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Control-Structure Ratings on the Fox River at McHenry and Algonquin, Illinois

Scientific Investigations Report 2009–5186

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph:
Downstream side of sluice gates, fish ladder, hinged-crest gate, and broad-crested weir on the Fox River at McHenry, Illinois.

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By Timothy D. Straub, Gary P. Johnson, Jon E. Hortness, and Joseph R. Parker

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Conversion Factors and Vertical Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Velocity	
foot per second (ft/s)	.3048	meter per second (m-/s)
	Flow rate	
cubic foot per second (ft^3/s)	.02832	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Abbreviations, Acronyms, and Symbols

ADCP	Acoustic Doppler Current Profiler
AFF	affected flow
B	length of weir, spillway, or gate
BCW	broad-crested weir
C	computed flow
C/M	ratio of computed and measured flow
Comp.	computed
C_{BCW}	free-weir coefficient for the broad-crested weir
C_{HCG}	free-weir coefficient for the hinged-crest gate
$C_{HCG\text{-}S}$	submerged-weir coefficient for the hinged-crest gate
C_{OS}	free-weir coefficient for the ogee spillway
$C_{OS\text{-}A}$	affected-weir coefficient for the ogee spillway
C_S	free-weir coefficient for the spillway, which includes flow over the hinged-crest gate set at the elevation of the ogee spillway
C_{SLO}	free-orifice coefficient for the sluice gate
$C_{SLO\text{-}S}$	submerged-orifice coefficient for the sluice gate
C_{SLW}	free-weir coefficient for the sluice gate
$C_{SLW\text{-}S}$	submerged-weir coefficient for the sluice gate
FO	free-orifice flow
FW	free-weir flow

FW-FL	free-weir flow with flow over the hinged-crest gate (crest at elevation of ogee spillway)
FW-NF	free-weir flow with no flow over the hinged-crest gate
$h_{1_{BCW}}$	headwater depth above the broad-crested weir crest
$h_{1_{HCG}}$	headwater depth above the hinged-crest gate crest
$h_{1_{OS}}$	headwater depth above the ogee spillway crest
$h_{1_{SL}}$	headwater depth above the sluice-gate sill
$h_{3_{BCW}}$	tailwater depth above the broad-crested weir crest
$h_{3_{HCG}}$	tailwater depth above the hinged-crest gate crest
$h_{3_{OS}}$	tailwater depth above the ogee spillway crest
$h_{3_{SL}}$	tailwater depth above the sluice-gate sill
$h_{g_{HCG}}$	hinged-crest gate opening referenced to the broad-crested-weir crest or ogee spillway crest
$h_{g_{SL}}$	sluice gate opening referenced to the concrete sill
HCG	hinged-crest gate
HW	headwater stage
IDNR–OWR	Illinois Department of Natural Resources–Office of Water Resources
M	measured flow
Meas.	measured
NF	no flow
p_{HCG}	height of hinged-crest gate crest above approach invert
R^2	coefficient of determination
OS	ogee spillway
SL	sluice gate
SO	submerged-orifice flow
SW	submerged-weir flow
TW	tailwater stage
USGS	U.S. Geological Survey
WY	water year

Control-Structure Ratings on the Fox River at McHenry and Algonquin, Illinois

By Timothy D. Straub, Gary P. Johnson, Jon E. Hortness, and Joseph R. Parker

Abstract

The Illinois Department of Natural Resources–Office of Water Resources operates control structures on a reach of the Fox River in northeastern Illinois between McHenry and Algonquin. The structures maintain water levels in the river for flood-control and recreational purposes. This report documents flow ratings for hinged-crest gates, a broad-crested weir, sluice gates, and an ogee spillway on the control structures at McHenry and Algonquin. The ratings were determined by measuring headwater and tailwater stage along with streamflow at a wide range of flows at different gate openings. Standard control-structure rating techniques were used to rate each control structure.

The control structures at McHenry consist of a 221-feet(ft)-long broad-crested weir, a 4-ft-wide fish ladder, a 50-ft-wide hinged-crest gate, five 13.75-ft-wide sluice gates, and a navigational lock. Sixty measurements were used to rate the McHenry structures. The control structures at Algonquin consist of a 242-ft-long ogee spillway and a 50-ft-wide hinged-crest gate. Forty-one measurements were used to rate the Algonquin control structures.

Introduction

The Illinois Department of Natural Resources–Office of Water Resources (IDNR–OWR) operates control structures on a reach of the Fox River in northeastern Illinois between McHenry and Algonquin (fig. 1). The McHenry control structure is at river mile 97.8 and has a drainage area of 1,250 mi^2. The Algonquin control structure is at river mile 81.6 and has a drainage area of 1,403 mi^2 (fig. 1). Hinged-crest gates were installed at both structures in 2002, to allow more streamflow through the structures than was previously possible. This enhanced capability has had appreciable effects on the protocols for operating the control structures. To better understand these effects, a study was done during 2002–2008 by the U.S. Geological Survey (USGS), in cooperation with the IDNR–OWR.

Purpose and Scope

This report documents development of flow ratings for hinged-crest gates, a broad-crested weir, sluice gates, and an ogee spillway on the Fox River control structures at McHenry and Algonquin, Illinois. Streamflow data collected during water years 2003–2008 are summarized and used in the analysis. Also, historic streamflow data at McHenry were used to aid in documenting the effects of the broad-crested weir and sluice gates.

Streamflow During Study Period

Statistical streamflow summaries at USGS streamflow gaging station (05550000) on the Fox River at Algonquin, Illinois, during the study for water years (WY) 2003–2008 are presented in table 1 and compared to statistics for the full period of record (WY 1916–2008) at this station. A water year (WY) is the 12-month period from October 1 through September 30 and is designated by the calendar year in which it ends and includes 9 of 12 months. For example, WY 2004 is from October 1, 2003, to September 30, 2004. The summary shows that both low and high streamflows occurred during the data-collection period, including the highest daily mean and peak flows.

Approach

The Fox River control-structure ratings were determined by measuring headwater (HW) and tailwater (TW) stage along with streamflow at a wide range of flows at different gate openings. The HW and TW streamflow gaging stations used on the Fox River near McHenry were 05549500 and 05549501, respectively. The HW and TW stations were installed in 1941 and 1987, respectively. The stations were operated as stage-only with miscellaneous streamflow measurements during 1985, 1986, 1991, 1993, and 2002–2008. The 1985 and 1986 streamflow measurements also included TW measurements consistent with the datum for the TW station. The HW and TW stations used on the Fox River at

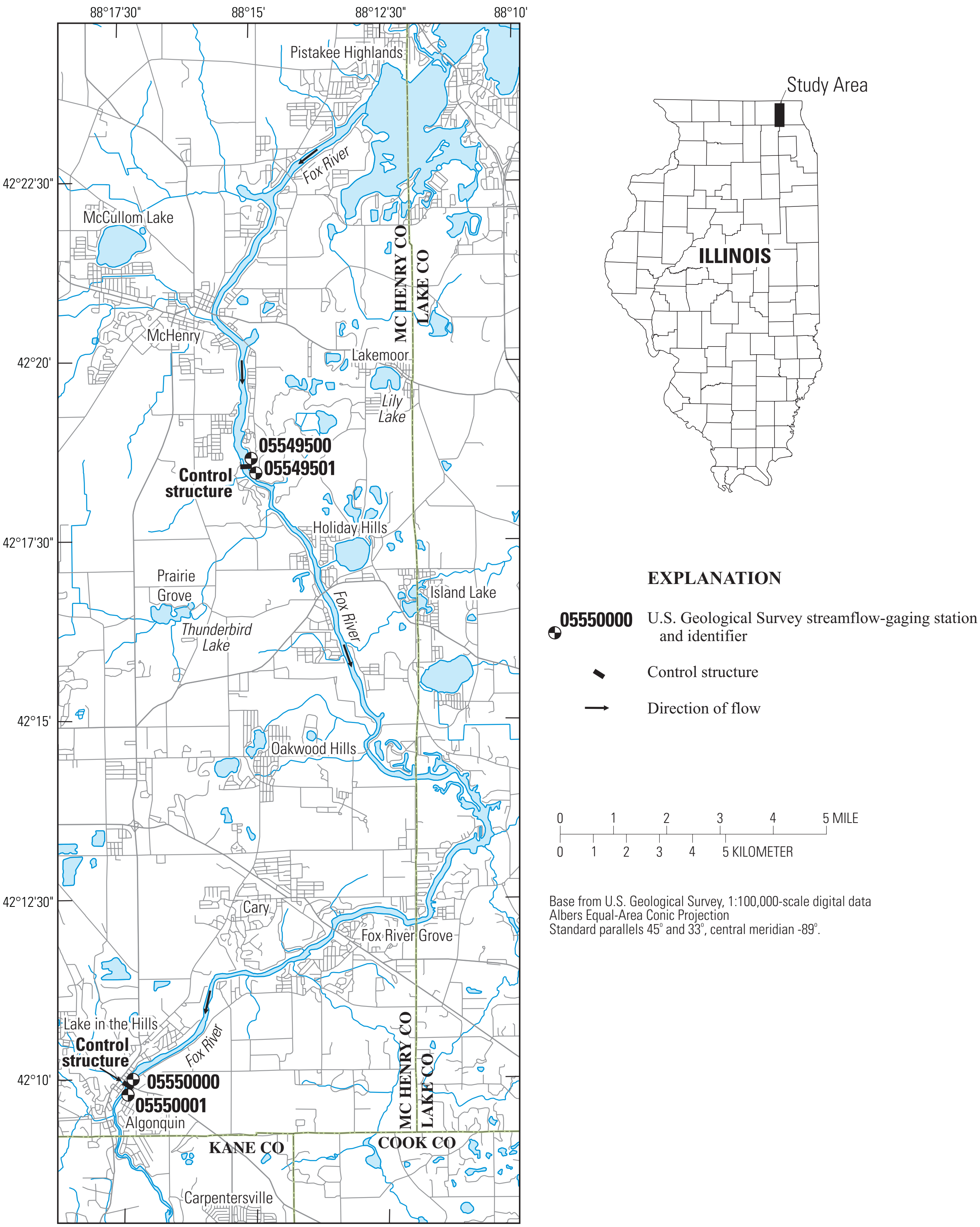


Figure 1. Location of Fox River control structures at McHenry and Algonquin, Illinois.

Table 1. Statistical summary of streamflow on the Fox River at Algonquin, Illinois, at USGS streamflow-gaging station 0555000.

[ft³/s, cubic foot per second; WY, water year]

Water year	Annual mean flow (ft³/s)	Daily mean flow				Maximum peak flow	
		Highest		Lowest			
		Streamflow (ft³/s)	Date	Streamflow (ft³/s)	Date	Streamflow (ft³/s)	Date
WY2003	516	2,000	May 13,14	90	Sep. 6	2,040	May 10,12–14
WY2004	1,118	6,020	May 31	110	Oct. 3	6,720	May 22
WY2005	665	*2,500	Feb. 19–21	89	Jul. 18	2,600	Feb. 18
WY2006	877	3,200	Mar. 17	140	Oct. 30	3,710	Mar. 14
WY2007	1,673	6,690	Aug. 26	423	Jul. 25	6,720	Aug. 25
WY2008	2,045	6,030	Jun. 19	449	Sept. 2	6,080	Jun. 19
WY1916–2008	910	6,690	Aug. 26, 2007	12	A	6,720	B

*estimated
A–Apr.6, 1960; Apr. 2, 1979
B–May 22, 2004; Aug. 25, 2007

Algonquin, were 05550000 and 05550001, respectively. The HW and TW gaging stations were installed in 1916 and 2002, respectively. Streamflow has been measured at the HW station since 1916.

To minimize the drawdown effect on the HW stage, the HW stations at the McHenry and Algonquin control structures are approximately 275 and 140 ft upstream of the structures, respectively. For the 50-ft-wide hinged-crest gates at both control structures, the upstream distances are greater than two times the contraction width recommended for a completely eccentric contraction with all flow on one bank (Matthai, 1967). The TW stage gages at both control structures are located beyond the influence of the hinged-crest gate and beyond the influence of the sluice gates at McHenry. Streamflow measurements were made for a wide range of streamflows and gate openings. Standard control-structure-rating techniques described in Chow (1959), Collins (1977), and Roberson and others (1998) were used to rate each structure.

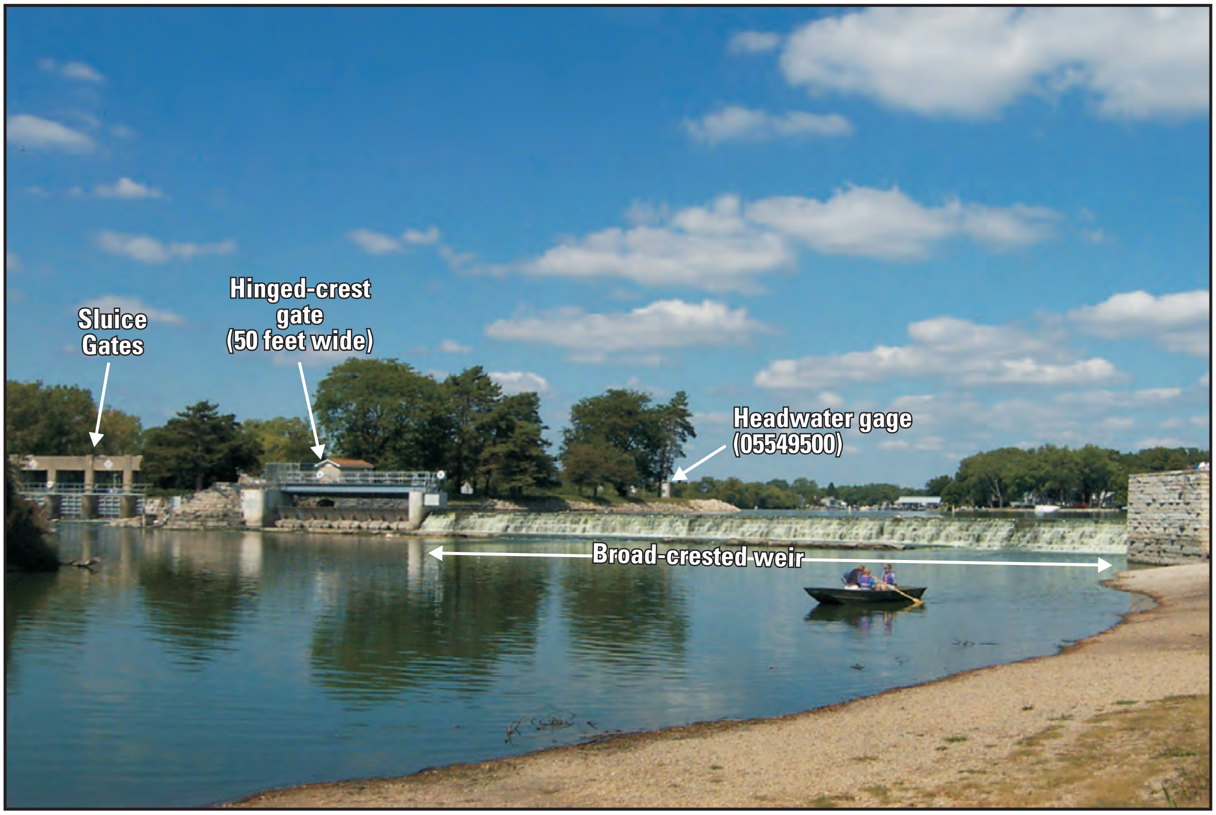
Previous Studies

To optimize the operational procedures of the gate structures for recreational and flood-control purposes, a hydraulic model (Franz and Melching, 1997a and 1997b) was applied to simulate flood-event scenarios on this reach of the Fox River (Knapp and Ortel, 1992). Dam-break analyses also were completed by the IDNR–OWR (Illinois Department of Natural Resources, 1999). Inputs to the hydraulic model throughout the studied reach included surveyed cross sections, slope, roughness, and stage-discharge ratings at control structures and were collected and documented by IDNR–OWR and the USGS (Illinois Department of Transportation, 1992; Fisk, 1988). The application of the hydraulic model through this reach has been calibrated and verified (Illinois Department of Natural Resources, 1999; Ishii and Turner, 1996; and Knapp and Ortel, 1992).

McHenry Control-Structure Ratings

The McHenry control structure is at river mile 97.8 on the Fox River in northeastern Illinois (fig. 1). The drainage area at the headwater gage is 1,250 mi². The 8,900 acre reservoir created by the dam is part of the Fox Chain of Lakes and is used primarily for recreation and flood control. The control structures at McHenry consist of a 221-ft broad-crested weir, a 4-ft-wide fish ladder, a 50-ft-wide hinged-crest gate, five 13.75-ft wide sluice gates, and a navigational lock (figs. 2, 3, 4, and 5). The elevations of structure components and headwater and tailwater gage datums are presented in table 2.

Figure 2. Layout of control structures on the Fox River at McHenry, Illinois.



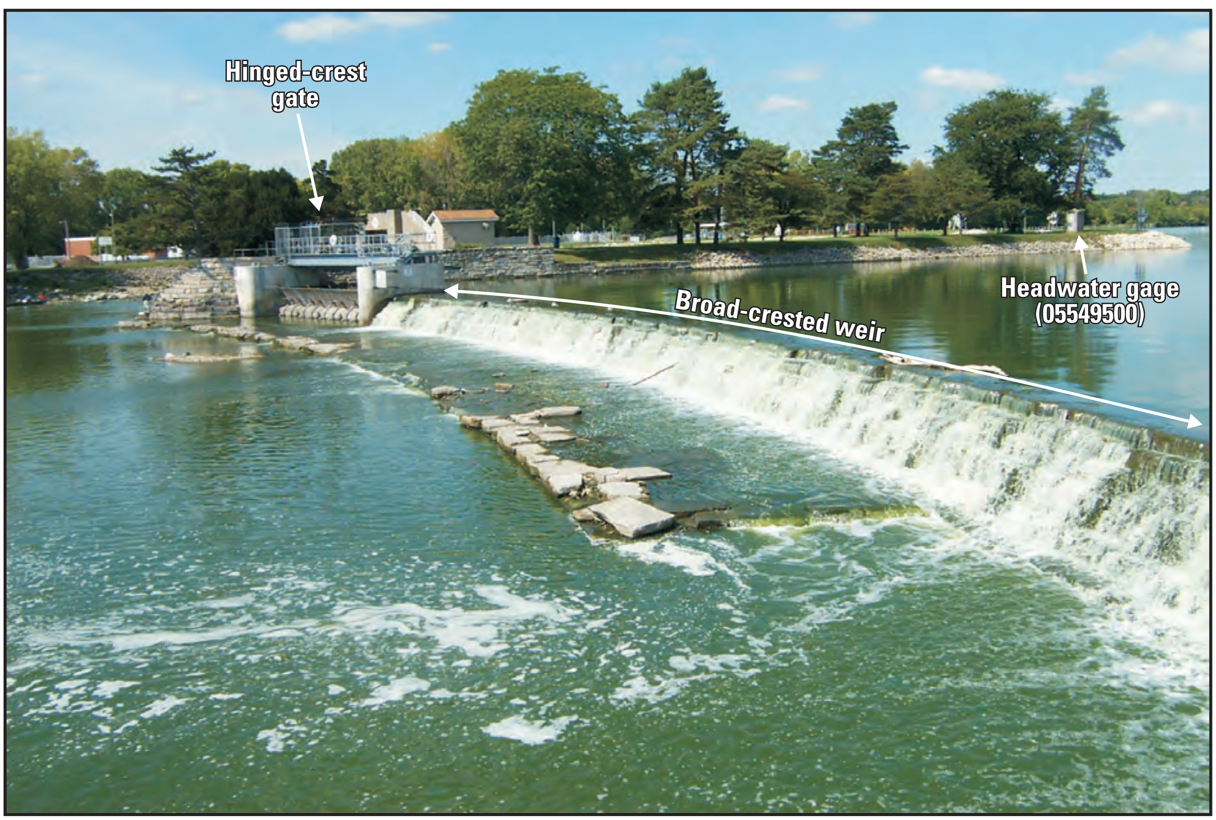


Figure 3. Downstream side of hinged-crest gate, broad-crested weir, and fish ladder on the Fox River at McHenry, Illinois.

