DISCHARGE RATINGS FOR CONTROL STRUCTURES AT McHENRY DAM ON THE FOX RIVER, ILLINOIS

By Gregory G. Fisk

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 87-4226

Prepared in cooperation with

ILLINOIS DEPARTMENT OF TRANSPORTATION,

DIVISION OF WATER RESOURCES

Urbana, Illinois

1988

DEPARTMENT OF THE INTERIOR

DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
4th Floor
102 E. Main Street
Urbana, IL 61801

Copies of this report can be
purchased from:

U.S. Geological Survey
Books and Open-file Reports Section
Federal Center, Bldg. 810
Box 25425
Denver, CO 80225

CONTENTS

ILLUSTRATIONS

TABLES

CONVERSION FACTORS AND ABBREVIATIONS

For the convenience of readers who prefer to use metric (International System) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	0.09294	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

SYMBOLS AND UNITS

Symbol	Definition	Unit
B	Sluice-gate width, or spillway and fish ladder length	ft
C	Coefficient of discharge for free orifice flow under sluice gates	
C_s	Coefficient of discharge for submerged orifice flow under sluice gates	
C_w	Coefficient of discharge for free weir flow	
C_{ws}	Coefficient of discharge for submerged weir flow	
g	Acceleration due to gravity (32.2)	ft/s^2
h_1	Headwater depth referenced to sluice-gate sill or spillway crest	ft
h_3	Tailwater depth referenced to sluice-gate sill or spillway crest	ft
h_g	Sluice-gate opening	ft
Q	Discharge	ft^3/s

DISCHARGE RATINGS FOR CONTROL STRUCTURES AT McHENRY DAM

ON THE FOX RIVER, ILLINOIS

by Gregory G. Fisk

ABSTRACT

Twenty-three measurements of discharge were used to determine discharge ratings for the five adjustable sluice gates, spillway, and fish ladder at McHenry Dam on the Fox River in Illinois. Discharge ratings were determined for free weir, free orifice, and submerged orifice flow regimes.

Hydraulic conditions that identify flow regimes at McHenry Dam are defined by ratios between headwater depth (h_1), tailwater depth (h_3), and gate opening (h_g). Flow under the sluice gates is identified as weir flow when the ratio of gate opening to headwater depth is greater than 0.73, and as orifice flow when h_g/h_1 is less than 0.73. Free orifice flow occurs when the ratio of tailwater depth to gate opening is less than 1.3, and submerged orifice flow occurs when h_3/h_g is greater than 1.3. Flow under the sluice gates is identified as free weir flow when the ratio of tailwater depth to headwater depth is less than 0.75, and as submerged weir flow when h_3/h_1 is greater than 0.75. Flow over the spillway is identified as free weir flow when the ratio of tailwater depth to headwater depth is less than 0.60, and as submerged weir flow when h_3/h_1 is greater than 0.60.

Discharge coefficients to be used in equations to compute discharge for various hydraulic conditions were determined. Four discharge measurements, ranging from 169 to 2,990 cubic feet per second, were used to define discharge coefficients that varied from 2.61 to 3.14 for free weir flow over the spillway.

Nineteen discharge measurements, ranging from 180 to 4,050 cubic feet per second, were used to define discharge coefficients for free weir, free orifice, and submerged orifice flow under the sluice gates. The average value of the discharge coefficient for free weir flow under the sluice gates is 3.17. Discharge coefficients for free orifice flow varied from 0.48 to 0.66 and the discharge coefficients for submerged orifice flow from the two measurements were 0.59 and 0.67.

INTRODUCTION

Background

McHenry Dam is located on the Fox River in northeastern Illinois, 42 miles northwest of Chicago and 2.5 miles south of McHenry (fig. 1). The Illinois Department of Transportation, Division of Water Resources (DWR) operates the

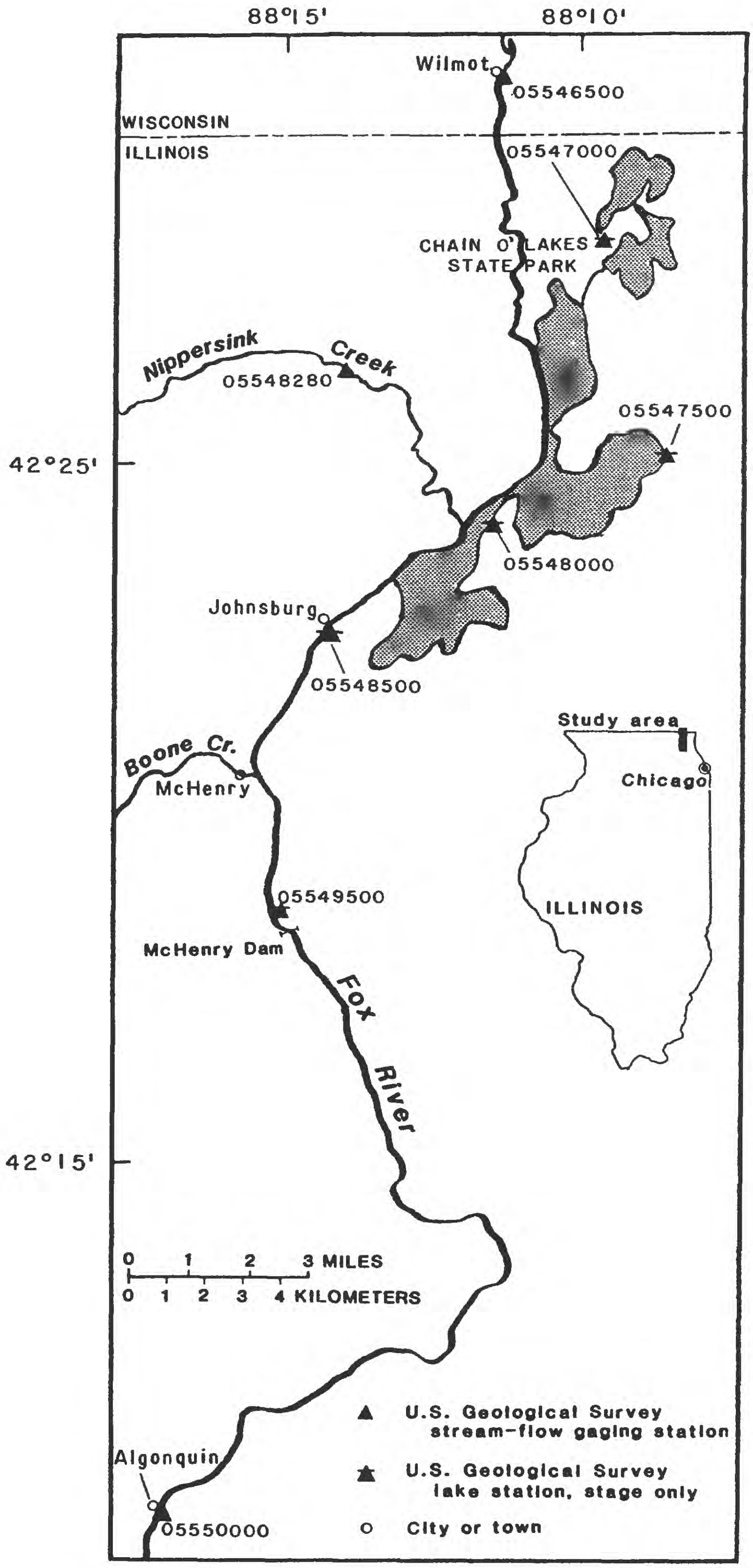

Figure 1.--Location of McHenry Dam and gaging stations on the Fox River.

dam for recreational and flood-control purposes. Reliable computation of discharge at McHenry Dam is needed in order to effectively operate the dam for those purposes. The U.S. Geological Survey (Survey), in cooperation with DWR, began a study in March 1985 to develop a method for computing discharge at McHenry Dam. The method was to include discharge ratings for the various flow regimes related to hydraulic conditions involving headwater depth, tailwater depth, and sluice-gate openings.

Purpose and Scope

The purpose of this report is to describe the results of a study to develop discharge ratings for the control structures at McHenry Dam. The methods are limited in scope to three types of flow--free weir, free orifice, and submerged orifice--that occurred during the study period.

Approach

Discharge ratings at McHenry Dam are affected by headwater and tailwater stages, and gate openings. Because it was not feasible to make measurements under all hydraulic conditions, measurements were made to determine discharge coefficients in equations that relate discharge to headwater depth, tailwater depth, and gate openings. Discharge coefficients were then related to depths and gate openings applicable to each measurement.

