, with an intermediate section at Wyandotte. This model branches into two channels in the lower portion of the river to give separate flows around Grosse Ile, namely, the main channel to the east of the island and the Trenton Channel to the west. The three-gage designation for the Detroit River models, based on river reaches involved, is as follows:

WP-FW-WY

WP-WY-FE.

Operation of the models for both rivers is similar, except that the total Detroit River model provides four additional flow values, corresponding to the upstream and downstream sections of the branching channels. The hydraulic parameters and roughness coefficients required for the flow computations are listed in Tables 5 and 6, respectively. Two methods were used to derive the roughness coefficients for the various reaches along the river. Roughness coefficients for the reaches of (WP-FW), (FW-WY), and the Trenton Channel (WY-FE, west) were derived from actual discharge measurements. In order to maintain consistency between the two Detroit River models, the roughness coefficients for the (WP-WY) and (WY-FE, east) or the main downstream channel were determined from the 1964-73 average monthly summer flows computed by the upper river model (WP-FW-WY). Flow in the main downstream channel (WY-FE, east) for model calibration was derived from the measured percentage of river flow around Grosse Ile (total minus Trenton). Accuracy of both models for open-water flows is similar (2% or 4 TCFS). The monthly Detroit River open-water flows determined by GLERL are given in Table 7. Selection criteria for the summer flows for both rivers were similar.

Table 5. Detroit River Hydraulic Parameters

Reach from-to	Average width (ft)	Length (ft)	Reference elevation IGLD*(1955)	Base area (ft^2)
Windmill Point-Fort Wayne	3650	54,400	571.2	85,960
Fort Wayne-Wyandotte	3510	37,800	570.5	92,800
Windmill Point Wyandotte	3590	92,220	570.93	88,780
Wyandotte-Fermi east of Grosse Ile	5055	48,630	570.80	81,700
Fermi west of Grosse Ile-Trenton Channel	1685	54,150	569.47	20,800

*IGLD--International Great Lakes Datum

Table 6. Detroit River Roughness Coefficients

Reach from – to	Roughness coefficient, n	Flow basis
Windmill Point-Fort Wayne	0.0006875 WP – 0.3714	Measured flows
Windmill Point-Wyandotte	0.0004198 WP – 0.2171	Computed flows
Fort Wayne-Wyandotte	0.0241	Measured flows
Wyandotte-Fermi east of Grosse Ile	0.001241 Fermi – 0.6776	Computed flows
Wyandotte-Fermi Trenton Channel	0.0253	Measured flows

Table 7. Detroit River Flows Recommended by GLERL (in HCFS)*

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1959	115	120	161	173	169	171	169	172	176	178	176	183
1960	179	148	163	196	194	198	197	200	201	201	199	184
1961	170	181	191	194	193	185	187	188	185	192	192	182
1962	154	135	185	183	188	191	187	183	188	186	177	173
1963	146	123	169	179	169	177	177	178	173	171	164	160
1964	129	129	154	155	162	162	165	168	170	162	167	158
1965	140	145	162	175	169	176	179	177	178	188	181	184
1966	178	164	180	188	188	188	187	190	186	179	180	181
1967	179	161	181	196	194	196	203	199	199	199	196	194
1968	167	187	183	186	188	192	196	197	198	202	202	200
1969	168	199	192	199	201	200	205	208	207	207	209	199
1970	143	168	198	198	199	203	207	206	208	207	208	202
1971	183	175	207	210	209	212	214	217	216	213	214	206
1972	205	189	203	202	206	212	212	216	220	222	222	210
1973	210	195	221	217	219	221	226	228	231	227	228	218
1974	209	207	218	221	222	221	226	225	225	224	221	210
1975	212	210	202	217	216	220	222	223	224	216	213	213
1976	165	185	215	218	226	222	227	224	215	212	206	185

*HCFS--Hundred cubic feet per second

3.4 Detroit River--Winter Flows

Both oper-water models were used to compute winter flows, but the upper river model is considered more reliable since it spans what is normally an ice-free reach. However, during periods of discrepancies between computed flows for both rivers, the recommended flows are based primarily on the transferred St. Clair River flows under the minimum flow criteria described previously. It appears that these criteria may not be valid. Because resulting winter flows for both rivers may contain considerable errors during ice retardation periods, it is recommended that final coordination of monthly winter flows of questionable accuracy be withheld until they are reevaluated. The monthly winter Detroit River flows selected by GLERL under the minimum flow criteria are given in Table 7.

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