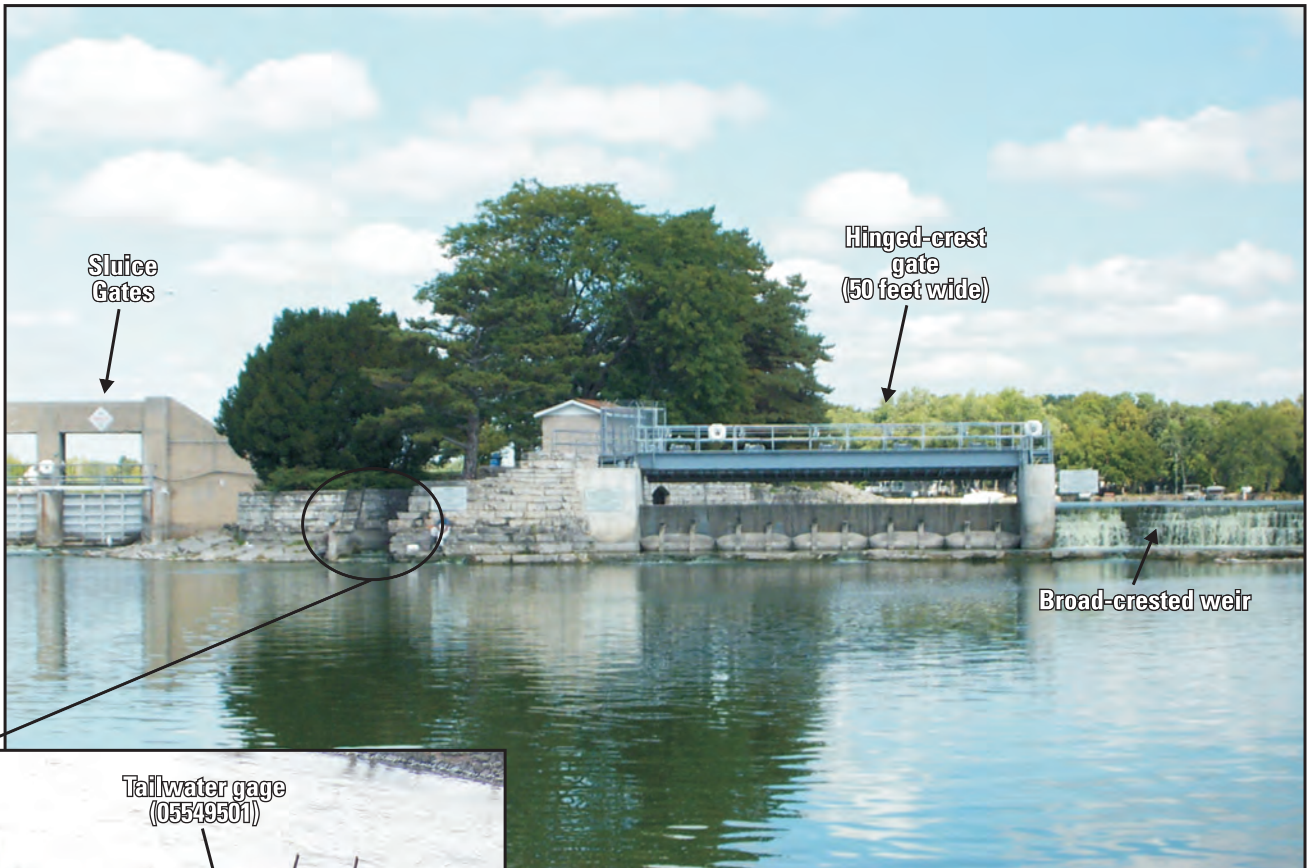
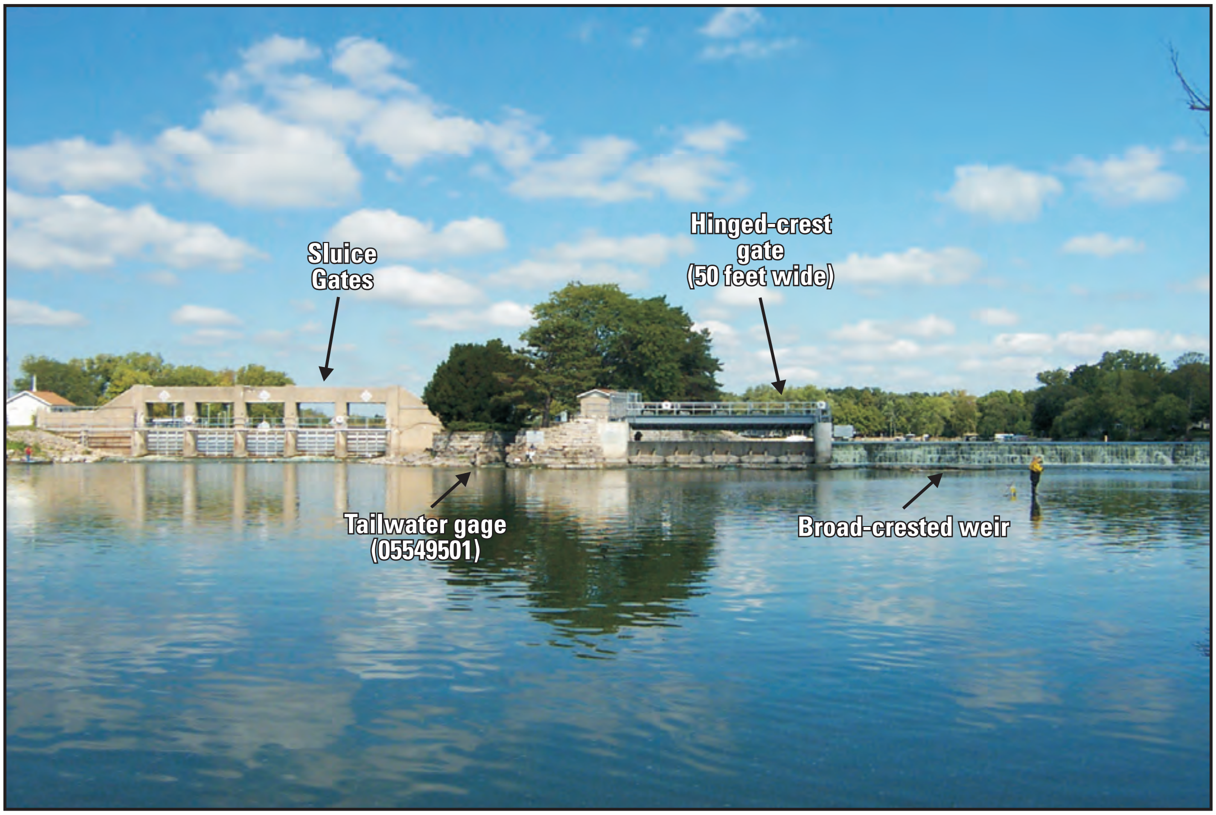


Figure 4. Fish ladder with respect to the hinged-crest gate and broad-crested weir on the Fox River at McHenry, Illinois. (Top photo looking upstream, and bottom photo looking downstream.)

Table 2. Elevation of structures and streamflow-gaging station datums on the Fox River at McHenry, Illinois.

[NGVD 1929, National Geodetic Vertical Datum of 1929]

Structure or gage	Elevation, in feet (NGVD 1929)
McHenry Dam broad-crested weir minimum crest elevation	736.68
McHenry Dam broad-crested weir average crest elevation	736.76
McHenry Dam hinged-crest gate floor elevation	730.08
McHenry Dam sluice gate concrete sill	731.15
Headwater station datum, Fox River at McHenry, Illinois	733.00
Tailwater station datum, Fox River at McHenry, Illinois	730.15



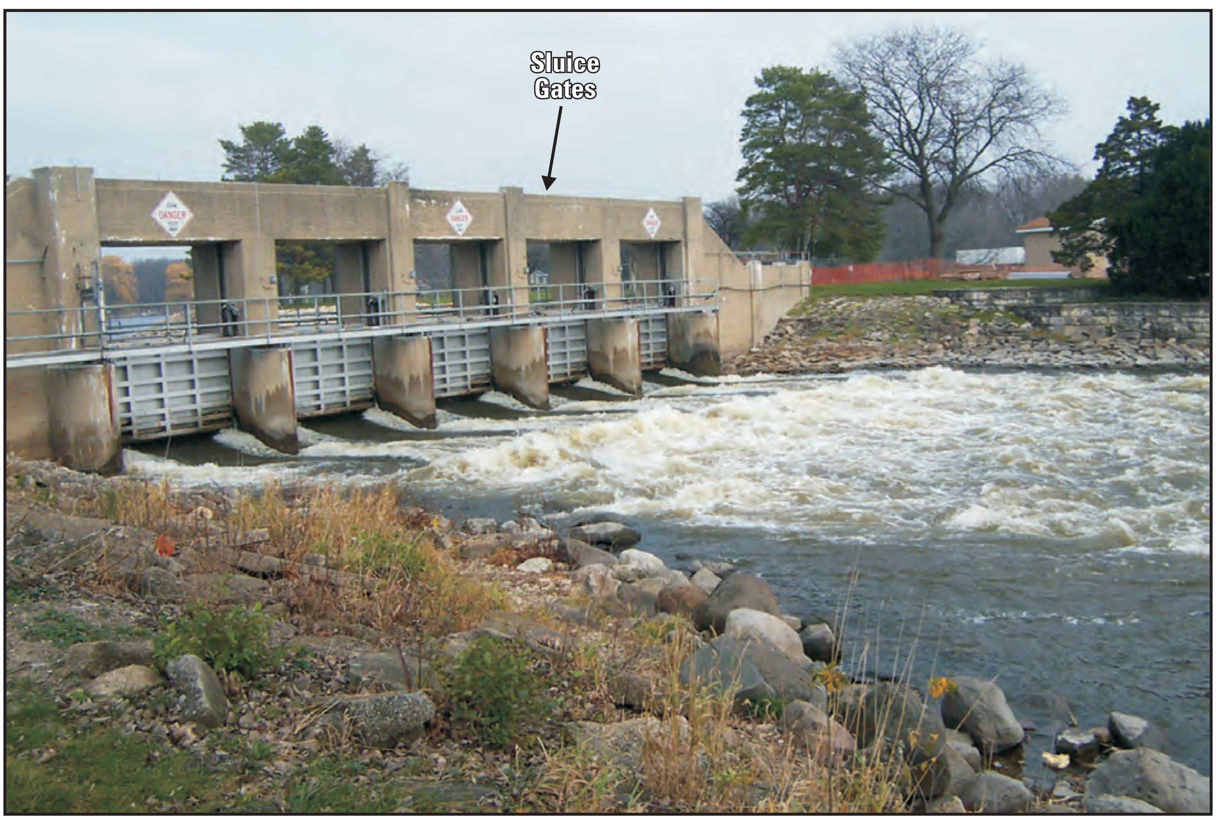


Figure 5. Downstream side of sluice gates on the Fox River near McHenry, Illinois.

Broad-Crested Weir

A side-view schematic of the broad-crested weir and parameters used in the control-structure rating are shown in figure 6. The broad-crested weir was rated by the USGS and the results were published in Fisk (1988). Streamflow measurements 5, 13, 15, and 20 listed in table 3 were used by Fisk to develop a free-weir-flow coefficient equation (fig. 7 and appendix A). A standard weir equation (equation 1 in table 4) described in Chow (1959), Collins (1977), and Roberson and others (1998) is used. Fisk used a total weir length of 288 ft, which included the fish ladder. The measured C_{BCW} in table 3 is obtained by using the measured BCW flow and measured headwater depth, and calculating for C_{BCW} from equation 1. The computed C_{BCW} in table 3 is obtained by using regression equation 2 (fig. 7 and table 4).

For the purposes of the current study, the free-weir coefficient equation is assumed valid and only the length of the weir is adjusted (221 ft for the new weir length after construction of the HCG, plus 4 ft for the fish ladder, equals 225 ft) to compute broad-crested weir flow (tables 3 and 4). The hinged-crest gate was closed with no flow over it during measurement 48. The calculated flow (173 ft^3/s) (using the modified Fisk equation (equation 3) with only the length of weir reduced) was 28 ft^3/s greater than the measured flow (145 ft^3/s) (table 3) with an average velocity of 0.102 ft/s.

As the tailwater depth increases, the submergence ratio ($h_{3_{BCW}}/h_{1_{BCW}}$) approaches unity, and the flow potentially can be overestimated using the free-weir flow equation; therefore, a submerged-flow coefficient equation may need to be developed. The greatest $h_{3_{BCW}}/h_{1_{BCW}}$ of 0.43 during a measurement occurred on August 27, 2007. Submerged flow, according to Collins (1977), occurs when the submergence ratio is equal to or greater than 0.60. Given that $h_{3_{BCW}}/h_{1_{BCW}}$ did not exceed 0.60 during the study by Fisk (1988) or during this study, the submergence ratio suggested by Collins (1977) is assumed to be applicable and no submerged-flow coefficient equation could be developed.

Table 3. Broad-crested weir flow characteristics and coefficients on the Fox River control structure near McHenry, Illinois.

[USGS, U.S. Geological Survey; BCW, broad-crested weir; HCG, hinged-crest gate; ft^3/s, cubic foot per second; $h_{1_{BCW}}$, headwater depth above the broad-crested weir crest; ft, foot; $h_{3_{BCW}}$, tailwater depth above the broad-crested weir crest; C_{BCW}, free-weir coefficient for the broad-crested weir; FW, free-weir flow; NF, no flow; ---, not determined]

USGS measurement number	Date	Measured BCW and (or) HCG flow (ft^3/s)	Broad-Crested Weir						
			$h_{1_{BCW}}$ (ft)	$h_{3_{BCW}}$ (ft)	$h_{3_{BCW}}/h_{1_{BCW}}$	Flow regime	Measured C_{BCW}	Computed C_{BCW}	Computed flow using modified Fisk[1] (ft^3/s)
5	05/16/1985	169	0.37	-5.18	-14.0	FW	2.61	2.70	---
13	08/28/1986	342	.55	-5.48	-9.96	FW	2.91	2.79	---
15	09/27/1986	1,880	1.66	-.41	-.25	FW	3.05	3.07	---
20	09/30/1986	2,990	2.22	.45	.20	FW	3.14	3.15	---
44	11/18/2002	565	.48	-5.60	-11.7	FW	---	2.76	206
45	11/19/2002	1,012	.30	-4.92	-16.4	FW	---	2.65	98
46	11/19/2002	1,345	-.06	-4.93	---	NF	---	---	0
47	11/20/2002	1,775	-.47	-4.41	---	NF	---	---	0
[A]48	04/04/2003	145	.43	-5.23	-12.2	FW	2.29	2.73	173
49	05/17/2004	803	.62	-3.03	-4.89	FW	---	2.82	310
50	05/17/2004	1,240	.38	-2.75	-7.24	FW	---	2.70	142
51	05/17/2004	2,040	.12	-2.54	-21.2	FW	---	2.44	23
52	05/24/2004	1,820	.36	-.68	-1.89	FW	---	2.69	131
53	03/17/2006	1,077	-1.04	-2.76	---	NF	---	---	0
54	03/17/2006	401	-.31	-3.22	---	NF	---	---	0
55	03/16/2007	1,132	-1.04	-2.21	---	NF	---	---	0
56	08/22/2007	1,710	-.01	-.95	---	NF	---	---	0
57	08/27/2007	2,550	1.15	.50	.43	FW	---	2.98	826
58	03/26/2008	1,440	-1.20	-2.15	---	NF	---	---	0
59	04/16/2008	1,930	.48	-.49	-1.02	FW	---	2.76	206
60	06/20/2008	2,450	1.08	.25	.23	FW	---	2.96	747

[A]No flow over hinged-crest gate. All other measurements from 2002–2008 had flow over the hinged-crest gate.

[1]Fisk (1988)

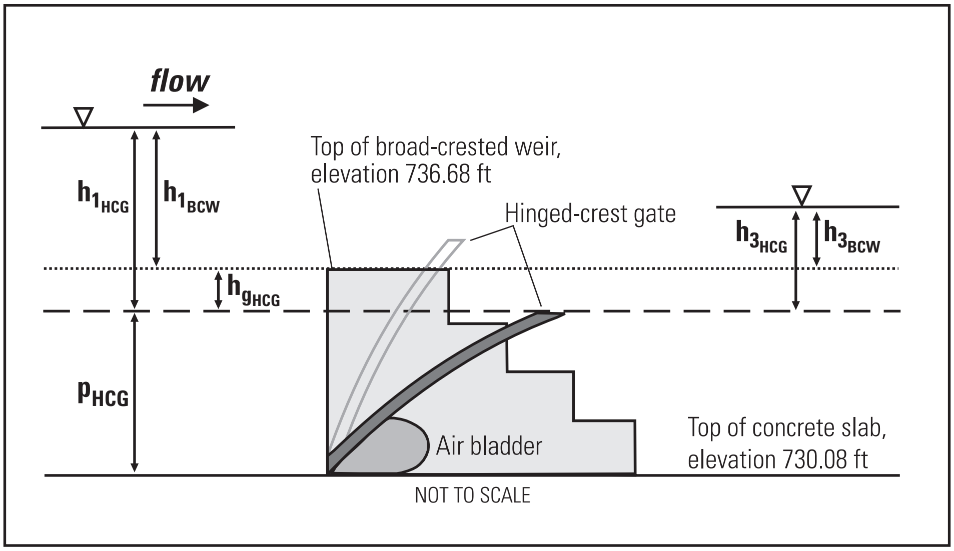


Figure 6. Schematic (side view) of hinged-crest gate and broad-crested weir on the Fox River at McHenry, Illinois (ft, foot; $h_{1_{HCG}}$, headwater depth above the hinged-crest gate crest; $h_{3_{HCG}}$, tailwater depth above the hinged-crest gate crest; $h_{g_{HCG}}$, hinged-crest gate opening referenced to the broad-crested-weir crest; p_{HCG}, height of hinged-crest gate crest above approach invert; $h_{1_{BCW}}$, headwater depth above the broad-crested weir crest; $h_{3_{BCW}}$, tailwater depth above the broad-crested weir crest).