Standard Survey techniques (Buchanan and Somers, 1969) were used to make discharge measurements. Current-meter measurements of low flows were made by wading across the spillway crest and wading 50 feet (ft) downstream from the sluice gates. Medium and high flows were measured from a boat about 100 ft upstream from the gates and 150 ft upstream from the spillway (fig. 2).

Acknowledgments

The Illinois Department of Transportation and Bill Rice, in particular, provided historical data used in this report. McHenry Dam Lockmaster, Frank Novak, Jr., was very helpful in providing various gate openings to provide the desired flow regime. Their cooperation on this study is gratefully acknowledged.

DESCRIPTION OF McHENRY DAM

McHenry Dam is located at river mile 97.8 on the Fox River in northeastern Illinois (fig. 1). The drainage area at the dam is 1,250 square miles (mi^2). The 8,900-acre reservoir created by the dam is part of the Fox Chain O' Lakes and is used primarily for recreation and flood control. The control structures at the dam consist of five sluice gates, a spillway, a fish ladder, and a navigation lock.

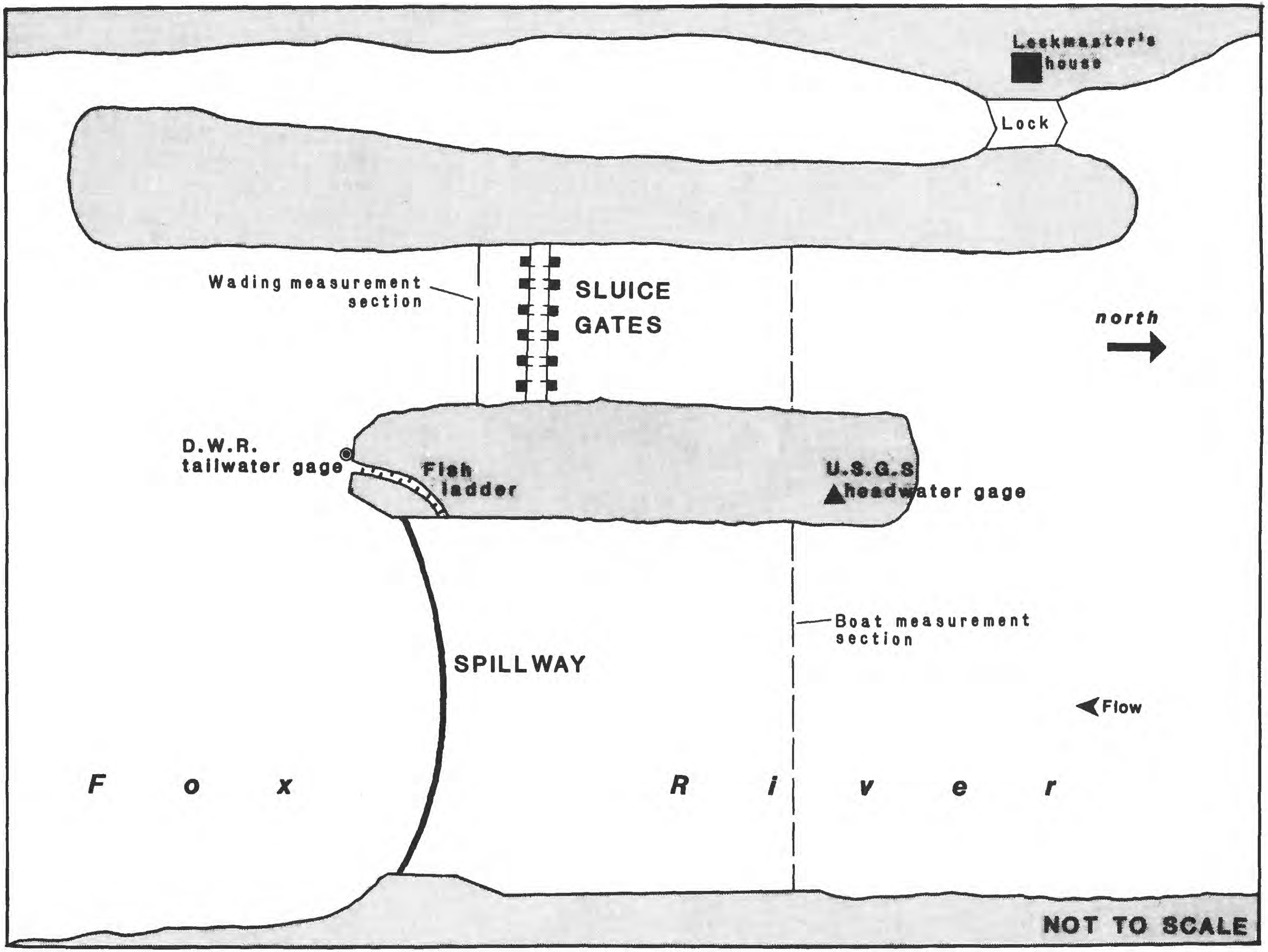

Figure 2.--Location of control structures at McHenry Dam.

The sluice gates (figs. 2, 3) are operated to regulate discharge when the headwater-pool stage is below the crest of the spillway. Each sluice gate is 13.75 ft wide and can be raised to a maximum opening of 9.0 ft to regulate flow under the gate; flow over the top of the gates does not occur. The sill on which a closed gate rests (fig. 4) is at an elevation of 731.15 ft above sea level. All gates are set to similar openings, ranging from 0 to 9 ft, to maintain the headwater-pool stage at 4.00 ft during the recreational season, April through October. Headwater-pool stages are referenced to a datum of 733.00 ft above sea level. In November of each year, the sluice gates are gradually adjusted to lower the headwater pool to a stage between 1.5 and 2.0 ft to provide storage for flood control during spring runoff. The tailwater-pool stage, which is referenced to a datum of 730.15 ft above sea level, can be partially regulated during floods by adjustment of the sluice-gate openings.

The spillway is a broad-crested, concrete and stone-faced weir that is arced upstream and measures 282 ft along the arc. Water begins to flow over the spillway (figs. 2, 5) when the headwater pool rises above the weir-crest elevation of 736.68 ft. A 6-foot-long fish ladder, also having a crest elevation of 736.68 ft, is adjacent to and in the same approach section as the spillway (figs. 2, 5). The discharge rating for flow over the spillway includes flow over the 6-foot-long fish ladder.

DISCHARGE RATINGS

The four flow regimes that may occur at dams are discussed by Collins (1977). The flow regimes and hydraulic conditions defining each regime, along with equations for computing discharge, are listed in table 1. Collins states that the hydraulic conditions (table 1) are general criteria for defining the flow regimes.

Table 1.--Equations of flow

[Equations from Collins, 1977. Q, Discharge, in cubic feet per second; C, Free orifice discharge coefficient; C_s, Submerged orifice discharge coefficient; C_w, Free weir discharge coefficient; C_{ws}, Submerged weir discharge coefficient; h_g, Gate opening; h_1, Headwater depth; h_3, Tailwater depth; B, Sluice gate width or spillway length; g, Acceleration due to gravity; Δh equals h_1-h_3]

Flow regime	Hydraulic condition	Equations	Equation number
Free orifice	$h_g<0.67h_1$ and $h_3<h_g$	$Q=C[h_gB(2gh_1)^{0.5}]$	(1)
Submerged orifice	$h_g<0.67h_1$ and $h_3\geq h_g$	$Q=C_s[h_3B(2g\Delta h)^{0.5}]$	(2)
Free weir	$h_g\geq 0.67h_1$ and $h_3/h_1<0.6$	$Q=C_w[Bh_1{}^{1.5}]$	(3)
Submerged weir	$h_g\geq 0.67h_1$ and $h_3/h_1\geq 0.6$	$Q=C_wC_{ws}$ $[Bh_1{}^{1.5}]$	(4)

Figure 3.--Downstream side of sluice gates.