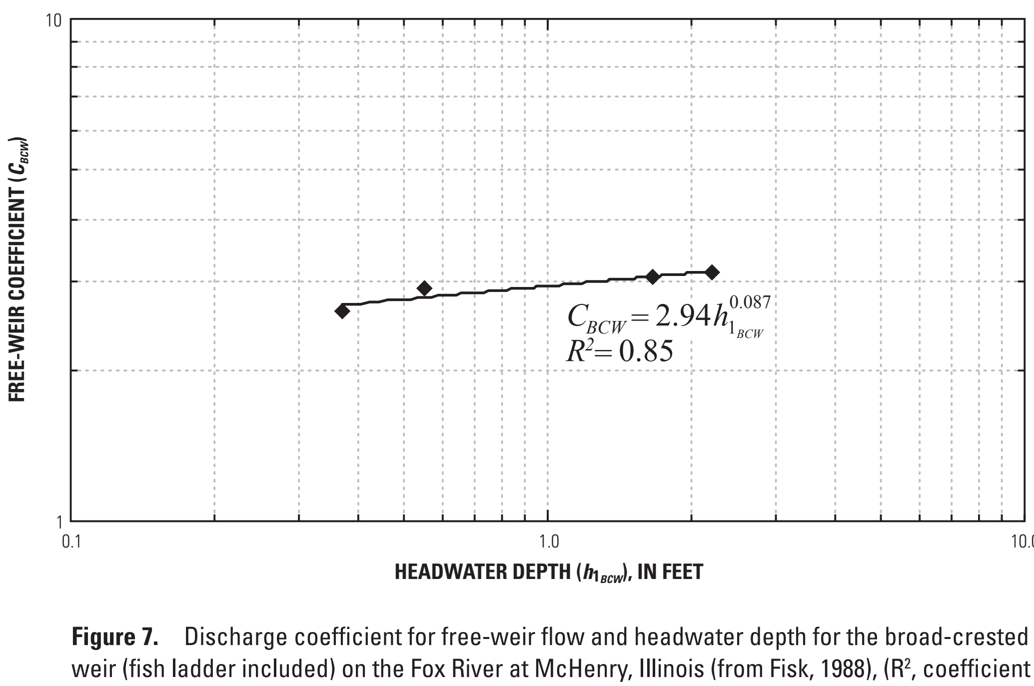


Figure 7. Discharge coefficient for free-weir flow and headwater depth for the broad-crested weir (fish ladder included) on the Fox River at McHenry, Illinois (from Fisk, 1988), (R^2, coefficient of determination).

Table 4. Hydraulic conditions, parameters, and equations for different flow regimes for the broad-crested weir and hinged-crest gate on the Fox River at McHenry, Illinois.

[$h_{3_{BCW}}$, tailwater depth above the broad-crested weir crest, in feet; $h_{1_{BCW}}$, headwater depth above the broad-crested weir crest, in feet; Q_{BCW}, flow over the broad-crested weir, in ft^3/s; C_{BCW}, free-weir coefficient for the broad-crested weir; B, length of weir or gate, in feet; $h_{3_{HCG}}$, tailwater depth above the hinged-crest gate crest, in feet; $h_{1_{HCG}}$, headwater depth above the hinged-crest gate crest, in feet; Q_{HCG}, flow through the hinged-crest gate, in ft^3/s; C_{HCG}, free-weir coefficient for the hinged-crest gate; p_{HCG}, height of hinged-crest gate crest above approach invert; C_{HCG-S}, submerged-weir coefficient for the hinged-crest gate]

Structure	Flow regime	Hydraulic conditions	Parameters and equations	Equation number
Broad-crested weir	Free weir (FW)	$\frac{h_{3_{BCW}}}{h_{1_{BCW}}} < 0.60$	$Q_{BCW} = C_{BCW} B h_{1_{BCW}}^{1.5}$	1
			$C_{BCW} = 2.94 h_{1_{BCW}}^{0.087}$	2
			$B = 225\,ft$	
			$Q_{BCW} = 661.5 h_{1_{BCW}}^{1.587}$	3
Hinged-crest gate	Free weir (FW)	$\frac{h_{3_{HCG}}}{h_{1_{HCG}}} \le 0.75$	$Q_{HCG} = C_{HCG} B h_{1_{HCG}}^{1.5}$	4
			$C_{HCG} = 3.87\left(\frac{h_{1_{HCG}}}{p_{HCG}}\right)^{-0.135}$	5
			$B = 50\,ft$	
			$Q_{HCG} = 193.5 h_{1_{HCG}}^{1.365} p_{HCG}^{0.135}$	6
Hinged-crest gate	Submerged weir (SW)	$\frac{h_{3_{HCG}}}{h_{1_{HCG}}} > 0.75$	$Q_{HCG} = C_{HCG} C_{HCG-S} B h_{1_{HCG}}^{1.5}$	7
			$C_{HCG-S} = 0.471\left(\frac{h_{3_{HCG}}}{h_{1_{HCG}}}\right)^{-2.94}$	8
			$Q_{HCG} = 91.14 h_{1_{HCG}}^{4.305} h_{3_{HCG}}^{-2.94} p_{HCG}^{0.135}$	9

Hinged-Crest Gate

A side-view schematic of the hinged-crest gate and parameters used in control structure rating are shown in figure 6. Sixteen measurements, ranging from 359 to 2,017 ft^3/s, were used to describe free and submerged flow through the hinged-crest gate. Characteristics of the flow and the measured and computed discharge coefficients are listed in table 5 and appendix A. A standard weir equation (equation 4 in table 4) described in Chow (1959), Collins (1977), and Roberson and others (1998) is used to describe flow over the hinged-crest gate. Free- and submerged-weir coefficient equations are presented in table 4, and in figures 8 and 9. The data indicate submerged flow occurs when $h_{3_{HCG}}/h_{1_{HCG}}$ is greater than 0.75.

The measured and computed broad-crested weir and hinged-crest gate flows for the control structures at McHenry are presented in table 6 and figure 10 for comparison. Thirteen of the 14 computed hinged-crest gate flows are within 10 percent of measured flows, and the remaining measurement is within 16 percent. The combined BCW and HCG flows show similar results, and all eight combined measured flows above 1,400 ft^3/s were computed within 6 percent.

Table 5. Hinged-crest gate flow characteristics and coefficients near McHenry, Illinois.

[USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; $h_{g_{HCG}}$, hinged-crest gate opening referenced to the broad-crested-weir crest; $h_{1_{HCG}}$, headwater depth above the hinged-crest gate crest; ft, foot; $h_{3_{HCG}}$, tailwater depth above the hinged-crest gate crest; p_{HCG}, height of hinged-crest gate crest above approach invert; C_{HCG}, free-weir coefficient for the hinged-crest gate; $C_{HCG\text{-}S}$, submerged-weir coefficient for the hinged-crest gate; FW, free-weir flow; SW, submerged-weir flow; HCG, hinged-crest gate; BCW, broad-crested weir; SL, sluice gate; ---, not determined]

USGS measurement number	Date	Hinged-Crest Gate											
		Measured flow[1] (ft^3/s)	Gate opening $h_{g_{HCG}}$ (ft)	$h_{1_{HCG}}$ (ft)	$h_{3_{HCG}}$ (ft)	p_{HCG} (ft)	$h_{1_{HCG}}/p_{HCG}$	$h_{3_{HCG}}/h_{1_{HCG}}$	Flow regime	Measured C_{HCG}	Computed C_{HCG}	Measured[2] $C_{HCG\text{-}S}$	Computed $C_{HCG\text{-}S}$
44	11/18/2002	359	1.0	1.48	-4.60	5.60	0.3	-3.11	FW	3.98	4.63	---	---
45	11/19/2002	914	2.2	2.50	-2.72	4.40	.6	-1.09	FW	4.63	4.18	---	---
46	11/19/2002	1,345	4.1	4.04	-.83	2.50	1.6	-.21	FW	3.31	3.63	---	---
47	11/20/2002	1,775	6.0	5.53	1.59	.60	9.2	.29	FW	2.73	2.87	---	---
49	05/17/2004	493	1.0	1.62	-2.03	5.60	.3	-1.25	FW	4.78	4.58	---	---
[A]50	05/17/2004	1,098	2.0	2.38	-.75	4.60	.5	-.32	FW	---	---	---	---
51	05/17/2004	2,017	5.0	5.12	2.46	1.60	3.2	.48	FW	3.48	3.31	---	---
52	**05/24/2004**	**1,689**	**6.0**	**6.36**	**5.32**	**.60**	**10.6**	**.84**	**SW**	**2.11**	**2.81**	**0.75**	**0.80**
53	03/17/2006	1,077	4.0	2.96	1.24	2.60	1.1	.42	FW	4.23	3.80	---	---
[B]54	03/17/2006	401	2.0	1.69	-1.22	4.60	.4	-.72	FW	---	---	---	---
[C]55	03/16/2007	1,132	4.5	3.46	2.29	2.10	1.6	.66	FW	3.52	3.62	---	---
56	**08/22/2007**	**1,710**	**6.0**	**5.99**	**5.05**	**.60**	**10.0**	**.84**	**SW**	**2.33**	**2.84**	**.82**	**.78**
57	**08/27/2007**	**1,724**	**6.0**	**7.15**	**6.50**	**.60**	**11.9**	**.91**	**SW**	**1.80**	**2.77**	**.65**	**.62**
58	**03/26/2008**	**1,440**	**5.5**	**4.30**	**3.35**	**1.10**	**3.9**	**.78**	**SW**	**3.23**	**3.22**	**1.00**	**.98**
59	**04/16/2008**	**1,724**	**6.0**	**6.48**	**5.51**	**.60**	**10.8**	**.85**	**SW**	**2.09**	**2.81**	**.74**	**.76**
60	**06/20/2008**	**1,703**	**6.0**	**7.08**	**6.25**	**.60**	**11.8**	**.88**	**SW**	**1.81**	**2.77**	**.65**	**.68**

[1]Determined by subtracting the computed BCW flow from the measured total BCW and HCG flow.

[2]Ratio of measured and computed C_{HCG}.

[A]Hinged-crest gate opening changed 30 minutes before measurement, measurement not used in equation development.

[B]Outlier, measurement not used in equation development.

[C]Total flow (BCW, HCG, and SL) measured without a separate measurement of sluice gate flow. The SL flow is calculated and subtracted from total flow.

Bold text rows indicate submerged HCG conditions.

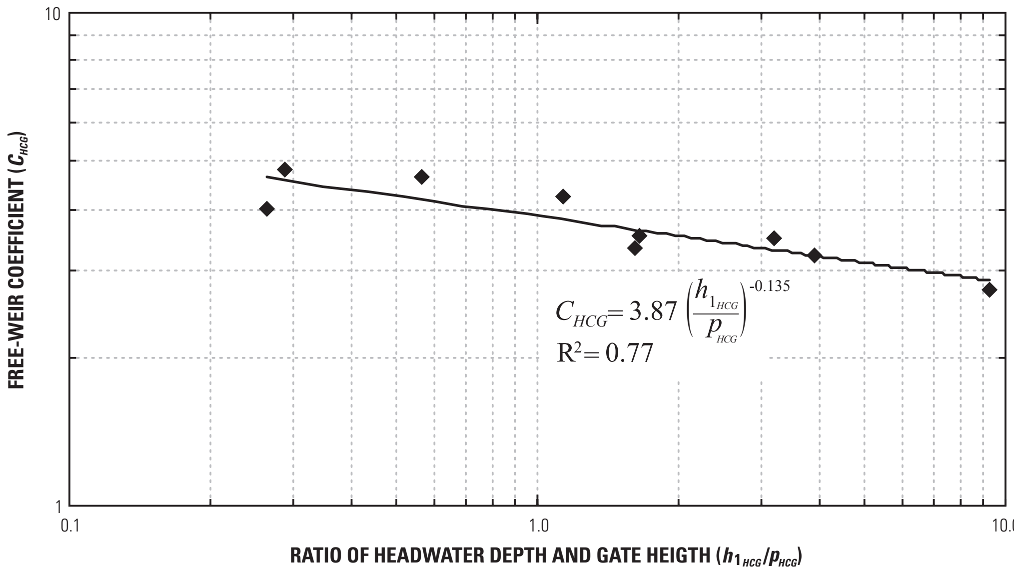


Figure 8. Discharge coefficient for free-weir flow and the ratio of headwater depth and gate height for the hinged-crest gate on the Fox River at McHenry, Illinois, (R^2, coefficient of determination).

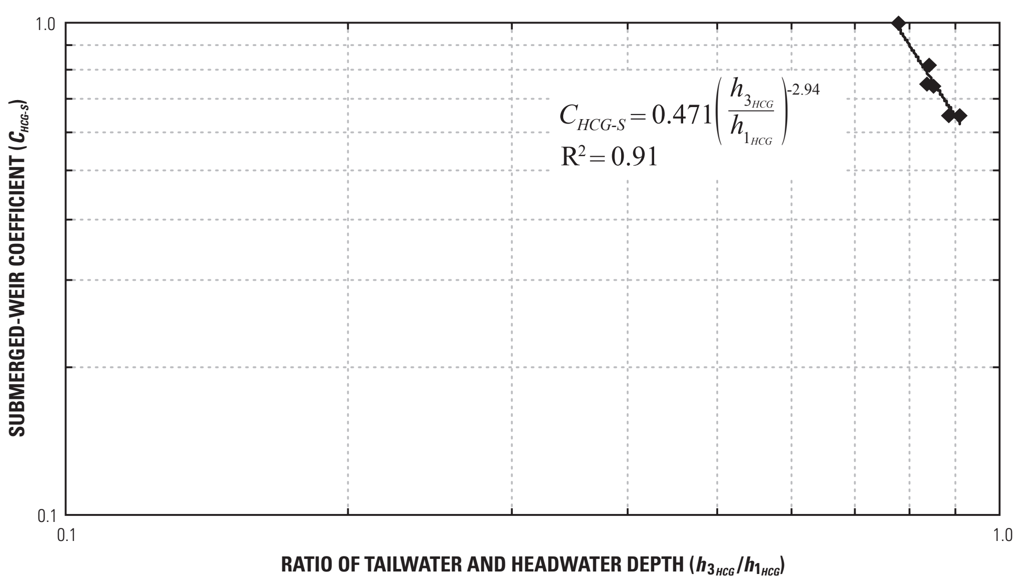


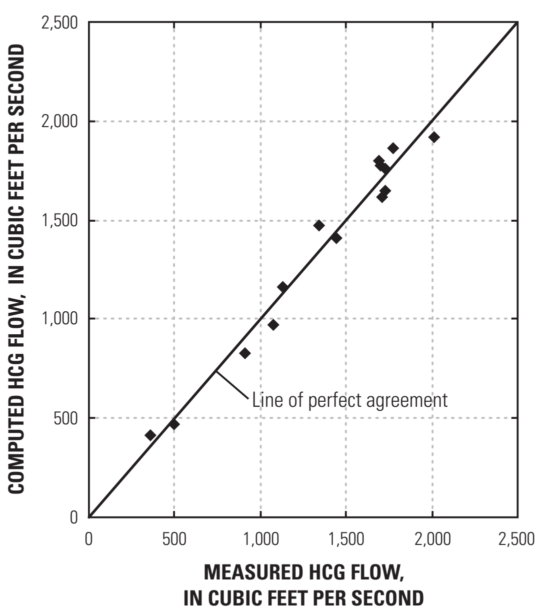
Figure 9. Discharge coefficient for submerged-weir flow and the ratio of headwater and tailwater depth for the hinged-crest gate on the Fox River at McHenry, Illinois, (R^2, coefficient of determination).

Table 6. Measured and computed flows for the broad-crested weir and hinged-crest gate near McHenry, Illinois.

[USGS, U.S. Geological Survey; BCW, broad-crested weir; ft³/s, cubic foot per second; HCG, hinged-crest gate; C/M, ratio of computed and measured flow]

USGS measurement number	Date	BCW computed flow (ft³/s)	HCG Measured flow[1] (M) (ft³/s)	HCG Computed flow (C) (ft³/s)	HCG C/M	BCW and HCG Measured flow (M) (ft³/s)	BCW and HCG Computed flow (C) (ft³/s)	BCW and HCG C/M
44	11/18/2002	206	359	417	1.16	565	623	1.10
45	11/19/2002	98	914	826	.90	1,012	924	.91
46	11/19/2002	0	1,345	1,473	1.09	1,345	1,473	1.09
47	11/20/2002	0	1,775	1,864	1.05	1,775	1,864	1.05
49	05/17/2004	310	493	472	.96	803	782	.97
51	05/17/2004	23	2,017	1,916	.95	2,040	1,939	.95
52	05/24/2004	131	1,689	1,797	1.06	1,820	1,927	1.06
53	03/17/2006	0	1,077	968	.90	1,077	968	.90
55	03/16/2007	0	1,132	1,164	1.03	1,132	1,164	1.03
56	08/22/2007	0	1,710	1,618	.95	1,710	1,618	.95
57	08/27/2007	826	1,724	1,650	.96	2,550	2,476	.97
58	03/26/2008	0	1,440	1,408	.98	1,440	1,408	.98
59	04/16/2008	206	1,724	1,756	1.02	1,930	1,962	1.02
60	06/20/2008	747	1,703	1,775	1.04	2,450	2,522	1.03

[1]Determined by subtracting the computed BCW flow from the measured total BCW and HCG flow.



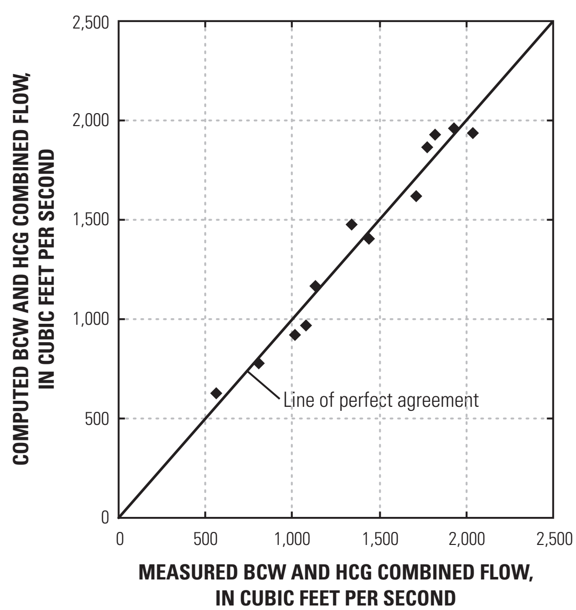


Figure 10. Measured and computed flows for the broad-crested weir and hinged-crest gate near McHenry, Illinois, (BCW, broad-crested weir; HCG, hinged-crest gate).

Sluice Gates

A side-view schematic of the sluice gates and parameters used in the control-structure rating are shown in figure 11. Fifty measurements, ranging from 64 to 4,054 ft^3/s, were used to describe free- and submerged-weir and orifice flow through the sluice gates. Characteristics of the flow and the measured and computed discharge coefficients are listed in table 7 and appendix B. Standard weir and orifice equations (table 8) described in Chow (1959), Collins (1977), and Roberson and others (1998) are used to describe flow through the sluice gates. Chow (1959) stated the following regarding the orifice equation presented in table 8:

> "For the purpose of experimental studies, … The form of this equation is the same for both free and submerged flows."

For this reason, a submergence coefficient is simply added to equation 16 (table 8) to develop the submerged-orifice equation (equation 19); Roberson and others (1998) show the same orifice equation. For the purpose of this study, the submerged-orifice equation presented by Collins (1977) and Fisk (1988) is not used.

Utilizing the measurement data, the resulting free- and submerged-weir and orifice-coefficient equations are presented in table 8, figures 12, 13, and 14. There is no figure for the free-orifice coefficient. Multiple-linear regression instead was used to develop the free-orifice coefficient equation in table 8. The coefficient of determination (R^2) for this equation (0.80) regressing $h_{g_{SL}}$ and $h_{1_{SL}}$ was 0.15 higher compared to using the ratio $h_{g_{SL}}$ and $h_{1_{SL}}$.

The data indicate the following flow-regime criteria conditions. Weir flow occurs when $h_{g_{SL}}/h_{1_{SL}}$ is greater than or equal to 0.73. Submerged-weir flow occurs when $h_{3_{SL}}/h_{1_{SL}}$ is greater than 0.80. Orifice flow occurs when $h_{g_{SL}}/h_{1_{SL}}$ is less than 0.73 and either $h_{3_{SL}}/h_{g_{SL}}$ is less than 1.0 or $h_{3_{SL}}/h_{1_{SL}}$ is less than or equal to 0.70. Submerged-orifice flow occurs when $h_{3_{SL}}/h_{g_{SL}}$ is greater than or equal to 1.0 and $h_{3_{SL}}/h_{1_{SL}}$ is greater than 0.70.

The measured and computed sluice gate flows for McHenry are presented in table 7 and figure 15 for comparison. All 50 computed sluice gate flows are within 11 percent of measured flows. All 17 measured flows above 2,000 ft^3/s were computed within 6 percent.

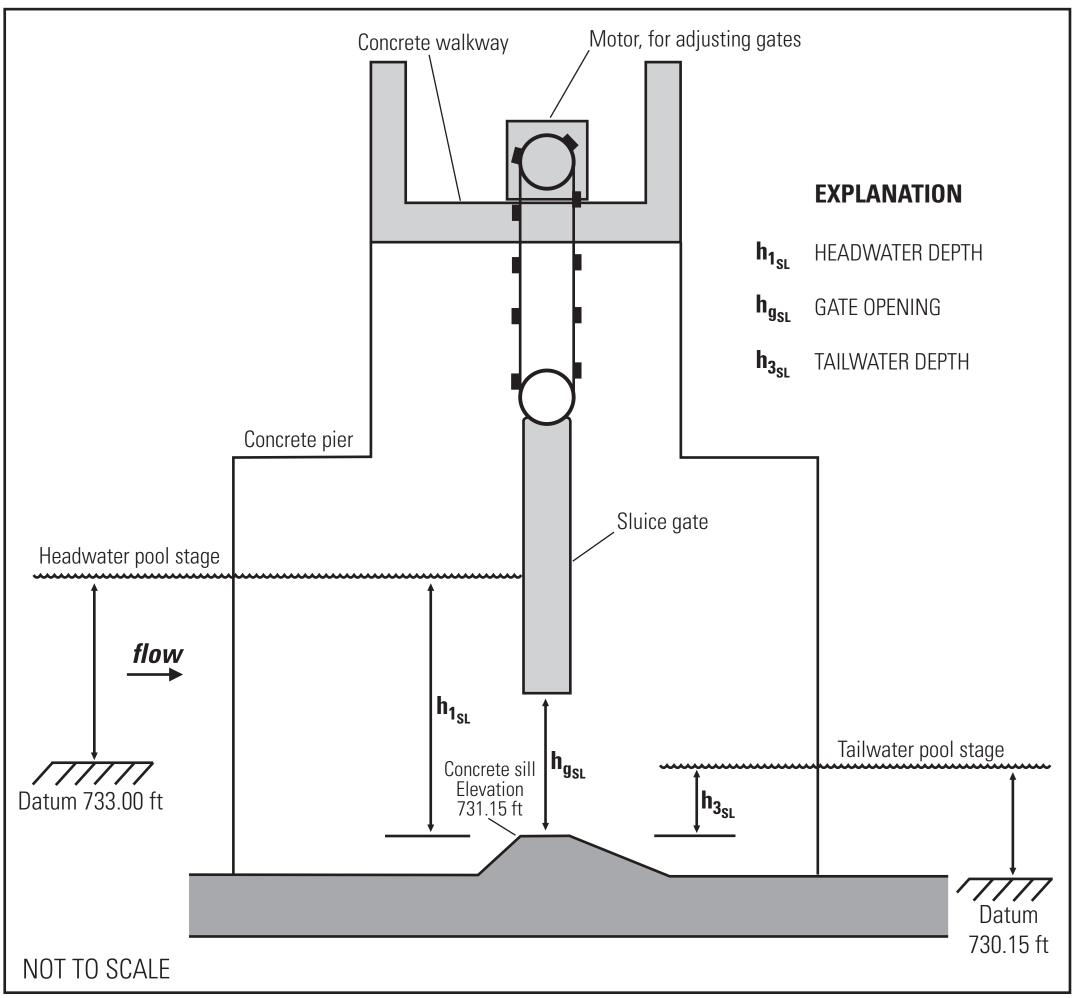


Figure 11. Schematic (side view) of sluice gates on the Fox River at McHenry, Illinois, (ft, foot).

Table 7. Sluice gate measured and computed flow characteristics and coefficients near McHenry, Illinois.

[USGS, U.S. Geological Survey; ft³/s, cubic foot per second; h_{gSL}, sluice gate opening referenced to the concrete sill; ft, foot; $h_{1_{SL}}$, headwater depth above the sluice-gate sill; $h_{3_{SL}}$, tailwater depth above the sluice-gate sill; C_{SLW}, free-weir coefficient for the sluice gate; C_{SLO}, free-orifice coefficient for the sluice gate; $C_{SLW\text{-}S}$, submerged-weir coefficient for the sluice gate; $C_{SLO\text{-}S}$, submerged-orifice coefficient for the sluice gate; C/M, ratio of computed and measured flow; FW, free-weir flow; FO, free-orifice flow; SO, submerged-orifice flow; ---, not determined]

USGS measure-ment number	Date	Measured flow (M) (ft³/s)	Gate opening h_{gSL} (ft)	h_{1SL} (ft)	h_{3SL} (ft)	h_{3SL}/h_{1SL}	h_{3SL}/h_{gSL}	h_{gSL}/h_{1SL}	Flow Regime	Measured C_{SLW} or C_{SLO}	Computed C_{SLW} or C_{SLO}	Measured $C_{SLW\text{-}S}$ or $C_{SLO\text{-}S}$	Computed $C_{SLW\text{-}S}$ or $C_{SLO\text{-}S}$	Computed flow (C) (ft³/s)	C/M
1	*03/22/1985*	*2,790*	*4.0*	*5.36*	*2.90*	*0.54*	*0.72*	*0.75*	*FW*	*3.27*	*3.17*	*---*	*---*	*2,700*	*0.97*
2	03/22/1985	1,990	3.0	5.53	2.70	.49	.90	.54	FO	.51	.53	---	---	2,052	1.03
3	*03/26/1985*	*2,100*	*3.8*	*4.49*	*2.45*	*.55*	*.64*	*.85*	*FW*	*3.21*	*3.22*	*---*	*---*	*2,108*	*1.00*
4	03/26/1985	1,850	3.3	4.56	2.42	.53	.73	.72	FO	.48	.48	---	---	1,876	1.01
6	05/16/1985	448	.6	5.88	.35	.06	.58	.10	FO	.56	.60	---	---	480	1.07
X7	10/04/1985	1,460	2.5	5.90	1.75	.30	.70	.42	FO	.54	.55	---	---	1,469	1.01
X8	11/04/1985	1,830	3.15	5.83	1.82	.31	.58	.54	FO	.55	.54	---	---	1,805	.99
9	*03/17/1986*	*3,230*	*6.5*	*6.16*	*4.03*	*.65*	*.62*	*1.06*	*FW*	*3.07*	*3.12*	*---*	*---*	*3,280*	*1.02*
10	04/22/1986	833	1.2	5.08	.71	.14	.59	.24	FO	.56	.54	---	---	803	.96
Y11	04/22/1986	1,047	2.0	4.98	.85	.17	.43	.40	FO	.53	.52	---	---	1,018	.97
Y11	04/22/1986	133	1.0	4.98	.85	.17	.85	.20	FO	---	---	---	---	---	---
12	05/23/1986	967	1.2	6.01	1.25	.21	1.04	.20	FO	.60	.58	---	---	939	.97
14	08/28/1986	180	.2	6.07	.05	.01	.25	.03	FO	.66	.65	---	---	176	.98
16	**09/27/1986**	**3,045**	**4.0**	**7.20**	**5.15**	**.72**	**1.29**	**.56**	**SO**	**.51**	**.58**	**0.89**	**0.94**	**3,229**	**1.06**
17	*09/27/1986*	*4,054*	*7.0*	*7.05*	*5.25*	*.74*	*.75*	*.99*	*FW*	*3.15*	*3.08*	*---*	*---*	*3,962*	*.98*
18	**09/27/1986**	**3,600**	**4.9**	**7.07**	**5.25**	**.74**	**1.07**	**.69**	**SO**	**.50**	**.57**	**.88**	**.83**	**3,411**	**.95**
19	**09/27/1986**	**3,320**	**4.5**	**7.11**	**5.30**	**.75**	**1.18**	**.63**	**SO**	**.50**	**.57**	**.88**	**.82**	**3,127**	**.94**
21	**09/30/1986**	**2,600**	**4.0**	**7.75**	**5.98**	**.77**	**1.50**	**.52**	**SO**	**.42**	**.60**	**.71**	**.74**	**2,719**	**1.05**
22	**09/30/1986**	**2,920**	**4.5**	**7.71**	**5.98**	**.78**	**1.33**	**.58**	**SO**	**.42**	**.59**	**.71**	**.73**	**2,973**	**1.02**
23	*10/15/1986*	*3,270*	*7.0*	*6.10*	*4.10*	*.67*	*.59*	*1.15*	*FW*	*3.16*	*3.12*	*---*	*---*	*3,236*	*.99*
24	11/01/1990	636	1.0	4.44	.32	.07	.32	.23	FO	.55	.51	---	---	597	.94
25	11/01/1990	63.9	.1	4.52	.11	.02	1.10	.02	FO	.54	.60	---	---	70	1.10
26	11/01/1990	74.4	.1	4.48	.05	.01	.50	.02	FO	.64	.59	---	---	69	.93
27	11/02/1990	73.9	.1	4.53	-.42	-.09	-4.20	.02	FO	.63	.60	---	---	70	.95
28	11/03/1990	74.1	.1	4.76	-.55	-.12	-5.50	.02	FO	.62	.61	---	---	73	.99
29	11/04/1990	75	.1	5.02	-.65	-.13	-6.50	.02	FO	.61	.62	---	---	77	1.03
30	11/04/1990	75.9	.1	5.02	-.65	-.13	-6.50	.02	FO	.61	.62	---	---	77	1.02
31	11/05/1990	82.6	.1	5.41	-.60	-.11	-6.00	.02	FO	.64	.64	---	---	83	1.00
32	11/05/1990	1,340	2.5	4.69	.74	.16	.30	.53	FO	.45	.50	---	---	1,484	1.11
33	11/05/1990	1,310	2.5	4.61	.89	.19	.36	.54	FO	.44	.49	---	---	1,461	1.11

Table 7. Sluice gate measured and computed flow characteristics and coefficients near McHenry, Illinois.—Continued

[USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; h_{gSL}, sluice gate opening referenced to the concrete sill; ft, foot; $h_{1_{SL}}$, headwater depth above the sluice-gate sill; $h_{3_{SL}}$, tailwater depth above the sluice-gate sill; C_{SLW}, free-weir coefficient for the sluice gate; C_{SLO}, free-orifice coefficient for the sluice gate; $C_{SLW\text{-}S}$, submerged-weir coefficient for the sluice gate; $C_{SLO\text{-}S}$, submerged-orifice coefficient for the sluice gate; C/M, ratio of computed and measured flow; FW, free-weir flow; FO, free-orifice flow; SO, submerged-orifice flow; ---, not determined]

USGS measurement number	Date	Measured flow (M) (ft^3/s)	Gate opening h_{gSL} (ft)	h_{1SL} (ft)	h_{3SL} (ft)	h_{3SL}/h_{1SL}	h_{3SL}/h_{gSL}	h_{gSL}/h_{1SL}	Flow Regime	Measured C_{SLW} or C_{SLO}	Computed C_{SLW} or C_{SLO}	Measured $C_{SLW\text{-}S}$ or $C_{SLO\text{-}S}$	Computed $C_{SLW\text{-}S}$ or $C_{SLO\text{-}S}$	Computed flow (C) (ft^3/s)	C/M
34	11/06/1990	1,370	2.5	4.51	1.19	0.26	0.48	0.55	FO	0.47	0.49	---	---	1,431	1.04
35	11/06/1990	1,500	2.5	4.45	1.38	.31	.55	.56	FO	.52	.49	---	---	1,413	.94
36	11/07/1990	1,360	2.5	4.54	1.52	.33	.61	.55	FO	.46	.49	---	---	1,440	1.06
37	11/07/1990	1,510	2.5	4.54	1.52	.33	.61	.55	FO	.51	.49	---	---	1,440	.95
38	11/07/1990	1,480	2.5	4.54	1.56	.34	.62	.55	FO	.50	.49	---	---	1,440	.97
39	11/08/1990	1,480	2.5	4.56	1.60	.35	.64	.55	FO	.50	.49	---	---	1,446	.98
40	11/08/1990	1,580	2.5	4.56	1.60	.35	.64	.55	FO	.54	.49	---	---	1,446	.92
41	11/09/1990	1,460	2.5	4.54	1.58	.35	.63	.55	FO	.50	.49	---	---	1,440	.99
42	*04/24/1993*	*3,920*	*6.0*	*7.02*	*2.24*	*.32*	*.37*	*.85*	*FW*	*3.07*	*3.08*	*---*	*---*	*3,938*	*1.00*
43	*04/28/1993*	*3,664*	*6.0*	*6.83*	*1.78*	*.26*	*.30*	*.88*	*FW*	*2.99*	*3.09*	*---*	*---*	*3,790*	*1.03*
49	05/17/2004	1,760	2.2	6.14	2.50	.41	1.14	.36	FO	.59	.56	---	---	1,691	.96
50	05/17/2004	1,690	2.2	5.95	2.74	.46	1.25	.37	FO	.57	.55	---	---	1,642	.97
[X]51	05/17/2004	1,250	2.2	5.62	3.00	.53	1.36	.39	FO	.54	.54	---	---	1,246	1.00
52	***05/24/2004***	***3,020***	***5.7***	***5.89***	***4.85***	***.82***	***.85***	***.97***	***SW***	***3.07***	***3.14***	***0.98***	***0.97***	***2,992***	***.99***
53	03/17/2006	1,664	3.0	4.49	2.77	.62	.92	.67	FO	.47	.48	---	---	1,691	1.02
54	03/17/2006	1,890	3.0	5.22	2.31	.44	.77	.57	FO	.50	.51	---	---	1,945	1.03
Z55	*03/16/2007*	*---*	*4.0*	*4.49*	*3.32*	*.74*	*.83*	*.89*	*FW*	*---*	*3.22*	*---*	*---*	*2,108*	*---*
56A	***08/22/2007***	***2,760***	***5.0***	***5.58***	***4.59***	***.82***	***.92***	***.90***	***SW***	***3.05***	***3.15***	***.97***	***.97***	***2,778***	***1.01***
57A	***08/27/2007***	***3,140***	***6.2***	***6.68***	***6.03***	***.90***	***.97***	***.93***	***SW***	***2.65***	***3.10***	***.85***	***.86***	***3,158***	***1.01***
58A	*03/26/2008*	*1,970*	*4.5*	*4.32*	*3.36*	*.78*	*.75*	*1.04*	*FW*	*3.19*	*3.23*	*---*	*---*	*1,997*	*1.01*
59A	***04/16/2008***	***2,960***	***5.3***	***5.99***	***5.02***	***.84***	***.95***	***.88***	***SW***	***2.94***	***3.13***	***.94***	***.95***	***2,992***	***1.01***
60A	***06/20/2008***	***3,280***	***6.0***	***6.60***	***5.76***	***.87***	***.96***	***.91***	***SW***	***2.81***	***3.10***	***.91***	***.90***	***3,247***	***.99***

[X]Four gates open, one gate closed. All other measurements had five gates open, unless otherwise noted.

[Y]Four gates were set to 2.0 ft, and one gate was set to 1.0 ft. Equations developed in this study were used to subtract flow from the gate open to 1.0 ft; a coefficient for a 2.0 ft opening was determined from the measurement.

[Z]Sluice gate flow was not measured directly. The sluice gate flow is calculated to help determine the broad-crested weir and hinged-crest gate flow.

Black plain text indicates free-orifice measurements.

Red bold text indicates submerged-orifice measurements.

Blue italic text indicates free-weir measurements.

Green bold italic text indicates submerged-weir measurements.

Table 8. Hydraulic conditions, parameters, and equations for different flow regimes for the sluice gates on the Fox River at McHenry, Illinois.