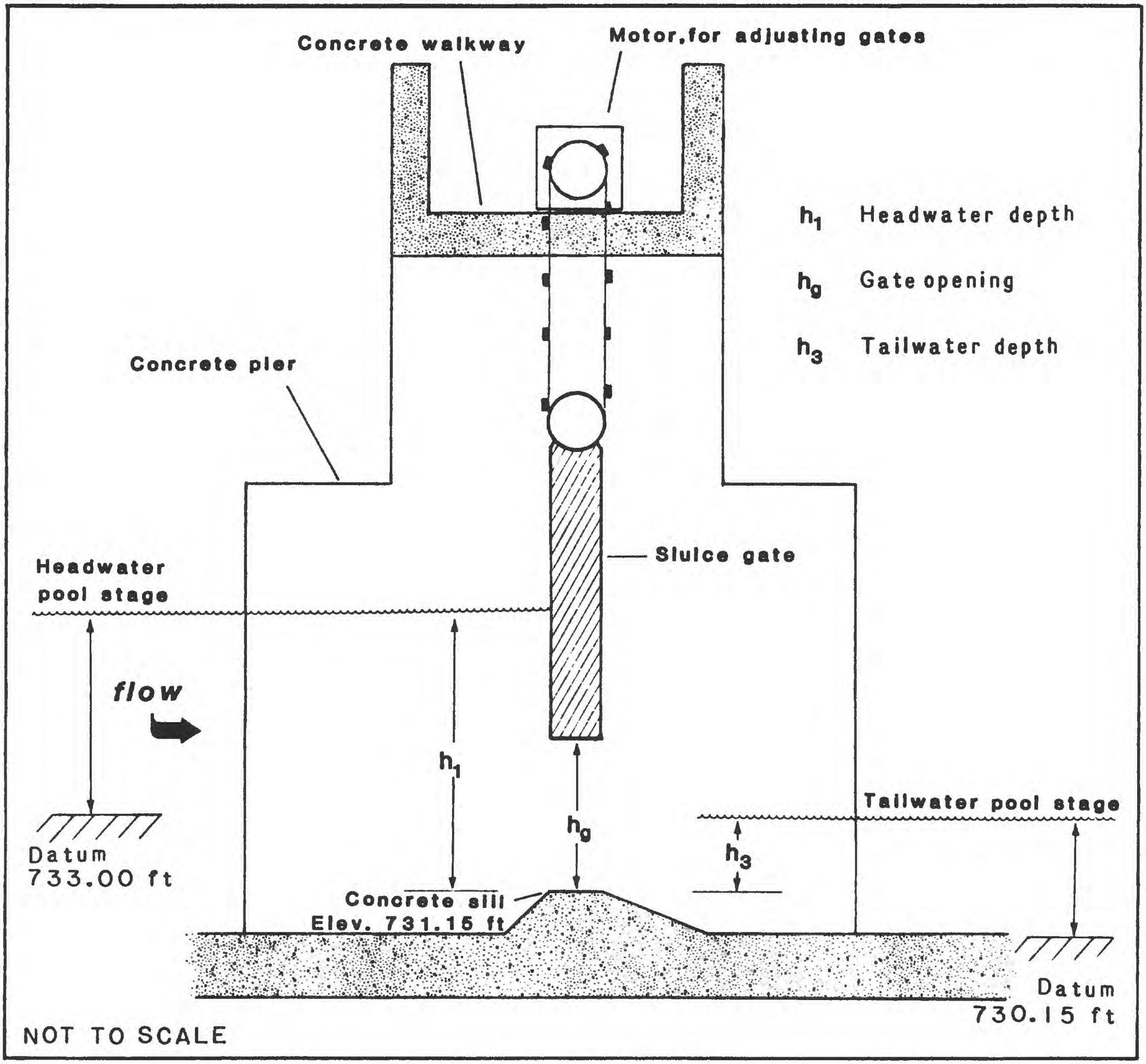

Figure 4.--Cross section of sluice gate.

Figure 5.--Downstream side of spillway and fish ladder.

Spillway

Discharge measurements 5, 13, 15, and 20 (table 2) were made during free weir flow over the spillway. Free weir flow over a spillway, as defined by Collins (table 1), occurs when the ratio of tailwater depth (h_3) to headwater depth (h_1) is less than 0.6. Both depths are referenced to the spillway crest. The greatest submergence ratio (h_3/h_1) measured for the spillway was only 0.20. Submerged weir flow, which occurs when the submergence ratio (h_3/h_1) is equal to or greater than 0.6, did not occur during the study period; thus, the general submergence ratio suggested by Collins (0.6) is assumed to be applicable for the spillway.

Upstream pool stage for the discharge measurements ranged from 4.05 to 5.90 ft, and discharge ranged from 169 to 2,990 cubic feet per second (ft^3/s). The discharge coefficients for free weir flow defined by the measurements ranged from 2.61 to 3.14 (table 2). The relation between headwater depth (h_1) and free weir discharge coefficient for the spillway is shown in figure 6. The resulting equation relating the discharge coefficient for free weir flow to headwater depth is

$$C_w = 2.94\ h_1^{0.087}\ . \tag{5}$$

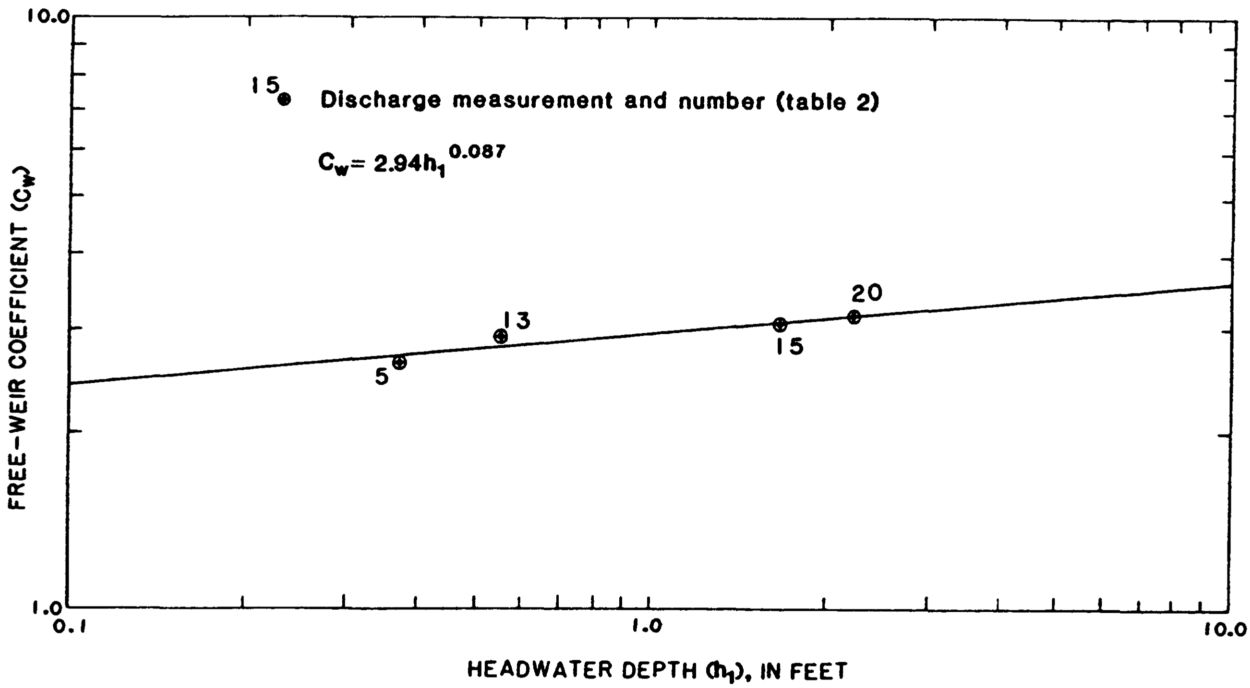

Figure 6.--Relation between discharge coefficient for free weir flow and headwater depth for spillway (fish ladder included).