[$h_{g_{SL}}$, sluice gate opening referenced to the concrete sill, in feet; $h_{1_{SL}}$, headwater depth above the sluice-gate sill, in feet; $h_{3_{SL}}$, tailwater depth above the sluice-gate sill, in feet; Q_{SL}, flow through the sluice gates, ft³/s; C_{SLW}, free-weir coefficient for the sluice gate; B, length of gates, in feet; C_{SLW-S}, submerged-weir coefficient for the sluice gate; C_{SLO}, free-orifice coefficient for the sluice gate; C_{SLO-S}, submerged-orifice coefficient for the sluice gate]

Structure	Flow regime	Hydraulic conditions		Parameters and equations	Equation number
Sluice gate weir	Free weir (FW)	$\frac{h_{g_{SL}}}{h_{1_{SL}}} \geq 0.73$	and	$Q_{SL} = C_{SLW} B h_{1_{SL}}^{1.5}$	10
		$\frac{h_{3_{SL}}}{h_{1_{SL}}} \leq 0.80$		$C_{SLW} = 3.75 h_{1_{SL}}^{-0.101}$	11
				$B = 5 gates \times 13.75 ft = 68.75 ft$	
				$Q_{SL} = 257.8 h_{1_{SL}}^{1.401}$	12
Sluice gate weir	Submerged weir	$\frac{h_{g_{SL}}}{h_{1_{SL}}} \geq 0.73$	and	$Q_{SL} = C_{SLW} C_{SLW-S} B h_{1_{SL}}^{1.5}$	13
		$\frac{h_{3_{SL}}}{h_{1_{SL}}} > 0.80$		$C_{SLW-S} = 0.750 \left(\frac{h_{3_{SL}}}{h_{1_{SL}}}\right)^{-1.33}$	14
				$Q_{SL} = 193.4 h_{1_{SL}}^{2.731} h_{3_{SL}}^{-1.33}$	15
Sluice gate orifice	Free orifice	$\frac{h_{g_{SL}}}{h_{1_{SL}}} < 0.73$	and	$Q_{SL} = C_{SLO} B h_{g_{SL}} \left(2 g h_{1_{SL}}\right)^{0.5}$	16
		$\frac{h_{3_{SL}}}{h_{g_{SL}}} < 1$	or	$C_{SLO} = 0.271 h_{1_{SL}}^{0.429} h_{g_{SL}}^{-0.062}$	17
		$\frac{h_{3_{SL}}}{h_{1_{SL}}} \leq 0.70$		$B = 5 gates \times 13.75 ft = 68.75 ft$	
				$g = 32.2 ft / s^2$	
				$Q_{SL} = 149.5 h_{1_{SL}}^{0.929} h_{g_{SL}}^{0.938}$	18
Sluice gate orifice	Submerged orifice	$\frac{h_{g_{SL}}}{h_{1_{SL}}} < 0.73$	and	$Q_{SL} = C_{SLO} C_{SLO-S} B h_{g_{SL}} \left(2 g h_{1_{SL}}\right)^{0.5}$	19
		$\frac{h_{3_{SL}}}{h_{g_{SL}}} \geq 1$	and	$C_{SLO-S} = 0.325 \left(\frac{h_{3_{SL}}}{h_{1_{SL}}}\right)^{-3.17}$	20
		$\frac{h_{3_{SL}}}{h_{1_{SL}}} > 0.70$		$Q_{SL} = 48.6 h_{1_{SL}}^{4.099} h_{g_{SL}}^{0.938} h_{3_{SL}}^{-3.17}$	21

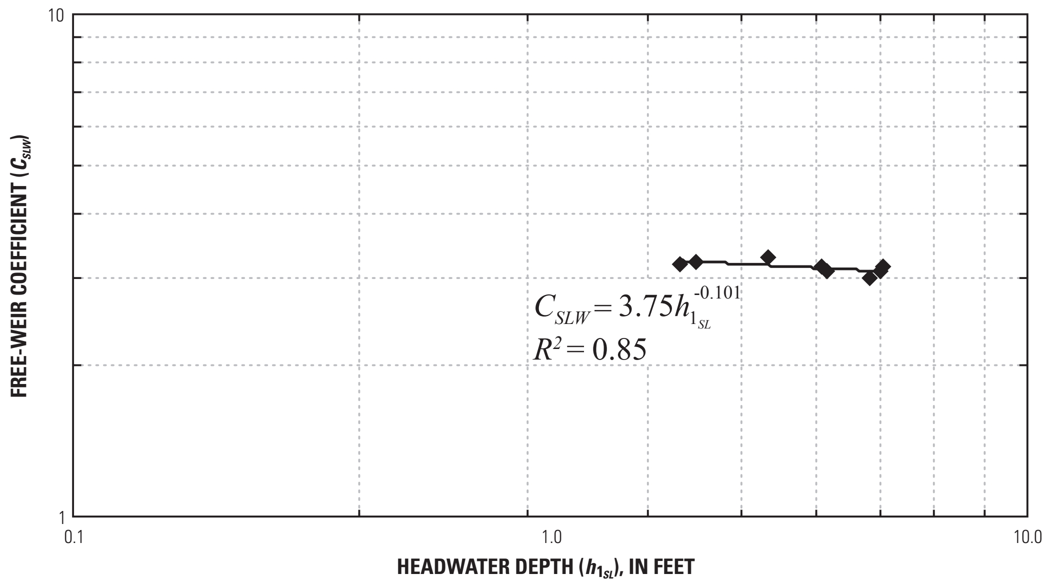


Figure 12. Discharge coefficient for free-weir flow and headwater depth for sluice gates on the Fox River at McHenry, Illinois, (R^2, coefficient of determination).

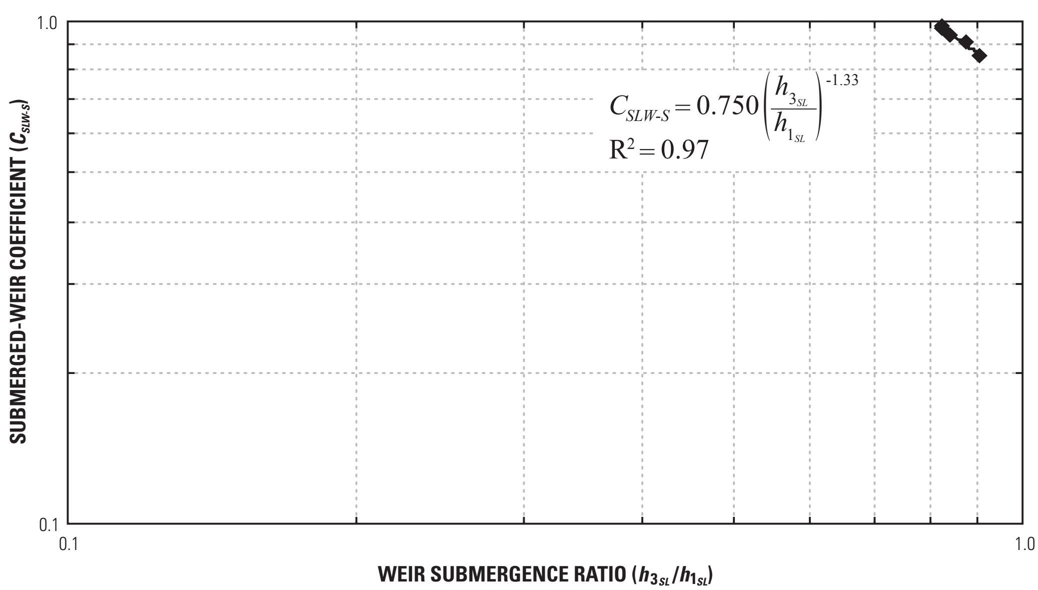


Figure 13. Discharge coefficient for submerged-weir flow and ratio of tailwater and headwater depth for sluice gates on the Fox River at McHenry, Illinois, (R^2, coefficient of determination).

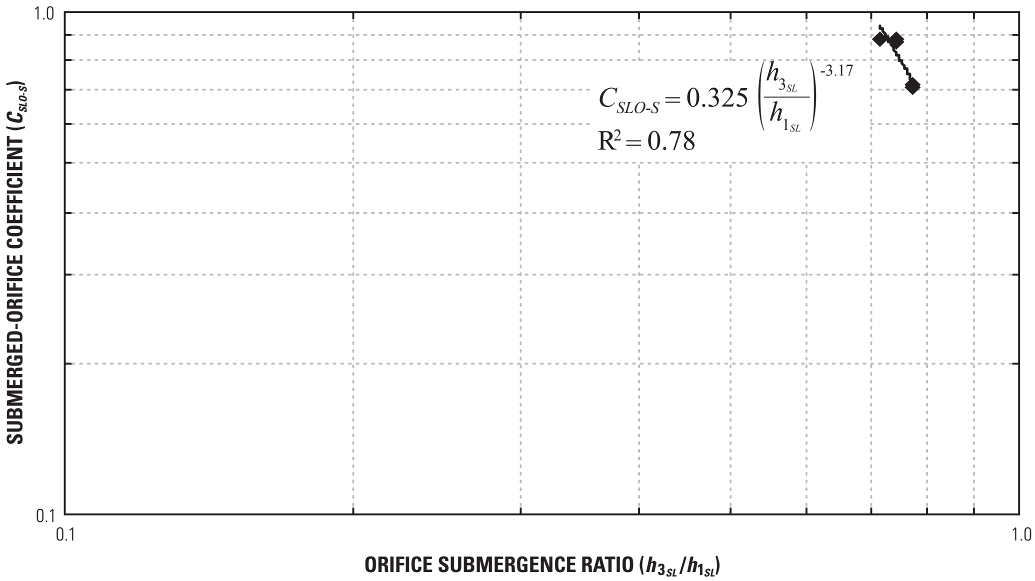


Figure 14. Discharge coefficient for submerged-orifice flow and submergence ratio for sluice gates on the Fox River at McHenry, Illinois, (R^2, coefficient of determination).

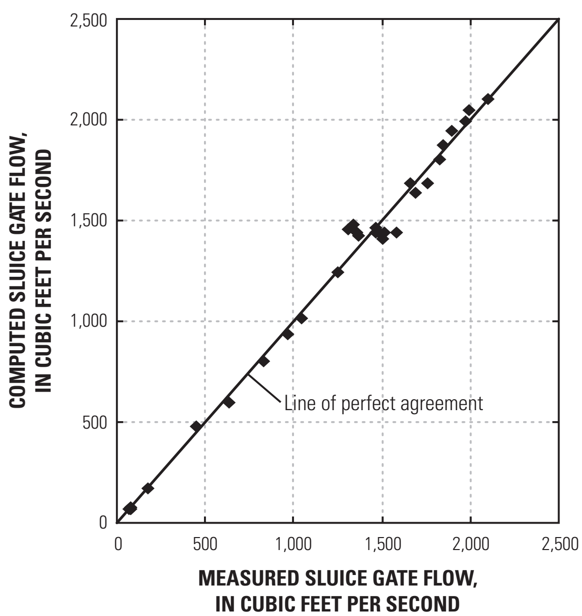


Figure 15. Measured and computed flows for the sluice gates near McHenry, Illinois.

Example Calculations

The following are examples of how streamflow was calculated using equations in table 8 and table 4. Note that total flow on the Fox River at McHenry is the summation of flow through the sluice gates, broad-crested weir, and hinged-crest gate. Thus, flow must be calculated at each of those structures separately. At times, the broad-crested weir may experience no flow over it, as shown in example 2.

Example 1: The following conditions exist:

Headwater pool stage is 5.15 ft, tailwater pool stage is 6.20 ft, all gates are opened to 7.0 ft ($h_{g_{SL}}$), and the hinged-crest gate opening is 1.0 ft ($h_{g_{HCG}}$). See figures 6 and 11 for schematic of hinged-crest gate, broad crested weir, sluice gate, and variables.

Flow over the broad-crested weir (which includes the fish ladder) is determined by first converting the headwater stage to depth above the weir crest. This is done by subtracting the difference between headwater gage datum (733.00 ft) and the elevation of the spillway crest (736.68) from the headwater stage reading,

$$h_{1_{BCW}} = 5.15 - (736.68 - 733.00) = 1.47\ ft,$$

and using equation 3 from table 4.

$$Q_{BCW} = 661.5 h_{1_{BCW}}^{1.587}$$

$$= 661.5(1.47)^{1.587}$$

$$= 1219\ ft^3/s\ .$$

Flow over the hinged-crest gate is determined by first converting the stages to depths above the crest of the gate. This is done by subtracting the difference between headwater gage datum (733.00 ft) and the elevation of the gate crest (736.68 ft - $h_{g_{HCG}}$) from the headwater stage and then subtracting the difference between the tailwater gage datum (730.15 ft) and the elevation of gate crest from the tailwater stage.

$$h_{1_{HCG}} = 5.15 - [(736.68 - 1.00) - 733.00] = 2.47\ ft$$

$$h_{3_{HCG}} = 6.20 - [(736.68 - 1.00) - 730.15] = .67\ ft$$

Because $h_{3_{HCG}} / h_{1_{HCG}}$ (0.67/2.47=0.27) is less than 0.75, FW flow exists. Before calculating flow, the depth from the concrete slab to the crest of the gate must be determined by calculating the difference between the gate crest elevation (736.68 ft - $h_{g_{HCG}}$) and the elevation of the top of the concrete slab (730.08).

$$p_{HCG} = (736.68 - 1.00) - 730.08 = 5.6\ ft.$$

Using equation 6 from table 4, flow is

$$Q_{HCG} = 193.5 h_{1_{HCG}}^{1.365} p_{HCG}^{0.135}$$

$$= 193.5(2.47)^{1.365}(5.6)^{0.135}$$

$$= 838.9\ ft^3/s$$

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.

$$h_{1_{SL}} = 5.15 + 1.85 = 7.00\ ft$$

$$h_{3_{SL}} = 6.20 - 1.00 = 5.20\ ft$$

Because $h_{g_{SL}} / h_{1_{SL}}$ (7.0/7.0=1.0) is greater than 0.73 and $h_{3_{SL}} / h_{1_{SL}}$ (0.74) is less than 0.80 (table 8), free-weir flow exists.

Using equation 12 from table 8, flow is,

$$Q_{SL} = 257.8 h_{1_{SL}}^{1.401}$$

$$= 257.8(7.00)^{1.401}$$

$$= 3938\ ft^3/s$$

Therefore, total flow, Q_{TOTAL}, is

$$Q_{TOTAL} = 838.9 + 1219 + 3938 = 5996\ ft^3/s$$

Example 2: The following conditions exist:

Headwater pool stage is 2.57 ft, tailwater pool stage is 3.70 ft, all sluice gates are set to 3.0 ft ($h_{g_{SL}}$), and the hinged-crest gate opening is 5.0 ft ($h_{g_{HCG}}$).

To find flow over the broad-crested weir, first, convert pool stages to depths above weir crest as in example 1.

$$h_{1_{BCW}} = 2.57 - (736.68 - 733.00) < 0\ ft$$

Because $h_{1_{BCW}}$ is a negative number, the weir experiences zero flow.

Flow over the hinged-crest gate is determined using the same method as in example 1.

$$h_{1_{HCG}} = 2.57 - [(736.68 - 5.00) - 733.00] = 3.89\ ft$$

$$h_{3_{HCG}} = 3.70 - [(736.68 - 5.00) - 730.15] = 2.17\ ft$$

Because $h_{3_{HCG}} / h_{1_{HCG}}$ (2.17/3.89 = 0.56) is less than 0.75, FW flow exists.

$$p_{HCG} = (736.68 - 5.00) - 730.08 = 1.6\, ft.$$

Using equation 6 from table 4:

$$Q_{HCG} = 193.5(3.89)^{1.365}(1.6)^{0.135}$$

$$Q_{HCG} = 1317\, ft^3 / s$$

To find flow through the sluice gates, pool stages must be converted to depths above the sluice-gate sill

$$h_{1_{SL}} = 2.57 + 1.85 = 4.42\, ft$$

$$h_{3_{SL}} = 3.70 - 1.00 = 2.70\, ft$$

Because $h_{g_{SL}} / h_{1_{SL}}$ (3.0/4.42=0.68) is less than 0.73, orifice flow exists. Since $h_{3_{SL}} / h_{g_{SL}}$ (2.70/3.0=0.90) is less than 1.0, free-orifice flow exists. Alternatively, free-orifice flow also exists because $h_{3_{SL}} / h_{1_{SL}}$ (2.70/4.42=0.61) is less than 0.70.

Using equation 18 from table 8, the flow is.

$$Q_{SL} = 149.5 h_{1_{SL}}^{0.929} h_{g_{SL}}^{0.938}$$

$$= 149.5(4.42)^{0.929}(3.0)^{0.938}$$

$$= 1666\, ft^3 / s$$

Therefore, total flow, Q_{TOTAL}, is

$$Q_{TOTAL} = 1317 + 1666 = 2983\, ft^3 / s$$

Example 3: The following conditions exist:

Headwater pool stage is 4.14 ft, tailwater pool stage is 5.95 ft, all gates are set to 5.7 ft ($h_{g_{SL}}$), and the hinged-crest gate opening is 6.0 ft ($h_{g_{HCG}}$).

Flow over the broad-crested weir is calculated in the same manner as in example 1.

$$h_{1_{BCW}} = 4.14 - (736.68 - 733.00) = 0.46\, ft$$

Using Equation 3 from table :

$$Q_{BCW} = 661.5 h_{1_{BCW}}^{1.587}$$

$$= 661.5(0.46)^{1.587}$$

$$Q_{BCW} = 192.9\, ft^3 / s$$

Flow over the hinged-crest gate is determined by first converting the pool stages to depths above the gate and determining the value of p_{HCG}.

$$h_{1_{HCG}} = 4.14 - [(736.68 - 6.0) - 733.00] = 6.46\, ft$$

$$h_{3_{HCG}} = 5.95 - [(736.68 - 6.0) - 730.15] = 5.42\, ft$$

$$p_{HCG} = (736.68 - 6.0) - 730.08 = 0.6\, ft.$$

Because $h_{3_{HCG}} / h_{1_{HCG}}$ (5.42/6.46=0.84) is greater than 0.75, submerged-weir flow exists.

Using equation 9 from table 4,

$$Q_{HCG} = 91.14 h_{1_{HCG}}^{4.305} h_{3_{HCG}}^{-2.94} p_{HCG}^{0.135}$$

$$= 91.14(6.46)^{4.305}(5.42)^{-2.94}(0.6)^{0.135}$$

$$= 1819\, ft^3 / s$$

To find flow through the sluice gates, pool stages must be converted to depths above the sluice-gate sill

$$h_{1_{SL}} = 4.14 + 1.85 = 5.99\, ft$$

$$h_{3_{SL}} = 5.95 - 1.00 = 4.95\, ft$$

Because $h_{g_{SL}} / h_{1_{SL}}$ $(5.7/5.99 = 0.95)$ is greater than 0.73 and $h_{3_{SL}} / h_{1_{SL}}$ $(4.95/5.99 = 0.83)$ is greater than 0.80, submerged-weir flow exists.

Using equation 15 from table 8,

$$Q_{SL} = 193.4 h_{1_{SL}}^{2.73} h_{3_{SL}}^{-1.33}$$

$$= 193.4(5.99)^{2.73}(4.95)^{-1.33}$$

$$= 3060\, ft^3 / s$$

Therefore, total flow, Q_{TOTAL}, is

$$Q_{TOTAL} = 192.9 + 1819 + 3060 = 5072\, ft^3 / s$$

Example 4: The following conditions exist:

Headwater pool stage is 5.30 ft, tailwater pool stage is 6.10 ft, all sluice gates are set to 4.0 ft ($h_{g_{SL}}$), and the hinged-crest gate opening is 5.5 ft ($h_{g_{HCG}}$).