Table 2.--Characteristics of discharge at McHenry Dam

[ft, feet; ft^3/s, cubic feet per second]

Structure[1]	Measurement number	Date	Gate opening (h_g) (ft)	Flow regime[2]	Headwater-pool stage[3] (ft)	Headwater depth (h_1)[4] (ft)	Tailwater-pool stage[5] (ft)	Tailwater depth (h_3)[6] (ft)	Measured discharge (ft^3/s)	Computed coefficient	Deviation from rating (percent)
Sluice gates	1	03-22-85	out of water	FW	3.51	5.36	3.90	2.90	2,790	3.27	3.0
Do.	2	03-22-85	[7]3.00	FO	3.68	5.53	3.70	2.70	1,990	.51	-1.5
Do.	3	03-26-85	out of water	FW	2.64	4.49	3.45	2.45	2,100	3.21	1.4
Do.	4	03-26-85	[7]3.30	FO	2.71	4.56	3.42	2.42	1,850	.48	-7.5
Spillway	5	05-16-85	--	FW	4.05	.37	1.35	--	169	2.61	-2.9
Sluice gates	6	05-16-85	[7].60	FO	4.03	5.88	1.35	.35	448	.56	-6.1
Do.	7	11-04-85	[8]3.15	FO	3.98	5.83	2.82	1.82	1,830	.54	5.7
Do.	8	11-04-85	[8]2.50	FO	4.05	5.90	2.75	1.75	1,460	.54	3.5
Do.	9	03-17-86	out of water	FW	4.31	6.16	5.03	4.03	3,230	3.07	-3.0
Do.	10	04-22-86	[7]1.2	FO	3.23	5.08	1.71	.71	833	.56	-.3
Do.	11	04-22-86	[9]4@2 1@1	FO	3.13	4.98	1.85	.85	1,180	.53	-1.9
Do.	12	05-23-86	[7]1.2	FO	4.16	6.01	2.25	1.25	967	.60	6.2
Spillway	13	08-28-86	--	FW	4.23	.55	1.05	--	342	2.91	4.6
Sluice gates	14	08-28-86	[7].2	FO	4.22	6.07	1.05	.05	180	.66	1.7

Table 2.--Characteristics of discharge at McHenry Dam--Continued

Structure[1]	Measurement number	Date	Gate opening (h_g) (ft)	Flow regime[2]	Headwater-pool stage[3] (ft)	Headwater depth (h_1)[4] (ft)	Tailwater-pool stage[5] (ft)	Tailwater depth (h_3)[6] (ft)	Measured discharge (ft^3/s)	Computed coefficient	Deviation from rating (percent)
Spillway	15	09-27-86	--	FW	5.34	1.66	6.12	--	1,880	3.05	-1.1
Sluice gates	16	09-27-86	[7]4.0	FO	5.35	7.20	6.15	5.15	3,040	.51	1.3
Do.	17	09-27-86	out of water	FW	5.20	7.05	6.25	5.25	4,050	3.15	-1.8
Do.	18	09-27-86	[7]4.9	FO	5.22	7.07	6.25	5.25	3,600	.50	1.1
Do.	19	09-27-86	[7]4.5	FO	5.26	7.11	6.30	5.30	3,320	.50	0
Spillway	20	09-30-86	--	FW	5.90	2.22	6.98	.45	2,990	3.14	-.7
Sluice gates	21	09-30-86	[7]4.0	SO	5.90	7.75	6.98	5.98	2,600	.59	-.4
Do.	22	09-30-86	[7]4.5	SO	5.86	7.71	6.98	5.98	2,920	.67	.3
Do.	23	10-15-86	out of water	FW	4.25	6.10	5.10	4.10	3,270	3.16	-.3

[1]Datum of spillway crest and sluice gates are 736.68 and 731.15 ft above sea level, respectively.

[2]FW designates free weir flow, FO designates free orifice flow, and SO designates submerged orifice flow.

[3]Referenced to Survey gage datum of 733.00 ft above sea level.

[4]Headwater depths are computed by applying an adjustment factor (-3.68 ft for spillway; 1.85 ft for sluice gates) to the headwater-pool stages.

[5]Referenced to Survey gage datum of 730.15 ft above sea level.

[6]Tailwater depths are computed by applying an adjustment factor (-6.53 ft for spillway; -1.00 ft for sluice gates) to the tailwater-pool stages.

[7]Five gates set to same opening.

[8]Four gates in operation set to same opening, one gate closed.

[9]Four gates were set to 2.0 ft and one gate at 1.0 ft; the coefficient from figure 8 was used to subtract flow for a 1.0-ft opening; a coefficient for a 2.0-ft opening was determined from the measurement.

Discharge for free weir flow over the spillway is computed by combining equation 3 in table 1 with equation 5 for the free weir coefficient (C_w). The resulting equation of discharge is

$$Q = 847 \ (h_1)^{1.59} \tag{6}$$

where h_1 is the headwater depth above the spillway crest. Discharges for free weir flow over the spillway are given in table 3 and are extrapolated to include the historical peak stage of 6.36 ft.

Sluice gates

Nineteen discharge measurements, ranging from 180 to 4,050 ft^3/s, were made to describe flow under the sluice gates. Characteristics of flow and the discharge coefficient associated with each measurement are listed in table 2. Discharge coefficients, required for the equations of flow (table 1), were determined for free weir, free orifice, and submerged orifice flow. Submerged weir flow did not occur during the study period.

Nineteen measurements of discharge, stage, and gate opening provided data for identifying the flow regimes for the sluice gates at McHenry Dam. The criteria for identifying free weir flow are that the ratio of gate opening (h_g) to headwater depth (h_1) is greater than 0.73, and the ratio of tailwater depth (h_3) to the headwater depth is less than 0.75 (fig. 4). Submerged weir flow occurs when h_g/h_1 is greater than 0.73, and h_3/h_1 is greater than 0.75. Orifice flow occurs when h_g/h_1 is less than 0.73 (the bottom of the gate must be touching the water surface) and is free orifice flow when the submergence ratio (h_3/h_g) is less than 1.3. Submerged orifice flow occurs when the submergence ratio is equal to or greater than 1.3.

Free weir flow under the sluice gates occurred during measurements 1, 3, 9, 17, and 23 (table 2). The headwater-pool stage ranged from 2.64 to 5.20 ft, and the discharge ranged from 2,100 to 4,050 ft^3/s. A discharge coefficient for free weir flow of 3.17 was defined by the measurements (fig. 7). Discharge for free weir flow under five sluice gates is computed by using using equation 3 in table 1 and a coefficient of 3.17. The resulting equation of discharge is

$$Q = 218 \ (h_1)^{1.5} \tag{7}$$

where h_1 is headwater depth above the sluice-gate sill. Discharges for free weir flow are given in table 4.

Measurements 2, 4, 6-8, 10-12, 14, 16, 18, and 19 were used to calculate discharge coefficients for free orifice flow. Discharge coefficients varied from 0.48 to 0.66 for free orifice flow for a range of gate openings (fig. 8). The resulting equation relating the discharge coefficient for free orifice flow to gate opening (h_g) is

$$C = 0.57 \ (h_g)^{-0.084}. \tag{8}$$

Table 3.--Discharge rating table for free weir flow over spillway (fish ladder included)

Headwater pool stage, in feet[1]	Headwater pool stage, in hundredths of feet									
	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
	Discharge, in cubic feet per second									
3.60	---	---	---	---	---	---	---	---	0.0	0.6
3.70	1.7	3.2	5.1	7.2	9.7	12	15	18	22	25
3.80	29	33	37	41	46	51	55	60	66	71
3.90	76	82	88	93	99	106	112	118	125	132
4.00	138	145	152	160	167	174	182	190	197	205
4.10	213	221	230	238	246	254	264	272	281	290
4.20	299	309	318	327	334	347	356	366	376	386
4.30	396	406	417	427	437	448	459	470	480	491
4.40	502	514	525	536	547	559	571	582	594	606
4.50	618	630	642	654	666	679	691	704	716	729
4.60	742	755	768	781	794	807	820	836	847	861
4.70	874	888	898	915	929	943	957	971	986	1,000
4.80	1,010	1,030	1,040	1,060	1,070	1,090	1,100	1,120	1,130	1,150
4.90	1,160	1,180	1,190	1,210	1,220	1,240	1,250	1,270	1,290	1,300
5.00	1,320	1,330	1,350	1,360	1,380	1,400	1,410	1,430	1,450	1,460
5.10	1,480	1,500	1,510	1,530	1,550	1,560	1,580	1,600	1,610	1,630
5.20	1,650	1,670	1,680	1,700	1,720	1,740	1,750	1,770	1,790	1,810
5.30	1,820	1,840	1,860	1,880	1,900	1,910	1,930	1,950	1,970	1,990
5.40	2,010	2,020	2,040	2,060	2,080	2,100	2,120	2,140	2,160	2,180
5.50	2,190	2,210	2,230	2,250	2,270	2,290	2,310	2,330	2,350	2,370
5.60	2,390	2,410	2,430	2,450	2,470	2,490	2,510	2,530	2,550	2,570
5.70	2,590	2,610	2,630	2,650	2,670	2,690	2,710	2,730	2,760	2,780
5.80	2,800	2,820	2,840	2,860	2,880	2,900	2,920	2,950	2,970	2,990
5.90	3,010	3,030	3,050	3,080	3,100	3,120	3,140	3,160	3,180	3,210
6.00	3,230	3,250	3,270	3,300	3,320	3,340	3,360	3,380	3,410	3,430
6.10	3,450	3,480	3,500	3,520	3,540	3,570	3,590	3,610	3,640	3,660
6.20	3,680	3,710	3,730	3,750	3,780	3,800	3,820	3,850	3,870	3,890
6.30	3,920	3,940	3,960	3,990	4,010	4,040	4,060	---	---	---

[1]Referenced to Survey gage datum of 733.00 ft above sea level.

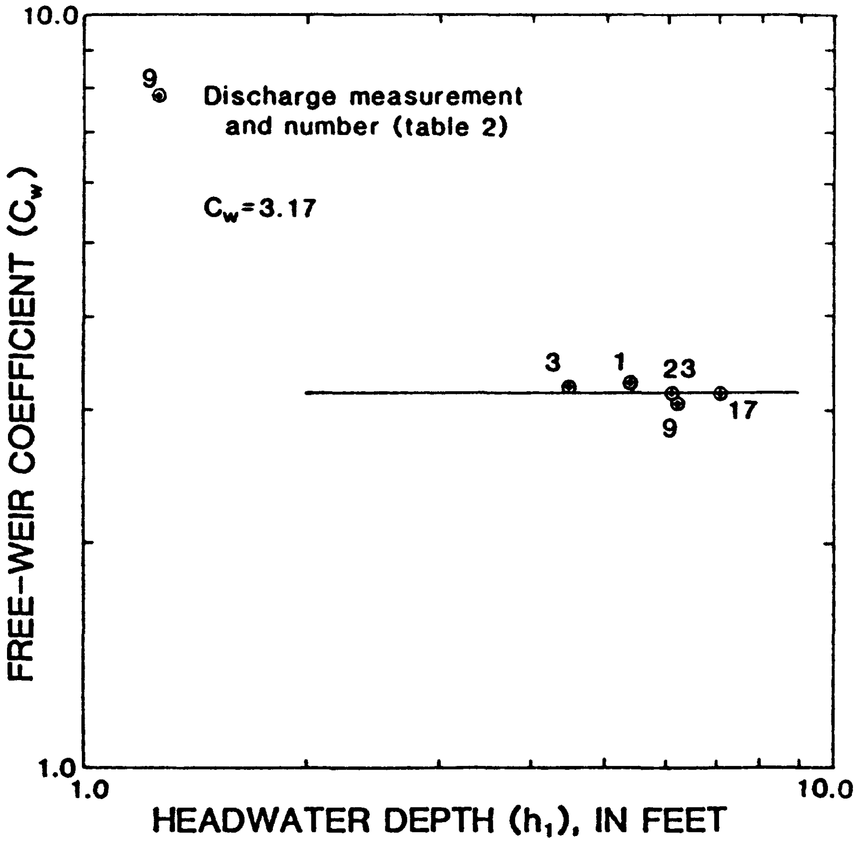

Figure 7.--Relation between discharge coefficient for free weir flow and headwater depth for sluice gates.

Table 4.--Discharge rating table for free weir flow under five sluice gates

Headwater pool stage, in feet[1]	Headwater pool stage, in hundredths of feet									
	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
	Discharge, in cubic feet per second									
0.2	640	645	649	654	659	663	668	673	678	682
0.3	687	692	697	702	707	711	716	721	726	731
0.4	736	741	746	751	755	760	765	770	775	780
0.5	785	790	795	800	805	811	816	821	826	831
0.6	836	841	846	851	857	862	867	872	877	882
0.7	888	893	898	903	909	914	919	924	930	936
0.8	940	946	951	956	962	967	973	978	983	989
0.9	994	1,000	1,000	1,010	1,020	1,020	1,030	1,030	1,040	1,040
1.0	1,050	1,050	1,060	1,070	1,070	1,080	1,080	1,090	1,090	1,100
1.1	1,100	1,110	1,120	1,120	1,130	1,130	1,140	1,140	1,150	1,160
1.2	1,160	1,170	1,170	1,180	1,180	1,190	1,200	1,200	1,210	1,210
1.3	1,220	1,220	1,230	1,240	1,240	1,250	1,250	1,260	1,270	1,270
1.4	1,280	1,280	1,290	1,290	1,300	1,310	1,310	1,320	1,320	1,330
1.5	1,340	1,340	1,350	1,350	1,360	1,370	1,370	1,380	1,380	1,390
1.6	1,400	1,400	1,410	1,420	1,420	1,430	1,430	1,440	1,450	1,450
1.7	1,460	1,460	1,470	1,480	1,480	1,490	1,500	1,500	1,510	1,510
1.8	1,520	1,530	1,530	1,540	1,550	1,550	1,560	1,560	1,570	1,580
1.9	1,580	1,590	1,600	1,600	1,610	1,620	1,620	1,630	1,630	1,640
2.0	1,650	1,650	1,660	1,670	1,670	1,680	1,690	1,690	1,700	1,700
2.1	1,710	1,720	1,720	1,730	1,740	1,740	1,750	1,760	1,760	1,770
2.2	1,780	1,780	1,790	1,800	1,800	1,810	1,820	1,820	1,830	1,840
2.3	1,840	1,850	1,860	1,860	1,870	1,880	1,880	1,890	1,900	1,900
2.4	1,910	1,920	1,920	1,930	1,940	1,940	1,950	1,960	1,960	1,970
2.5	1,980	1,980	1,990	2,000	2,010	2,010	2,020	2,030	2,030	2,040
2.6	2,050	2,050	2,060	2,070	2,070	2,080	2,090	2,090	2,100	2,110
2.7	2,120	2,120	2,130	2,140	2,140	2,150	2,160	2,160	2,170	2,180
2.8	2,190	2,190	2,200	2,210	2,210	2,220	2,230	2,240	2,240	2,250
2.9	2,260	2,260	2,270	2,280	2,290	2,290	2,300	2,310	2,310	2,320
3.0	2,330	2,340	2,340	2,350	2,360	2,360	2,370	2,380	2,390	2,390
3.1	2,400	2,410	2,420	2,420	2,430	2,440	2,440	2,450	2,460	2,470
3.2	2,470	2,480	2,490	2,500	2,500	2,510	2,520	2,530	2,530	2,540
3.3	2,550	2,560	2,560	2,570	2,580	2,590	2,590	2,600	2,610	2,610
3.4	2,620	2,630	2,640	2,640	2,650	2,660	2,670	2,680	2,680	2,690
3.5	2,700	2,710	2,710	2,720	2,730	2,740	2,740	2,750	2,760	2,770
3.6	2,770	2,780	2,790	2,800	2,800	2,810	2,820	2,830	2,830	2,840
3.7	2,850	2,860	2,870	2,870	2,880	2,890	2,900	2,900	2,910	2,920
3.8	2,930	2,940	2,940	2,950	2,960	2,970	2,970	2,980	2,990	3,000
3.9	3,010	3,101	3,020	3,030	3,040	3,040	3,050	3,060	3,070	3,080
4.0	3,080	3,090	3,100	3,110	3,120	3,120	3,130	3,140	3,150	3,160
4.1	3,160	3,170	3,180	3,190	3,200	3,200	3,210	3,220	3,230	3,240
4.2	3,240	3,250	3,260	3,270	3,280	3,280	3,290	3,300	3,310	3,320
4.3	3,320	3,330	3,340	3,350	3,360	3,370	3,370	3,380	3,390	3,400
4.4	3,410	3,410	3,420	3,430	3,440	3,450	3,460	3,460	3,470	3,480
4.5	3,490	3,500	3,500	3,510	3,520	3,530	3,540	3,550	3,550	3,560
4.6	3,570	3,580	3,590	3,600	3,600	3,610	3,620	3,630	3,640	3,650
4.7	3,650	3,660	3,670	3,680	3,690	3,700	3,700	3,710	3,720	3,730
4.8	3,740	3,750	3,760	3,760	3,770	3,780	3,790	3,800	3,810	3,810
4.9	3,820	3,830	3,840	3,850	3,860	3,870	3,870	3,880	3,890	3,900
5.0	3,910	3,920	3,930	3,930	3,940	3,950	3,960	3,970	3,980	3,990
5.1	3,990	4,000	4,010	4,020	4,030	4,040	4,050	4,050	4,060	4,070

Table 4.--Discharge rating table for free weir flow under five sluice gates--Continued