Flow over the broad-crested weir is calculated in the same manner as in example 1.

$$h_{1_{BCW}} = 5.30 - (736.68 - 733.00) = 1.62\, ft$$

$$Q_{BCW} = 661.5 h_{1_{BCW}}^{1.587}$$

$$= 661.5(1.62)^{1.587}$$

$$= 1422\, ft^3 / s$$

Flow over the hinged-crest gate is characterized as free-weir flow, so the flow can be found in the same manner as in example 1.

$$h_{1_{HCG}} = 5.30 - [(736.68 - 5.50) - 733.00] = 7.12\,ft$$

$$h_{3_{HCG}} = 6.10 - [(736.68 - 5.5) - 730.15] = 5.07\,ft$$

Because $h_{3_{HCG}} / h_{1_{HCG}}$ (5.07/7.12=0.71) is less than 0.75, FW flow exists.

$$p_{HCG} = (736.68 - 5.50) - 730.08 = 1.10\,ft.$$

Using equation 6 from table 4, flow is

$$Q_{HCG} = 193.5 h_{1_{HCG}}^{1.365} p_{HCG}^{0.135}$$

$$= 193.5(7.12)^{1.365}(1.10)^{0.135}$$

$$= 2857\,ft^3/s$$

To calculate flow through the sluice gates, headwater and tailwater pool stages must be converted to depths above the sluice gate sill.

$$h_{1_{SL}} = 5.30 + 1.85 = 7.15\,ft$$

$$h_{3_{SL}} = 6.10 - 1.00 = 5.10\,ft$$

Because $h_{g_{SL}} / h_{1_{SL}} (4.0/7.15 = 0.56)$ is less than 0.73, $h_{3_{SL}} / h_{g_{SL}} (5.10/4.0 = 1.28)$ is greater than 1, and $h_{3_{SL}} / h_{1_{SL}}$ $(5.10/7.15 = 0.71)$ is greater than 0.70, submerged-orifice flow exists.

Using equation 21 from table 8,

$$Q_{SL} = 48.6 h_{1_{SL}}^{4.099} h_{g_{SL}}^{0.938} h_{3_{SL}}^{-3.17}$$

$$Q_{SL} = 48.6(7.15)^{4.099}(4.0)^{0.938}(5.10)^{-3.17}$$

$$= 3237\,ft^3/s$$

Therefore, total flow, Q_{TOTAL}, is

$$Q_{TOTAL} = 1422 + 2857 + 3237 = 7516\,ft^3/s$$

Algonquin Control-Structure Ratings

The Algonquin control structure is at river mile 81.6 on the Fox River in northeastern Illinois (fig. 1), 16.2 miles downstream of McHenry control structure. The drainage area at the headwater gage is 1,403 mi^2. The 894-acre reservoir created by the dam is primarily for recreation. The control structures at Algonquin consist of a 242-ft ogee spillway and a 50-ft-wide hinged-crest gate (figs. 16, 17, and 18). The elevation of structure components and headwater and tailwater gage datums are presented in table 9.

At the Algonquin control structure, streamflow measurements collected by the USGS at high flows during this study were made with a tethered ADCP boat off the downstream end of the Route 62 Bridge (fig. 16). Given the ability to measure flows within a close proximity to the structure, the total flow could be separated into flow through the hinged-crest gate and flow over the ogee spillway for the majority of the measurements.

The flow separation was completed by analyzing the velocity data obtained by the ADCP during each measurement and determining the approximate location where the flow “splits” between the hinged-crest gate and the ogee spillway. The vertically averaged velocity vectors (fig. 19) show a clear separation in the area where the flow splits between the gate and the spillway. A similar separation can be seen in the velocity contour plot (fig. 20) where the velocities decrease appreciably in the area of the flow split.

The flow separations are more obvious under certain flow conditions and gate settings than others. Typically, the actual separation point was chosen to be at the center of the break in velocity vectors (fig. 19) or at the center of the slower velocity section (fig. 20). A sensitivity analysis was performed to determine the potential accuracy of this method. In general, selecting separation points at either end of the slower velocity section affected the estimated flow through the gate by about 5 to 8 percent.

Table 9. Elevation of structure and streamflow-gaging station datums on the Fox River at Algonquin, Illinois.

[NGVD 1929, National Geodetic Vertical Datum of 1929]

Structure or gage	Elevation, in feet (NGVD 1929)
Algonquin Dam ogee spillway crest elevation	730.10
Algonquin Dam hinged-crest gate floor elevation	723.58
Headwater station datum, Fox River at Algonquin, Illinois	729.48
Tailwater station datum, Fox River at Algonquin, Illinois	719.48

Figure 16. Location of control structures on the Fox River at Algonquin, Illinois.

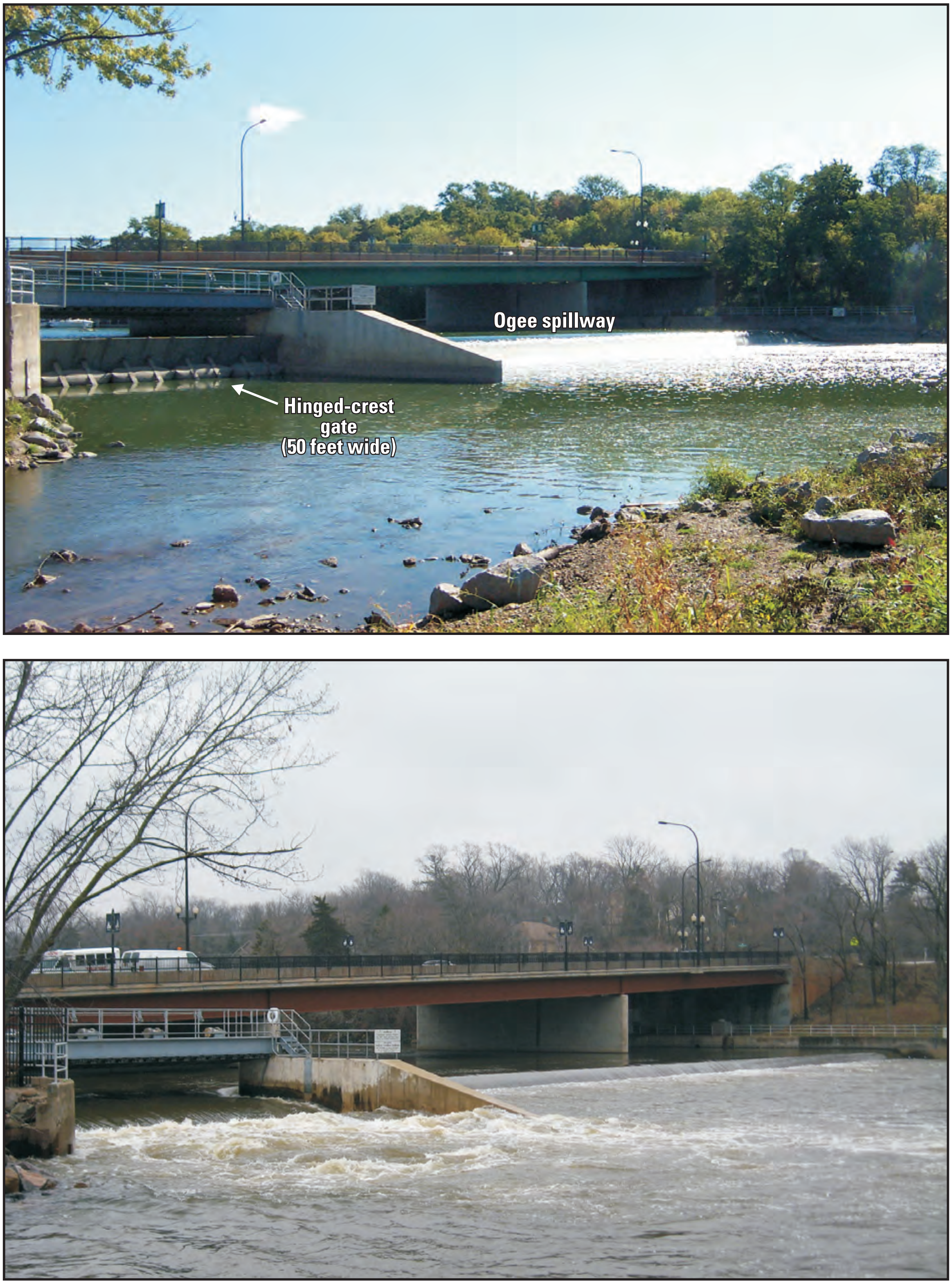


Figure 17. Downstream side of hinged-crest gate and ogee spillway on the Fox River at Algonquin, Illinois.

Figure 18. Close-up of downstream side of hinged-crest gate on the Fox River at Algonquin, Illinois.

Figure 19. Vertically averaged velocity vectors for a typical Acoustic Doppler Current Profiler streamflow measurement upstream of the control structure at Algonquin, Illinois, (ft, foot; ft/s, foot per second; BT, bottom tracking).

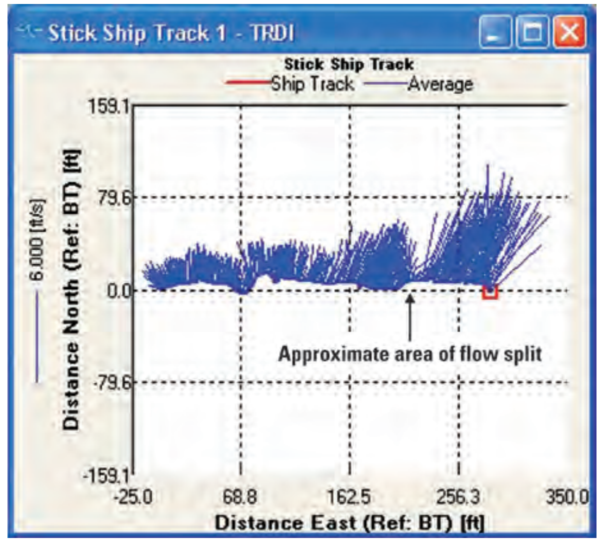
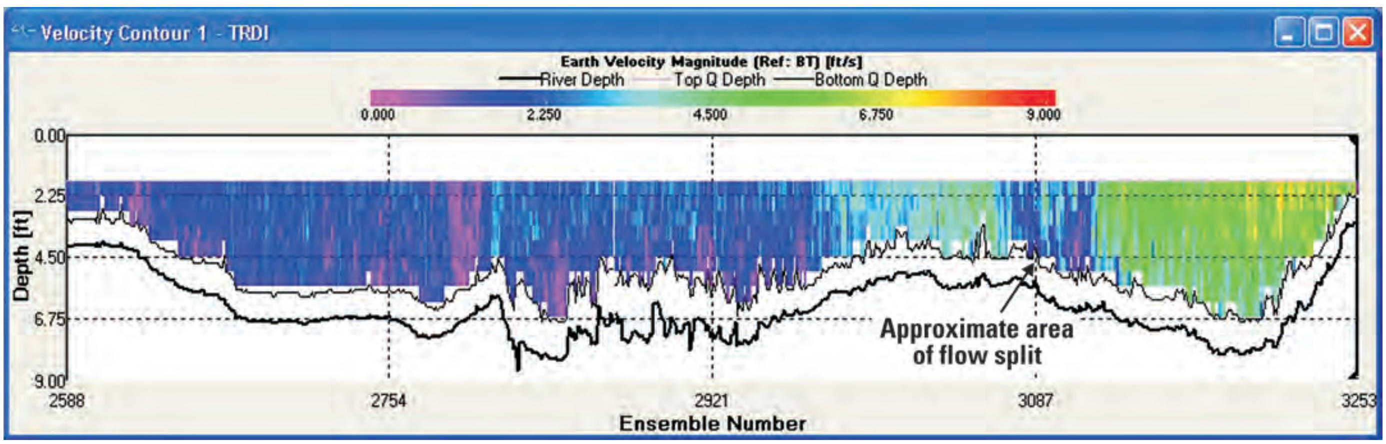


Figure 20. Velocity contour plot for the Acoustic Doppler Current Profiler streamflow measurement shown in figure 19 upstream of the control structure at Algonquin, Illinois, (ft, foot; ft/s, foot per second; BT, bottom tracking; Q, streamflow).

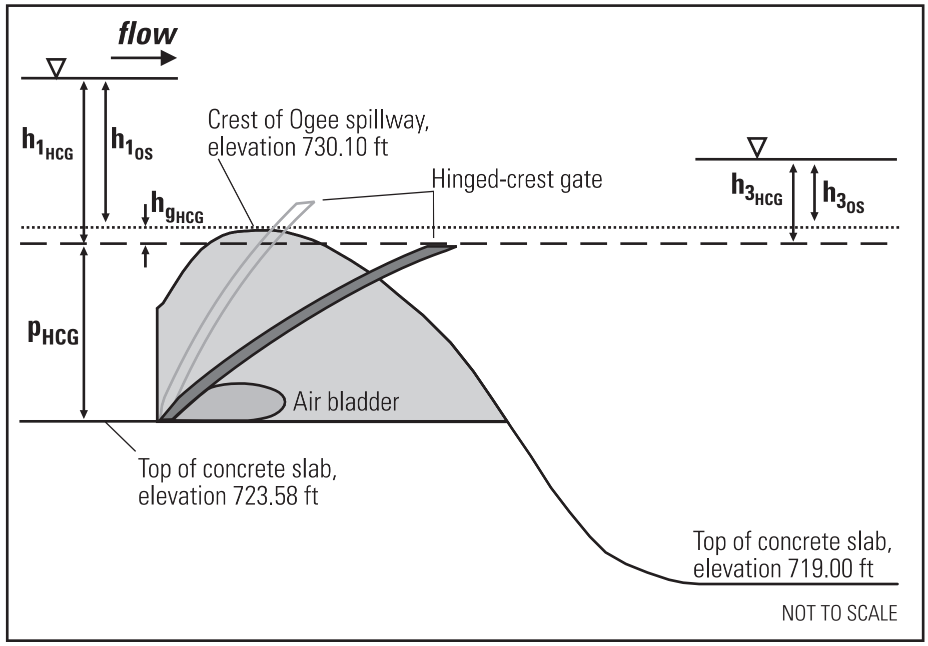


Ogee Spillway with Hinged-Crest Gate Closed (with and without flow over gate)

A side-view schematic of the ogee spillway, hinged-crest gate, and parameters used in the control-structure rating are shown in figure 21. Twelve measurements, ranging from 77 to 3,260 ft^3/s, were used to describe free-weir flow over the ogee spillway with the hinged-crest gate completely closed and no flow over the gate. Nine measurements, ranging from 406 to 1,960 ft^3/s, were used to describe free-weir flow over the ogee spillway and the crest of the hinged-crest gate set at the elevation of the ogee spillway with flow over the gate. Characteristics of the flow and the measured and computed discharge coefficients are listed in table 10 and appendix C. A standard weir equation (table 11) described in Chow (1959), Collins (1977), and Roberson and others (1998) is used to describe flow over the ogee spillway. The resulting free-weir equations are presented in table 11 and figure 22 for the conditions of flow over only the ogee spillway (Q_{OS}) and for flow over both the ogee spillway and the hinged-crest gate (denoted as Q_S for flow over the combined 292-ft "spillway"). Equations for conditions when the hinged-crest gate is open also are presented in tables 11 and 12 and are discussed in the next section. With the hinged-crest gate closed, the submergence ratios $(h_{3_{OS}} / h_{1_{OS}})$ were negative for all of the flow measurements, so submergence ratios could not be evaluated.

The measured and computed flows for the structure with the hinged-crest gate completely closed or with the crest set at the elevation of the ogee spillway at Algonquin are presented in table 10 and figure 23 for comparison. All 12 computed ogee spillway flows with the hinged-crest gate completely closed (no flow over the gate) are within 5 percent of measured flows. All nine computed ogee spillway flows with the crest of the hinged-crest gate set at the elevation of the ogee spillway with flow over the gate are within 11 percent of measured.

Figure 21. Schematic (side view) of hinged-crest gate and ogee spillway on the Fox River at Algonquin, Illinois, (ft, foot; $h_{1_{HCG}}$, headwater depth above the hinged-crest gate crest; $h_{3_{HCG}}$, tailwater depth above the hinged-crest gate crest; $h_{g_{HCG}}$, hinged-crest gate opening referenced to the ogee spillway crest; p_{HCG}, height of hinged-crest gate crest above approach invert; $h_{1_{OS}}$, headwater depth above the ogee spillway crest; $h_{3_{OS}}$, tailwater depth above the ogee spillway crest).



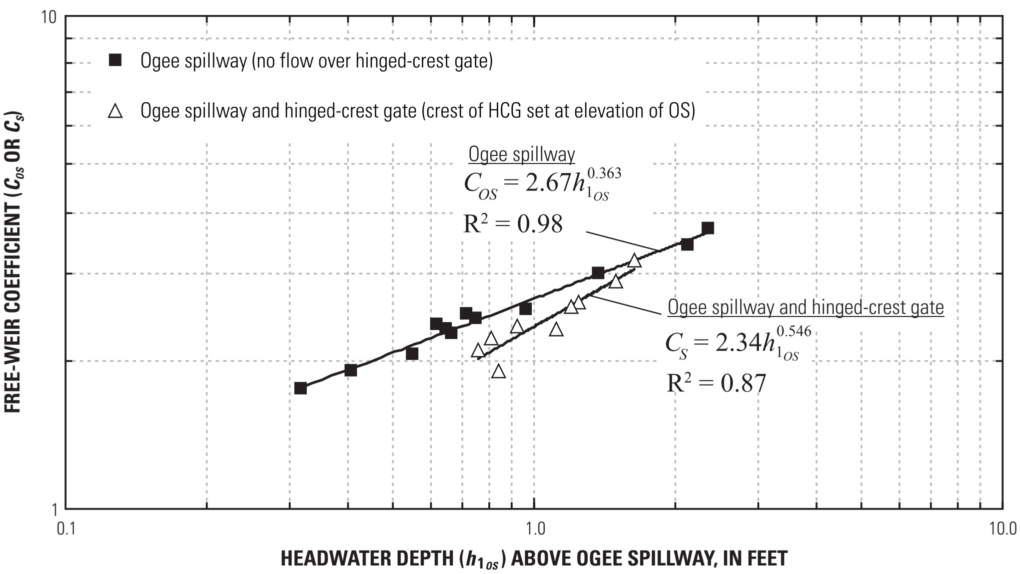


Figure 22. Discharge coefficient for free-weir flow and headwater depth for ogee spillway and hinged-crest gate (closed or at elevation of ogee spillway) on the Fox River at Algonquin, Illinois (R^2, coefficient of determination).

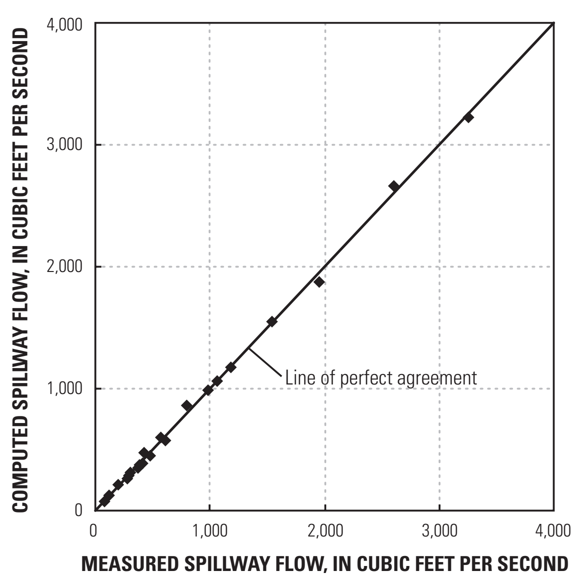


Figure 23. Measured and computed flows for the structure with the hinged-crest gate completely closed or with the crest set at the elevation of the ogee spillway at Algonquin, Illinois.