Headwater pool stage, in feet[1]	Headwater pool stage, in hundredths of feet									
	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
	Discharge, in cubic feet per second									
5.2	4,080	4,090	4,100	4,110	4,120	4,120	4,130	4,140	4,150	4,160
5.3	4,170	4,180	4,190	4,190	4,200	4,210	4,220	4,230	4,240	4,250
5.4	4,260	4,260	4,270	4,280	4,290	4,300	4,310	4,320	4,330	4,340
5.5	4,340	4,350	4,360	4,370	4,380	4,390	4,400	4,410	4,420	4,420
5.6	4,430	4,440	4,450	4,460	4,470	4,480	4,490	4,500	4,500	4,510
5.7	4,520	4,530	4,540	4,550	4,560	4,570	4,580	4,590	4,590	4,600
5.8	4,610	4,620	4,630	4,640	4,650	4,660	4,670	4,680	4,690	4,690
5.9	4,700	4,710	4,720	4,730	4,740	4,750	4,760	4,770	4,780	4,790
6.0	4,790	4,800	4,810	4,820	4,830	4,840	4,850	4,860	4,870	4,880
6.1	4,890	4,900	4,910	4,910	4,920	4,930	4,940	4,950	4,960	4,970
6.2	4,980	4,990	5,000	5,010	5,020	5,030	5,030	5,040	5,050	5,060
6.3	5,070	5,080	5,090	5,100	5,110	5,120	5,130	---	---	---

[1]Referenced to Survey gage datum of 733.00 ft above sea level.

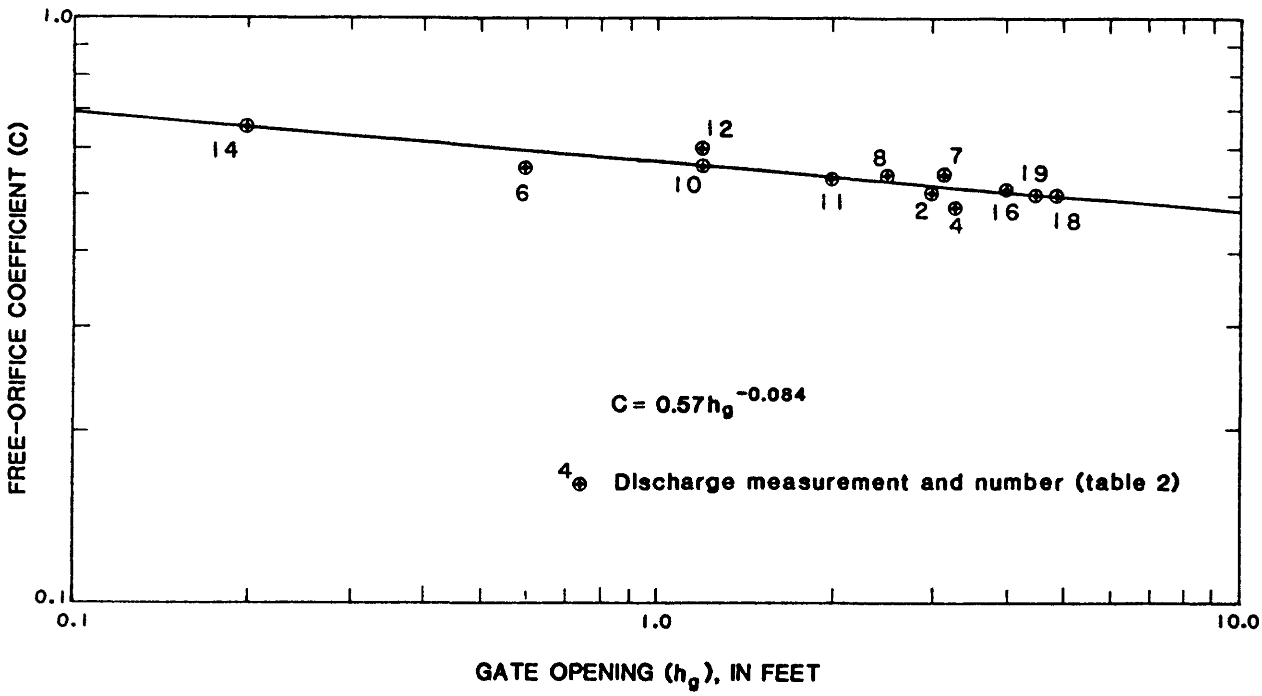

Figure 8.--Relation between discharge coefficient for free orifice flow and sluice-gate opening.

Discharge for free orifice flow under the five sluice gates is computed by combining equation 1 in table 1 with equation 8. The resulting equation of discharge is

$$Q = 314\ (h_g)^{0.916}\ (h_1)^{0.5} \qquad (9)$$

where h_g is sluice-gate opening and h_1 is headwater depth above the sluice-gate sill. The relation between upstream-pool stage, gate opening, and discharge is presented in table 5.

Measurements 21 and 22 were made during submerged orifice flow. The submergence ratio (h_3/h_g) for measurement 21 was 1.50 with a coefficient of 0.59. Measurement 22 had a submergence ratio of 1.33 and a coefficient of 0.67. The relation between the discharge coefficient for submerged orifice flow and submergence ratio is illustrated in figure 9. The resulting equation relating the discharge coefficient for submerged orifice flow to the submergence ratio (h_3/h_g) is

$$C_s = 0.89\ (h_3/h_g)^{-1.00}. \qquad (10)$$

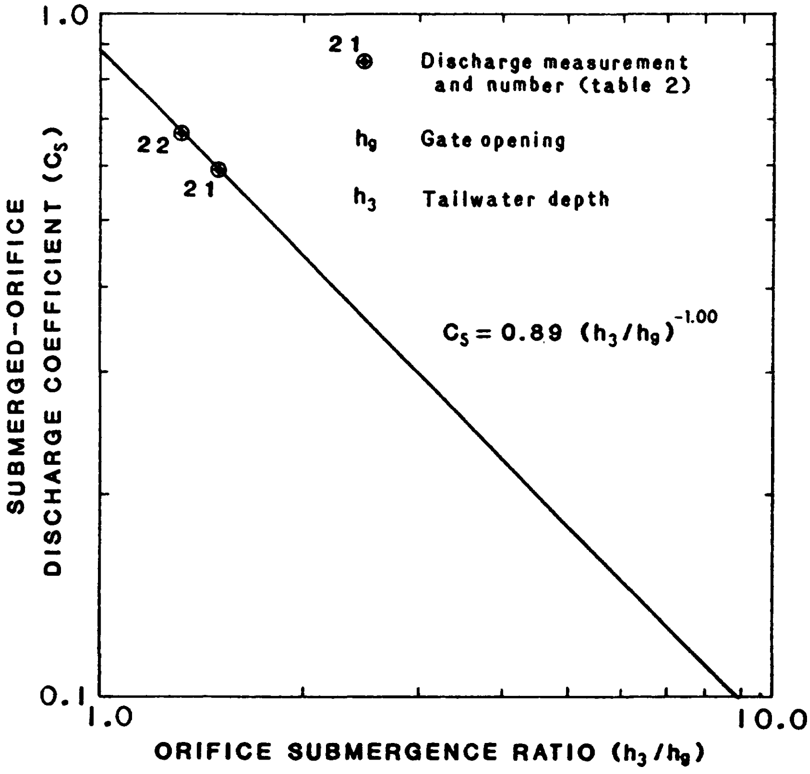

Figure 9.--Relation between discharge coefficient for submerged orifice flow and submergence ratio for sluice gates.

Table 5.--Discharge rating table for free orifice flow under five sluice gates set to same gate opening

[Free orifice flow does not occur in the areas marked by dashed lines]

Upstream pool stage, in feet[1]	Gate openings, in feet													
	0.1	0.2	0.4	0.6	0.8	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
	Discharge, in cubic feet per second													
1.0	64	121	229	332	432	530	768	1,000	---	---	---	---	---	---
1.2	67	126	237	343	447	548	795	1,030	---	---	---	---	---	---
1.4	69	130	244	355	462	566	821	1,070	---	---	---	---	---	---
1.6	71	134	252	365	475	583	845	1,100	1,340	---	---	---	---	---
1.8	73	137	259	376	489	600	869	1,130	1,370	---	---	---	---	---
2.0	75	141	266	386	502	616	893	1,160	1,410	---	---	---	---	---
2.2	77	145	273	396	515	632	916	1,190	1,450	---	---	---	---	---
2.4	79	148	280	406	528	647	939	1,220	1,480	1,770	---	---	---	---
2.6	80	152	286	415	540	663	960	1,250	1,520	1,810	---	---	---	---
2.8	82	155	292	424	552	677	981	1,280	1,550	1,850	---	---	---	---
3.0	84	158	299	433	564	691	1,000	1,300	1,580	1,890	2,180	---	---	---
3.2	86	162	305	442	575	706	1,020	1,330	1,620	1,930	2,220	---	---	---
3.4	87	165	311	451	586	719	1,040	1,360	1,650	1,970	2,270	---	---	---
3.6	89	168	317	459	598	733	1,060	1,380	1,680	2,010	2,310	---	---	---
3.8	91	171	322	468	609	746	1,080	1,410	1,710	2,040	2,350	2,660	---	---
4.0	92	174	328	476	619	760	1,100	1,430	1,740	2,080	2,390	2,700	---	---
4.2	94	177	334	484	630	772	1,120	1,460	1,770	2,110	2,430	2,750	---	---
4.4	95	180	339	492	640	785	1,140	1,480	1,800	2,150	2,470	2,800	3,110	---
4.6	97	183	344	500	650	798	1,160	1,500	1,830	2,180	2,510	2,840	3,160	---
4.8	98	185	350	507	660	810	1,170	1,530	1,850	2,220	2,550	2,880	3,210	---
5.0	100	188	355	515	670	822	1,190	1,550	1,880	2,250	2,590	2,930	3,260	3,590
5.2	---	---	---	---	---	---	---	---	---	---	2,630	2,970	3,310	3,640
5.4	---	---	---	---	---	---	---	---	---	---	2,660	3,010	3,350	3,690
5.6	---	---	---	---	---	---	---	---	---	---	2,700	3,050	3,400	3,740
5.8	---	---	---	---	---	---	---	---	---	---	2,740	3,090	3,440	3,790
6.0	---	---	---	---	---	---	---	---	---	---	2,770	3,130	3,490	3,840
6.2	---	---	---	---	---	---	---	---	---	---	2,810	3,170	3,530	3,890

[1]Referenced to Survey gage datum of 733.00 ft above sea level.

Discharge for submerged orifice flow under five sluice gates set to the same opening is computed by combining equation 2 in table 1 with equation 10. The resulting equation of discharge is

$$Q = 491\ h_g\ (\Delta h)^{0.5} \tag{11}$$

where h_g is the gate opening and Δh equals the difference between the headwater depth and tailwater depth.

Submerged orifice coefficients and the submergence ratio (h_3/h_g) generally plot on logarithmic paper as a straight line when submergence ratios are greater than 2.0 (Collins, 1977). For ratios less than 2.0, coefficients may be greater than those extrapolated from the straight line relation. The discharge coefficients for submergence ratios greater than 2.0 may be greater than those illustrated in figure 9 because the submergence ratios for discharge measurements 21 and 22 were less than 2.0. Additional discharge measurements are needed to determine if the discharge coefficients for submerged orifice flow are applicable when submergence ratios (h_3/h_g) are greater than 2.0.

Evaluation of ratings

The discharge of the Fox River over the spillway and fish ladder and through the sluice gates at McHenry Dam can be calculated from records of headwater- and tailwater-pool stages and gate openings using equations of discharge for free weir, free orifice, and submerged orifice flow regimes which are summarized in table 6. Hydraulic conditions used to identify flow regimes are also summarized in table 6. Discharge for free weir and free orifice flow can also be obtained from tables 3, 4, and 5.

Table 6.--Summary of hydraulic conditions and discharge equations for different flow regimes at McHenry Dam control structures

[Q, Discharge, in cubic feet per second; h_1, headwater depths are computed by applying an adjustment factor (-3.68 ft for spillway and 1.85 ft for sluice gates) to the headwater-pool stage; h_3, tailwater depths are computed by applying an adjustment factor (-6.53 ft for spillway and -1.00 ft for sluice gates) to the tailwater-pool stage; h_g, sluice-gate opening; Δh equals h_1-h_3]

Structure	Flow regime	Hydraulic conditions	Equation of discharge	Equation number
Spillway	Free weir	$h_3/h_1 <0.6$	$Q = 847\ (h_1)^{1.59}$	(6)
Sluice gates	Free weir	$h_g \geq 0.73\ h_1$ and $h_3/h_1 <0.75$	$Q = 218\ (h_1)^{1.5}$	(7)
Sluice gates	Free orifice	$h_g<0.73\ h_1$ and $h_3<1.3\ h_g$	$Q = 3.14\ (h_g)^{0.916}\ (h_1)^{0.5}$	(9)
Sluice gates	Submerged orifice	$h_g<0.73\ h_1$ and $h_3 \geq 1.3\ h_g$	$Q = 491\ h_g\ (\Delta h)^{0.5}$	(11)

Submerged weir flow did not occur during the study; therefore, discharge coefficients were not determined. Based on observations of flow during the near-record flood of September-October 1986, it is probable that the occurrence of submerged weir flow is rare. On occasions when it could have occurred, the operating procedure of the dam prevented it.

Figure 10 compares daily discharge for the Fox River at McHenry Dam to discharge at the gaging station on the Fox River at Algonquin for selected days in the 1986 and 1987 water years. Daily discharge at McHenry Dam was computed from hourly records of headwater-pool stage, twice-daily readings of the tailwater-pool stage and gate opening, and equations 6, 7, 9, and 11. The gaging station at Algonquin is 16 miles downstream from McHenry Dam and has a drainage area of 1,403 mi^2, 12 percent larger than at McHenry Dam. The solid line in figure 10 represents a 1:1 ratio of discharges at McHenry Dam and Algonquin. Daily discharge at Algonquin is 10 to 12 percent larger than McHenry Dam, except during periods of rapidly increasing discharge at McHenry Dam. During these periods, the daily discharge at Algonquin is only 1 to 2 percent larger than at McHenry Dam, but, after the initial rise, the relation returns to the 10 to 12 percent range.

Computation of discharge

The following are examples of how discharge may be calculated using equations in table 6 and discharge from the rating tables for free orifice and free weir flow.

Example 1: The following conditions exist:

> Headwater-pool stage is 5.20 ft, tailwater pool stage is 3.0 ft, and all gates are out of the water.

Flow through the sluice gates is determined by first converting the stages to depths above the sluice-gate sill. This is done by adding the difference between headwater gage datum and the elevation of the sill (1.85) to the headwater stage and then subtracting the difference between the tailwater gage datum and the elevation of the sill (1.00) from the tailwater stage.

$$h_1 = 5.20 + 1.85 = 7.05 \text{ ft}$$

$$h_3 = 3.00 - 1.00 = 2.00 \text{ ft}$$

Because the gates are out of the water and h_3/h_1 (0.28) is less than 0.75 (table 6), free weir flow exists.

Using equation 7 from table 6, discharge is

$$\begin{aligned} Q &= 218\ (h_1)^{1.5} \\ &= 218\ (7.05)^{1.5} \\ &= 4{,}080\ \text{ft}^3/\text{s}. \end{aligned}$$