Table 10. Ogee spillway and hinged-crest gate (closed or crest at elevation of ogee-spillway crest) measured and computed flow characteristics and coefficients at Algonquin, Illinois.

[USGS, U.S. Geological Survey; ft^3/s, cubic foot per second; $h_{1_{OS}}$, headwater depth above the ogee spillway crest; ft, foot; $h_{3_{OS}}$, tailwater depth above the ogee spillway crest; C_{OS}, free-weir coefficient for the ogee spillway; C_S, free-weir coefficient for the spillway which includes flow over the hinged-crest gate set at the elevation of the ogee spillway; C/M, ratio of computed and measured flow; FW-NF, free-weir flow with no flow over the hinged-crest gate; FW-FL, free-weir flow with flow over the hinged-crest gate (crest at elevation of ogee spillway); ---, not determined]

USGS measure-ment number	Date	Measured flow (M) (ft^3/s)	$h_{1_{os}}$ (ft)	$h_{3_{os}}$ (ft)	$h_{3_{os}}/h_{1_{os}}$	Flow regime	Measured C_{OS} or C_S	Computed C_{OS} or C_S	Computed flow (C) (ft^3/s)	C/M
[A]505	**03/26/2002**	**1,180**	**1.38**	**---**	**---**	**FW-NF**	**3.01**	**3.00**	**1,177**	**1.00**
[A]506	**04/11/2002**	**2,600**	**2.14**	**---**	**---**	**FW-NF**	**3.43**	**3.52**	**2,666**	**1.03**
[A]507	**06/11/2002**	**3,260**	**2.37**	**---**	**---**	**FW-NF**	**3.69**	**3.65**	**3,225**	**.99**
[A]508	**07/23/2002**	**280**	**.62**	**---**	**---**	**FW-NF**	**2.37**	**2.24**	**265**	**.95**
509	**09/24/2002**	**577**	**.96**	**-3.64**	**-3.79**	**FW-NF**	**2.53**	**2.63**	**599**	**1.04**
510	**11/07/2002**	**381**	**.75**	**-3.98**	**-5.31**	**FW-NF**	**2.42**	**2.41**	**378**	**0.99**
511	01/09/2003	406	.76	-3.52	-4.63	FW-FL	2.10	2.01	390	0.96
[B]512	03/12/2003	267	.55	-4.15	-7.55	---	---	---	---	---
513	05/05/2003	1,060	1.24	-2.66	-2.15	FW-FL	2.63	2.63	1,061	1.00
514	05/07/2003	1,960	1.64	-1.81	-1.10	FW-FL	3.20	3.07	1,880	.96
515	06/18/2003	473	.81	-3.74	-4.62	FW-FL	2.22	2.09	444	.94
516	**09/03/2003**	**76.5**	**.32**	**-4.57**	**-14.28**	**FW-NF**	**1.75**	**1.77**	**77**	**1.01**
517	**10/15/2003**	**203**	**.55**	**-3.85**	**-7.00**	**FW-NF**	**2.06**	**2.15**	**212**	**1.05**
518	12/02/2003	605	.92	-3.49	-3.79	FW-FL	2.35	2.24	576	.95
[B]519	02/02/2004	382	.72	-4.00	-5.56	---	---	---	---	---
520	03/23/2004	989	1.20	-2.85	-2.37	FW-FL	2.58	2.58	992	1.00
[C]525	07/08/2004	1,240	1.14	-2.74	-2.40	---	---	---	---	---
526	**09/14/2004**	**301**	**.67**	**-4.23**	**-6.31**	**FW-NF**	**2.27**	**2.31**	**306**	**1.02**
527	11/08/2004	800	1.12	-3.46	-3.09	FW-FL	2.31	2.49	862	1.08
528	03/10/2005	1,540	1.49	-2.52	-1.69	FW-FL	2.90	2.91	1,545	1.00
529	**06/28/2005**	**121**	**.41**	**-4.45**	**-10.85**	**FW-NF**	**1.90**	**1.93**	**123**	**1.01**
530	**10/04/2005**	**294**	**.65**	**-4.17**	**-6.42**	**FW-NF**	**2.32**	**2.28**	**290**	**.99**
535	**07/28/2006**	**368**	**.72**	**-4.07**	**-5.65**	**FW-NF**	**2.49**	**2.37**	**350**	**.95**
536	10/02/2006	429	.84	-4.03	-4.80	FW-FL	1.91	2.13	478	1.11
[D]538	06/28/2007	801	1.03	-3.56	-3.46	---	---	---	---	---
[E]541	11/09/2007	703	.91	-3.53	-3.88	---	---	---	---	---
[E]542	12/17/2007	1,140	1.12	-3.03	-2.71	---	---	---	---	---

[A]Tailwater gage was not yet installed. Flow regime conditions are considered free weir for computations.

[B]Ice-affected measurement, not used in equation development.

[C]Outlier, measurement not used in equation development.

[D]Hinged-crest gate opening changed 20 minutes before measurement, not used in equation development.

[E]Hinged-crest gate repairs, measurement not used in equation development.

Measurements in **bold** indicate that the hinged-crest gate was closed, and no flow was overtopping it.

Table 11. Hydraulic conditions, parameters, and equations for different flow regimes for the ogee spillway and hinged-crest gate on the Fox River at Algonquin, Illinois.

[$h_{1_{OS}}$, headwater depth above the ogee spillway crest, in feet; $h_{3_{OS}}$, tailwater depth above the ogee spillway crest, in feet; Q_{OS}, flow through the ogee spillway, in ft^3/s; C_{OS}, free-weir coefficient for the ogee spillway; $C_{OS\text{-}A}$, affected-weir coefficient for the ogee spillway; C_S, free-weir coefficient for the spillway which includes flow over the hinged-crest gate set at the elevation of the ogee spillway; FW-NF, free-weir flow with no flow over the hinged-crest gate; FW-FL, free-weir flow with flow over the hinged-crest gate (crest at elevation of ogee spillway)]

Structure	Flow regime	Hydraulic conditions	Parameters and equations	Eq. No.
Ogee spillway (hinged-crest gate closed)	Free weir–no flow over HCG (FW-NF)	$\frac{h_{3_{OS}}}{h_{1_{OS}}} < 0.60$	$Q_{OS} = C_{OS} B h_{1_{OS}}^{1.5}$	22
Ogee spillway (hinged-crest gate open)	Free weir (FW)	$\frac{h_{3_{OS}}}{h_{1_{OS}}} < -5.0$	$C_{OS} = 2.67 h_{1_{OS}}^{0.363}$	23
			$B = 242\,ft$	
			$Q_{OS} = 646.1 h_{1_{OS}}^{1.863}$	24
Ogee spillway and hinged-crest gate (crest of the hinged-crest gate set at elevation of ogee spillway)	Free weir with-flow over HCG (FW-FL)	$\frac{h_{3_{OS}}}{h_{1_{OS}}} < 0.60$	$Q_S = C_S B h_{1_{OS}}^{1.5}$	25
			$C_S = 2.34 h_{1_{OS}}^{0.546}$	26
			$B = 292\,ft$	
			$Q_S = 683.3 h_{1_{OS}}^{2.046}$	27
Ogee spillway (hinged-crest gate open)	Affected	$-5.0 < \frac{h_{3_{OS}}}{h_{1_{OS}}} < 1$	$Q_{OS} = C_{OS} C_{OS-A} B h_{1_{OS}}^{1.5}$	28
			$C_{OS-A} = 0.442 p_{HCG}^{0.149} \left(\frac{h_{1_{OS}} - h_{3_{OS}}}{h_{1_{OS}}}\right)^{0.930} \left(\frac{h_{1_{HCG}} - h_{3_{HCG}}}{h_{1_{HCG}}}\right)^{-0.905}$	29
			$Q_{OS} = 285.5 h_{1_{OS}}^{0.933} p_{HCG}^{0.149} \left(h_{1_{OS}} - h_{3_{OS}}\right)^{0.930} \left(\frac{h_{1_{HCG}} - h_{3_{HCG}}}{h_{1_{HCG}}}\right)^{-0.905}$	30

Table 12. Hydraulic conditions, parameters, and equations for different flow regimes for the hinged-crest gate on the Fox River at Algonquin, Illinois.

[$h_{3_{HCG}}$, tailwater depth above the hinged-crest gate crest, in feet; $h_{1_{HCG}}$, headwater depth above the hinged-crest gate crest, in feet; Q_{HCG}, flow through the hinged-crest gate; C_{HCG}, free-weir coefficient for the hinged-crest gate; B, length of gate, in feet; p_{HCG}, height of hinged-crest gate crest above approach invert, in feet; $C_{HCG\text{-}S}$, submerged-weir coefficient for the hinged-crest gate]

Structure	Flow regime	Hydraulic conditions	Parameters and equations	Eq. No.
Hinged-crest gate	Free	$\frac{h_{3_{HCG}}}{h_{1_{HCG}}} \leq 0.77$	$Q_{HCG} = C_{HCG} B h_{1_{HCG}}^{1.5}$	4
			$C_{HCG} = 3.33\left(\frac{h_{1_{HCG}}}{p_{HCG}}\right)^{-0.152}$	31
			$B = 50\,ft$	
			$Q_{HCG} = 166.5 h_{1_{HCG}}^{1.348} p_{HCG}^{0.152}$	32
Hinged-crest gate	Submerged	$\frac{h_{3_{HCG}}}{h_{1_{HCG}}} > 0.77$	$Q_{HCG} = C_{HCG} C_{HCG-S} B h_{1_{HCG}}^{1.5}$	7
			$C_{HCG-S} = 0.882\left(\frac{h_{3_{HCG}}}{h_{1_{HCG}}}\right)^{-0.472}$	33
			$Q_{HCG} = 146.9 h_{1_{HCG}}^{1.820} h_{3_{HCG}}^{-0.472} p_{HCG}^{0.152}$	34

Ogee Spillway and Hinged-Crest Gate Open

A side-view schematic of the ogee spillway, hinged-crest gate, and parameters used in the control-structure rating are shown in figure 21. Twenty-one measurements, ranging from 868 to 6,600 ft^3/s, were used to describe free, affected, and submerged flow over the ogee spillway and hinged-crest gate. Characteristics of the flow and the measured and computed discharge coefficients are listed in table 13 and 14, and appendix D. A standard-weir equation (table 11 and 12) described in Chow (1959), Collins (1977), and Roberson and others (1998) is used to describe flow over the ogee spillway and hinged-crest gate.

The ogee spillway free-weir coefficients in table 13 were computed with equation 23 in table 11. Determination of a submerged-weir coefficient was attempted, but 14 out of 17 coefficient values were greater than one, indicating more flow than expected going over the ogee spillway for the majority of the measurements. The resulting coefficients are labeled $C_{OS\text{-}A}$ for "affected"-weir coefficient (table 13 and fig. 24). When the data are subdivided into three submergence ratio ranges, equations for $C_{OS\text{-}A}$ are developed with R^2 values of 0.69, 0.49, and 0.74. With the majority of the coefficient values above one, the relation of the three submergence ranges show that there is more affecting the flow than submergence when the hinged-crest gate is open (for example: hinged-crest gate height, upstream and downstream flow paths, proximity and height of streambank downstream of HCG, and (or) narrow channel downstream of the structure (fig. 16)). Multiple-linear regression analysis using gate height and hinged-crest gate and ogee spillway submergence ratios yields an affected-weir coefficient equation for the ogee spillway with an R^2 of 0.97 (equation 29, table 11). From the range of measurements used, the resulting affected ogee spillway flow equation with the HCG open (table 11) is applicable for $h_{3_{OS}} / h_{1_{OS}}$ less than 1.0 and greater than -5.0. Split-flow values (OS and HCG separate) for the measurements in November 2002 could not be determined. Using the available OS equations presented in table 11 and the HCG equations described below and presented in table 12, it appears that the ogee spillway flow with the HCG open and with $h_{3_{OS}} / h_{1_{OS}}$ less than -5.0 are best described by equation 24 (table 11). Note that there are only two measurements in this range with computed ogee spillway flow values of 21 and 158 ft^3/s.

Hinged-crest gate free- and submerged-weir coefficient equations are presented in table 12, figures 25 and 26. The free-weir coefficient equation at Algonquin is similar to the one at McHenry for the hinged-crest gate. Also similarly, the data at Algonquin indicate submerged flow occurs when $h_{3_{HCG}} / h_{1_{HCG}}$ is greater than 0.77. The submerged-weir coefficient equation deviates from the McHenry equation, and this difference could be attributed to the complexities mentioned in the above paragraph.

The measured and computed ogee spillway and hinged-crest gate flows for Algonquin are presented in table 15 and figure 27 for comparison. Twelve of the 17 computed ogee spillway flows are within 5 percent of measured and the remaining 5 are within 11 percent. Eight of the 17 computed hinged-crest gate flows are within 5 percent of measured, 6 are within 10 percent, 2 are within 15 percent, and the remaining measurement is within 24 percent. The combined OS and HCG flows show similar results, and all 11 combined measured flows above 3,300 ft^3/s were computed within 7 percent.

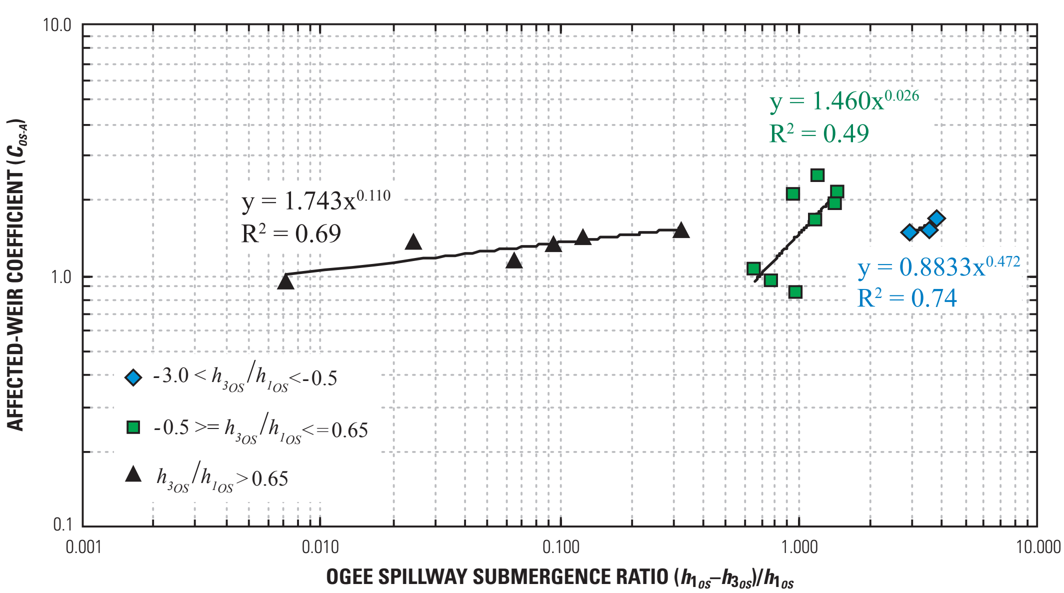


Figure 24. Discharge coefficient for affected-weir flow and ogee spillway submergence ratio on the Fox River at Algonquin, Illinois, (R^2, coefficient of determination).

Table 13. Ogee spillway weir-flow characteristics and coefficients at Algonquin, Illinois.

[USGS, U.S. Geological Survey; OS, ogee spillway; HCG, hinged-crest gate; ft³/s, cubic foot per second; $h_{1_{OS}}$, headwater depth above the ogee spillway crest; ft, foot; $h_{3_{OS}}$, tailwater depth above the ogee spillway crest; C_{OS}, free-weir coefficient for the ogee spillway; $C_{OS\text{-}A}$, affected-weir coefficient for the ogee spillway; C/M, ratio of computed and measured flow; FW, free-weir flow; NF, no flow; AFF, affected flow; IDNR, Illinois Department of Natural Resources–Office of Water Resources; ---, not determined]

USGS measurement number	Date	Measured OS and (or) HCG flow (ft³/s)	Ogee Spillway											
			Measured flow (M) (ft³/s)	$h_{1_{OS}}$ (ft)	$h_{3_{OS}}$ (ft)	$h_{3_{OS}}/h_{1_{OS}}$	Flow regime	$(h_{1_{OS}}-h_{3_{OS}})/h_{1_{OS}}$	Measured C_{OS}	Computed C_{OS}	Measured[1] $C_{OS\text{-}A}$	Computed $C_{OS\text{-}A}$	Computed flow (C) (ft³/s)	C/M
---	11/19/2002	868	---	0.47	-2.85	-6.06	FW	7.06	---	2.03	---	---	158	---
---	11/19/2002	1,410	---	.16	-1.85	-11.56	FW	12.56	---	1.37	---	---	21	---
---	11/20/2002	1,800	---	-.02	-1.43	---	NF	---	---	---	---	---	0	---
523	05/18/2004	3,570	**2,470**	**2.24**	**.04**	**.02**	**AFF**	**.98**	**3.04**	**3.57**	**0.85**	**0.80**	**2,306**	**0.93**
522	05/18/2004	3,730	**2,330**	**2.04**	**.44**	**.22**	**AFF**	**.78**	**3.30**	**3.45**	**.96**	**.97**	**2,369**	**1.02**
521	05/18/2004	3,890	**2,340**	**1.94**	**.67**	**.35**	**AFF**	**.65**	**3.58**	**3.39**	**1.06**	**1.12**	**2,481**	**1.06**
524	05/24/2004	5,580	***3,340***	***2.04***	***1.99***	***.98***	***AFF***	***.02***	***4.74***	***3.45***	***1.37***	***1.26***	***3,078***	***.92***
531	02/02/2006	1,580	*830*	*.86*	*-2.39*	*-2.78*	*AFF*	*3.78*	*4.30*	*2.53*	*1.70*	*1.70*	*827*	*1.00*
533	03/17/2006	3,160	**1,550**	**1.07**	**-.49**	**-.46**	**AFF**	**1.46**	**5.79**	**2.73**	**2.12**	**2.09**	**1,532**	**.99**
532	03/17/2006	3,320	**1,410**	**.93**	**-.20**	**-.22**	**AFF**	**1.22**	**6.50**	**2.60**	**2.50**	**2.53**	**1,425**	**1.01**
534	05/31/2006	2,000	*1,060*	*1.04*	*-2.59*	*-2.49*	*AFF*	*3.49*	*4.13*	*2.71*	*1.53*	*1.51*	*1,046*	*.99*
537	03/14/2007	3,220	**1,660**	**1.26**	**-.25**	**-.20**	**AFF**	**1.20**	**4.85**	**2.90**	**1.67**	**1.86**	**1,843**	**1.11**
539	08/22/2007	5,000	***2,910***	***1.85***	***1.62***	***.88***	***AFF***	***.12***	***4.78***	***3.33***	***1.43***	***1.41***	***2,856***	***.98***
540	08/27/2007	6,600	***4,220***	***2.83***	***2.81***	***.99***	***AFF***	***.01***	***3.66***	***3.89***	***.94***	***.99***	***4,443***	***1.05***
543	01/11/2008	3,010	**1,570**	**1.14**	**-.49**	**-.43**	**AFF**	**1.43**	**5.33**	**2.80**	**1.91**	**1.87**	**1,542**	**.98**
544	02/22/2008	1,980	*920*	*.98*	*-1.87*	*-1.91*	*AFF*	*2.91*	*3.92*	*2.65*	*1.48*	*1.55*	*966*	*1.05*
545	03/26/2008	3,850	**2,050**	**1.25**	**.06**	**.05**	**AFF**	**.95**	**6.06**	**2.89**	**2.10**	**1.86**	**1,815**	**.89**
546	04/16/2008	5,510	***3,140***	***2.00***	***1.81***	***.90***	***AFF***	***.10***	***4.59***	***3.43***	***1.34***	***1.32***	***3,110***	***.99***
547	06/11/2008	4,560	***2,540***	***1.66***	***1.12***	***.67***	***AFF***	***.33***	***4.91***	***3.21***	***1.53***	***1.55***	***2,580***	***1.02***
548	06/20/2008	6,030	***3,550***	***2.33***	***2.18***	***.94***	***AFF***	***.06***	***4.12***	***3.62***	***1.14***	***1.19***	***3,698***	***1.04***
IDNR	09/16/2008	2,936	---	**1.60**	**-.54**	**-.34**	**AFF**	**1.34**	---	**3.16**	---	**1.16**	**1,798**	---

[1]Ratio of measured and computed C_{OS}.