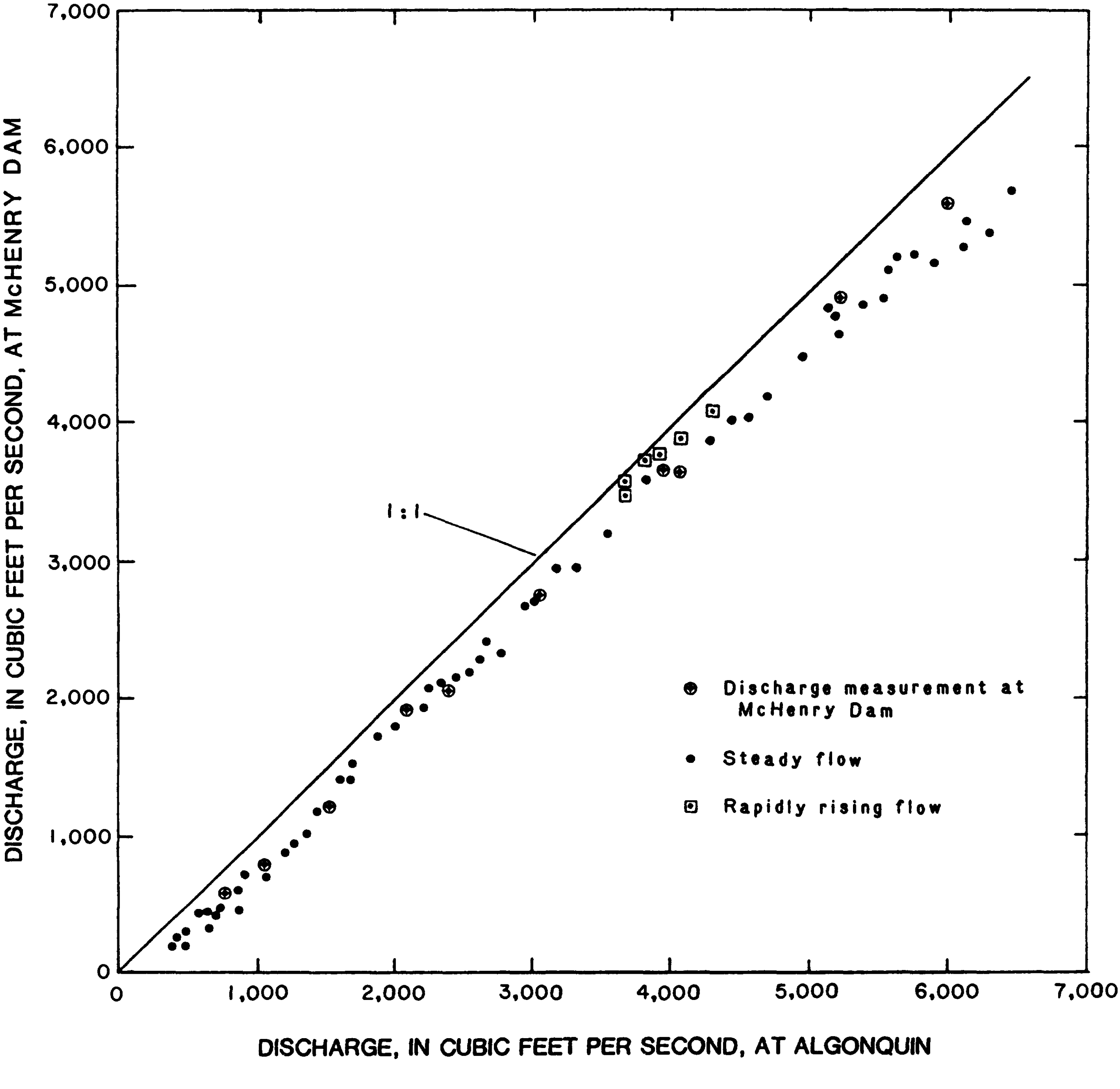

Figure 10.--Daily discharges for Fox River at McHenry Dam and Fox River at Algonquin for selected days during the data-collection period.

Flow over the spillway and through the fish ladder is determined by first converting the headwater stage to depth above the spillway crest. This is done by subtracting the difference between headwater gage datum and the elevation of the spillway crest (3.68) from the headwater stage reading,

$$h_1 = 5.20 - 3.68 = 1.52 \text{ ft},$$

and using equation 6 from table 6. The discharge is

$$\begin{aligned} Q &= 847\ (h_1)^{1.59} \\ &= 847\ (1.52)^{1.59} \\ &= 1{,}650\ \text{ft}^3/\text{s}. \end{aligned}$$

$$\text{Total discharge} = 4{,}080 + 1{,}650 = 5{,}730\ \text{ft}^3/\text{s}.$$

Alternately, the discharge may be computed from tables 3 and 4 for a headwater-pool stage of 5.20 ft.

Free weir flow over the spillway = 1,650

Free weir flow under the sluice gates = 4,080

Total discharge = 5,730 ft^3/s.

Example 2: The following conditions exist:

Headwater-pool stage is 3.68 ft, tailwater-pool stage is 3.70 ft, and five gates are set to 3.0 ft each.

First, pool stages must be converted to depths above the sluice-gate sill.

$$h_1 = 3.68 + 1.85 = 5.55 \text{ ft}$$

$$h_3 = 3.70 - 1.00 = 2.70 \text{ ft}$$

Because h_g/h_1 (0.54) is less than 0.73 and h_3/h_g (0.90) is less 1.30 (table 6), free orifice flow exists.

Using equation 9 in table 6, the discharge is

$$\begin{aligned} Q &= 314\ (h_g)^{0.916}\ (h_1)^{0.5} \\ Q &= 314\ (3.0)^{0.916}\ (5.55)^{0.5} \\ Q &= 2{,}020\ \text{ft}^3/\text{s}. \end{aligned}$$

Alternately, the discharge may be computed from table 6 for an upstream-pool stage of 3.68 ft.

Free orifice flow under five sluice gates = 2,020 ft^3/s.

Example 3: The following conditions exist:

Headwater-pool stage is 5.90 ft, tailwater-pool stage is 6.98 ft, and five gates are set to 4.0 ft each.

First, the pool stages must be converted to depths above the sluice-gate sill.

$$h_1 = 5.90 + 1.85 = 7.75 \text{ ft}$$

$$h_3 = 6.98 - 1.00 = 5.98 \text{ ft}$$

$$\Delta h = 1.77 \text{ ft}$$

Because h_g/h_1 (0.52) is less than 0.73 and h_3/h_g (1.50) is greater than 1.30 (table 6), submerged orifice flow exists.

Using equation 11 from table 6, the discharge is

$$Q = 491\, h_g\, (\Delta h)^{0.5}$$

$$= (491)(4.00)(1.77)^{0.5}$$

$$= 2{,}610 \text{ ft}^3/\text{s}.$$

Flow over the spillway and fish ladder is determined by converting the headwater-pool elevation to depth above the spillway crest,

$$h_1 = 5.90 - 3.68 = 2.22 \text{ ft},$$

and using equation 6 from table 6, the discharge is

$$Q = 847\, (h_1)^{1.59}$$

$$Q = 847\, (2.22)^{1.59}$$

$$Q = 3{,}010 \text{ ft}^3/\text{s}.$$

$$\text{Total discharge} = 2{,}610 + 3{,}010 = 5{,}620 \text{ ft}^3/\text{s}.$$

SUMMARY AND CONCLUSIONS

Twenty-three discharge measurements were used to develop discharge ratings for the control structures at McHenry Dam on the Fox River. Discharge ratings were developed for free weir flow over the spillway and fish ladder; and free weir, free orifice, and submerged orifice flow under the sluice gates. Hydraulic conditions that identify flow regimes at McHenry Dam were defined by ratios between headwater depth (h_1), tailwater depth (h_3), and gate opening (h_g). Flow under the sluice gates was identified as weir flow when the ratio of gate opening (h_g) to headwater depth (h_1) is greater than 0.73 and as orifice flow when h_g/h_1 is less than 0.73. Free orifice flow occurs when the ratio of tailwater depth (h_3) to gate opening (h_g) is less than 1.3, and submerged orifice flow occurs when h_g/h_3 is greater than 1.3. Flow under the sluice gates was identified as free weir flow when the ratio of tailwater depth (h_3) to headwater depth (h_1) is less than 0.75 and as submerged weir flow when h_3/h_1 is greater than 0.75. Flow over the spillway was identified as free weir flow when the ratio of tailwater depth (h_3) to headwater depth (h_1) is less than 0.60 and as submerged weir flow when h_3/h_1 is greater than 0.60.

Discharge coefficients used in equations to compute discharge were determined for free weir, free orifice, and submerged orifice flow. Equations that relate discharge coefficients to headwater depth, tailwater depth, gate opening, or a combination of these, were developed. These equations were combined with equations of flow to form discharge equations for the control structures at McHenry Dam.

Additional discharge measurements are needed to determine discharge coefficients for submerged weir flow. Additional discharge measurements are also needed to determine if the discharge coefficients for submerged orifice flow are applicable when submergence ratios (h_3/h_g) are greater than 2.0. Hydraulic conditions for submerged weir and submerged orifice flow occur only at very high streamflows and did not occur during the data-collection period of this project.

All of the measured flow regimes were used in a comparison of daily discharge with the Fox River at Algonquin. Computed daily discharges for Fox River at McHenry Dam are reasonable and consistent when compared with the computed daily discharge for Fox River at Algonquin.

REFERENCES CITED

Buchanan, T. J., and Somers, W. P., 1969, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations Book 3, Chapter A8, 65 p.

Collins, D. L., 1977, Computation of records of streamflow at control structures: U.S. Geological Survey Water-Resources Investigations 77-78, 57 p.

☆U.S. GOVERNMENT PRINTING OFFICE 1988—543-271/62103