Black plain text indicates free-weir or no flow conditions.

Green bold text indicates "Affected" conditions with $h_{3_{OS}}/h_{1_{OS}}$ ranging from -0.5 to 0.65.

Black bold italic text indicates "Affected" conditions with $h_{3_{OS}}/h_{1_{OS}}$ greater than 0.65.

Blue italic text indicates "Affected" conditions with $h_{3_{OS}}/h_{1_{OS}}$ less than -0.5 and greater than -5.0.

Table 14. Hinged-crest gate weir-flow characteristics and coefficients at Algonquin, Illinois.

[USGS, U.S. Geological Survey; Meas., Measured; ft^3/s, cubic foot per second; hg_{HCG}, hinged-crest gate opening referenced to the broad-crested-weir crest; ft, foot; $h1_{HCG}$, headwater depth above the hinged-crest gate crest; $h3_{HCG}$, tailwater depth above the hinged-crest gate crest; p_{HCG}, height of hinged-crest gate crest above approach invert; C_{HCG}, free-weir coefficient for the hinged-crest gate; Comp., computed; $C_{HCG\text{-}S}$, submerged-weir coefficient for the hinged-crest gate; C/M, ratio of computed and measured flow; FW, free-weir flow; SW, submerged-weir flow; IDNR, Illinois Department of Natural Resources–Office of Water Resources; OS, ogee spillway; HCG, hinged-crest gate; ---, not determined]

USGS measurement number	Date	Hinged-crest gate: Meas. flow[1] (M) (ft^3/s)	Gate opening $h_{g_{HCG}}$ (ft)	$h_{1_{HCG}}$ (ft)	$h_{3_{HCG}}$ (ft)	$(h_{3_{HCG}}-h_{1_{HCG}})$	Flow regime	$(h_{1_{HCG}}-h_{3_{HCG}})/h_{1_{HCG}}$	p_{HCG} (ft)	$(h_{1_{HCG}}-p_{HCG})$	Meas. C_{HCG}	Comp. C_{HCG}	Meas.[2] $C_{HCG\text{-}S}$	Comp. $C_{HCG\text{-}S}$	Comp. flow (C) (ft^3/s)	C/M
---	11/19/2002	710	2.0	2.47	-0.85	-0.344	FW	1.34	4.52	0.55	3.66	3.65	---	---	709	---
---	11/19/2002	1,389	4.0	4.16	2.15	.517	FW	.48	2.52	1.65	3.27	3.09	---	---	1,309	---
---	11/20/2002	1,800	6.0	5.98	4.57	.764	FW	.24	.52	11.50	2.46	2.30	---	---	1,680	---
523	05/18/2004	1,100	1.0	3.24	1.04	.321	FW	.68	5.52	.59	3.77	3.61	---	---	1,053	0.96
522	05/18/2004	1,400	1.8	3.80	2.20	.579	FW	.42	4.76	.80	3.78	3.45	---	---	1,276	.91
521	05/18/2004	1,550	2.4	4.34	3.07	.707	FW	.29	4.12	1.05	3.43	3.30	---	---	1,494	.96
524	05/24/2004	**2,240**	**6.0**	**8.04**	**7.99**	**.994**	**SW**	**.01**	**.52**	**15.46**	**1.97**	**2.20**	**0.89**	**0.88**	**2,215**	**.99**
531	02/02/2006	750	2.0	2.86	-.39	-.136	FW	1.14	4.52	.63	3.10	3.57	---	---	863	1.15
533	03/17/2006	1,610	4.0	5.07	3.51	.692	FW	.31	2.52	2.01	2.82	2.99	---	---	1,709	1.06
532	03/17/2006	**1,910**	**5.0**	**5.93**	**4.80**	**.809**	**SW**	**.19**	**1.52**	**3.90**	**2.65**	**2.71**	**.98**	**.97**	**1,905**	**1.00**
534	05/31/2006	940	2.0	3.04	-.59	-.194	FW	1.19	4.52	.67	3.55	3.54	---	---	937	1.00
537	03/14/2007	1,560	4.0	5.26	3.75	.713	FW	.29	2.52	2.09	2.59	2.98	---	---	1,796	1.15
539	08/22/2007	**2,090**	**6.0**	**7.85**	**7.62**	**.971**	**SW**	**.03**	**.52**	**15.10**	**1.90**	**2.20**	**.86**	**.89**	**2,168**	**1.04**
540	08/27/2007	**2,380**	**6.0**	**8.83**	**8.81**	**.998**	**SW**	**.002**	**.52**	**16.98**	**1.81**	**2.17**	**.84**	**.88**	**2,508**	**1.05**
543	01/11/2008	1,440	3.5	4.64	3.01	.649	FW	.35	3.02	1.54	2.88	3.12	---	---	1,559	1.08
544	02/22/2008	1,060	2.0	2.98	.13	.044	FW	.96	4.52	.66	4.12	3.55	---	---	913	.86
545	03/26/2008	**1,800**	**4.0**	**5.25**	**4.06**	**.773**	**SW**	**.23**	**2.52**	**2.08**	**2.99**	**2.98**	**1.00**	**1.00**	**1,784**	**.99**
546	04/16/2008	**2,370**	**6.0**	**8.00**	**7.81**	**.976**	**SW**	**.02**	**.52**	**15.38**	**2.09**	**2.20**	**.95**	**.89**	**2,218**	**.94**
547	06/11/2008	**2,020**	**6.0**	**7.66**	**7.12**	**.930**	**SW**	**.07**	**.52**	**14.73**	**1.91**	**2.21**	**.86**	**.91**	**2,141**	**1.06**
548	06/20/2008	**2,480**	**6.0**	**8.33**	**8.18**	**.982**	**SW**	**.02**	**.52**	**16.02**	**2.06**	**2.18**	**.94**	**.89**	**2,336**	**.94**
IDNR	09/16/2008	1,138	2.0	3.60	1.46	.406	FW	.59	4.52	.80	3.33	3.45	---	---	1,177	---

[1]November 2002 and September 16, 2008, "measured" values determined by subtracting the computed OS flow from the measured total OS and HCG flow.

[2]Ratio of measured and computed C_{HCG}

Black plain text indicates free-weir conditions.

Red bold text indicates submerged conditions.

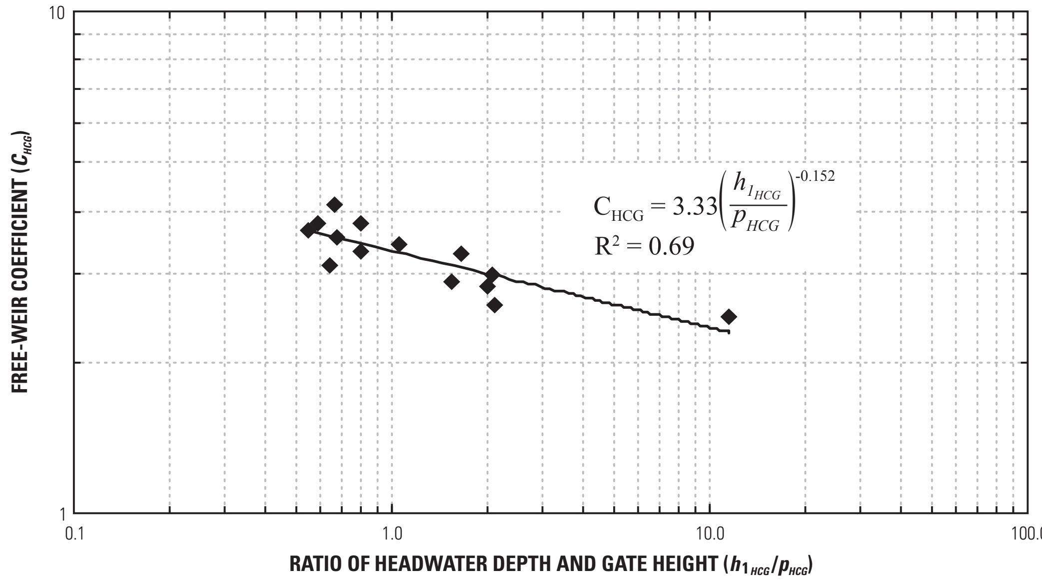


Figure 25. Discharge coefficient for free-weir flow, and the ratio of headwater depth and gate height for the hinged-crest gate on the Fox River at Algonquin, Illinois, (R^2, coefficient of determination).

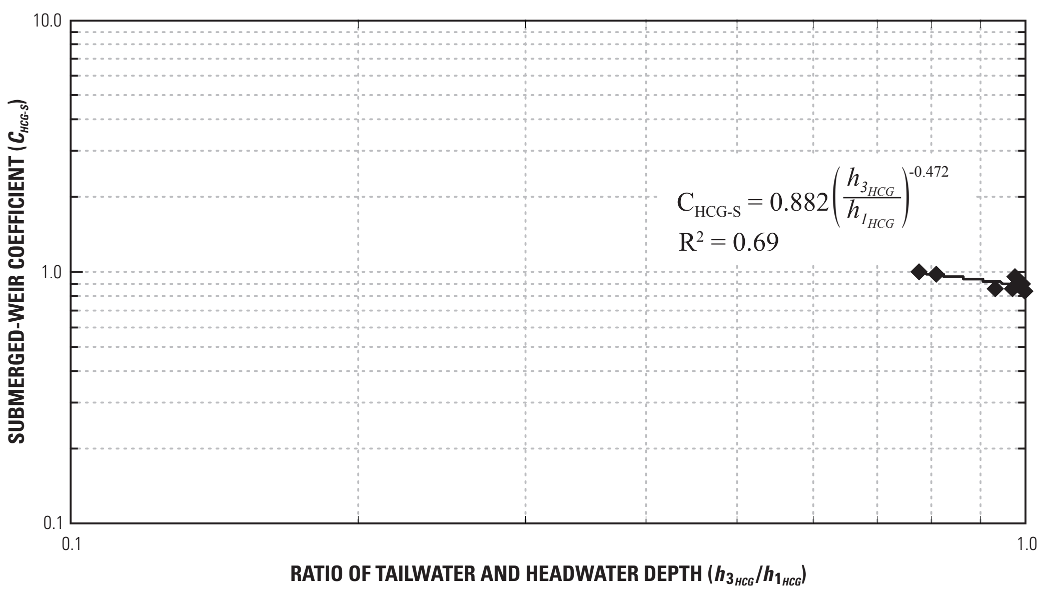


Figure 26. Discharge coefficient for submerged-weir flow, and the ratio of headwater and tailwater depth for the hinged-crest gate on the Fox River at Algonquin, Illinois, (R^2, coefficient of determination).

Table 15. Measured and computed flows for the ogee spillway and hinged-crest gate on the Fox River at Algonquin, Illinois.

[USGS, U.S. Geological Survey; OS, ogee spillway; ft³/s, cubic foot per second; C/M, ratio of computed and measured flow; HCG, hinged-crest gate; IDNR, Illinois Department of Natural Resources–Office of Water Resources; ---, not determined]

USGS measurement number	Date	OS			HCG			Total OS and HCG flow		
		Measured flow (M) (ft³/s)	Computed flow (C) (ft³/s)	C/M	Measured flow[1] (M) (ft³/s)	Computed flow (C) (ft³/s)	C/M	Measured flow (M) (ft³/s)	Computed flow (C) (ft³/s)	C/M
---	11/19/2002	---	158	---	710	709	---	868	867	1.00
---	11/19/2002	---	21	---	1,389	1,309	---	1,410	1,330	.94
---	11/20/2002	---	0	---	1,800	1,680	---	1,800	1,680	.93
523	05/18/2004	2,470	2,306	0.93	1,100	1,053	0.96	3,570	3,359	.94
522	05/18/2004	2,330	2,369	1.02	1,400	1,276	.91	3,730	3,646	.98
521	05/18/2004	2,340	2,481	1.06	1,550	1,494	.96	3,890	3,974	1.02
524	05/24/2004	3,340	3,078	.92	2,240	2,215	.99	5,580	5,292	.95
531	02/02/2006	830	827	1.00	750	863	1.15	1,580	1,690	1.07
533	03/17/2006	1,550	1,532	.99	1,610	1,709	1.06	3,160	3,241	1.03
532	03/17/2006	1,410	1,425	1.01	1,910	1,905	1.00	3,320	3,330	1.00
534	05/31/2006	1,060	1,046	.99	940	937	1.00	2,000	1,984	.99
537	03/14/2007	1,660	1,843	1.11	1,560	1,796	1.15	3,220	3,639	1.13
539	08/22/2007	2,910	2,856	.98	2,090	2,168	1.04	5,000	5,025	1.00
540	08/27/2007	4,220	4,443	1.05	2,380	2,508	1.05	6,600	6,951	1.05
543	01/11/2008	1,570	1,542	.98	1,440	1,559	1.08	3,010	3,101	1.03
544	02/22/2008	920	966	1.05	1,060	913	.86	1,980	1,879	.95
545	03/26/2008	2,050	1,815	.89	1,800	1,784	.99	3,850	3,599	.93
546	04/16/2008	3,140	3,110	.99	2,370	2,218	.94	5,510	5,328	.97
547	06/11/2008	2,540	2,580	1.02	2,020	2,141	1.06	4,560	4,721	1.04
548	06/20/2008	3,550	3,698	1.04	2,480	2,336	.94	6,030	6,034	1.00
IDNR	09/16/2008	---	1,798	---	1,138	1,177	---	2,936	2,975	1.01

[1]November 2002 and September 16, 2008, "measured" values determined by subtracting the computed OS flow from the measured total OS and HCG flow.

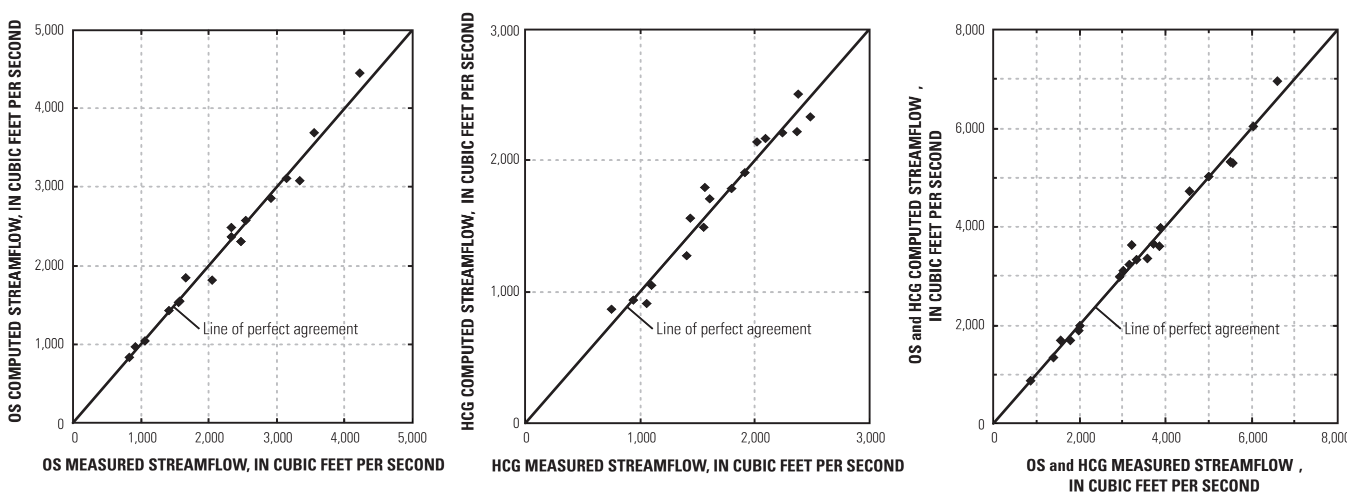


Figure 27. Measured and computed flows for the ogee spillway and hinged-crest gate on the Fox River at Algonquin, Illinois, (OS, ogee spillway; HCG, hinged-crest gate).

Example Calculations

The following are examples of how flow was calculated using equations in table 11 and table 12.

Example 1: The following conditions exist:

Headwater pool stage is 1.37 ft, tailwater pool stage is 6.64 ft, and the flow over the hinged-crest gate is zero because the crest is closed to an elevation above the ogee spillway and (or) the bulkheads are closed. See figure 21 for a schematic.

Flow is determined by first converting the stages to depths above the crest of the ogee spillway. This is done by subtracting the difference between the crest of the spillway (730.10 ft) and headwater gage datum (729.48 ft) from the headwater stage and then subtracting the difference between the spillway crest and tailwater gage datum (719.48 ft) from the tailwater stage.

$$h_{1_{OS}} = 1.37 - (730.10 - 729.48) = 0.75\,ft$$

$$h_{3_{OS}} = 6.64 - (730.10 - 719.48) = -3.98\,ft$$

Because $h_{3_{OS}} / h_{1_{OS}}$ (-3.98/0.75=-5.31) is less than 0.60 and the hinged-crest gate is closed, free-weir flow exists for the spillway and there is zero flow over the gate.

Using equation 24 from table 11,

$$Q_{OS} = 646.1 h_{1_{OS}}^{1.863}$$

$$= 646.1(0.75)^{1.863}$$

$$= 378.0\,ft^3/s\,.$$

Therefore the total flow is

$$Q_{TOTAL} = Q_{OS} = 378.0\,ft^3/s$$

Example 2: The following conditions exist:

Headwater pool stage is 1.86 ft, tailwater pool stage is 7.96 ft, there is flow over the hinged-crest gate because the crest is at the same elevation as the crest of the ogee spillway.

Flow is determined by first converting the pool stages to depths above the crest of the spillway, as in example 1.

$$h_{1_{OS}} = 1.86 - 0.62 = 1.24\,ft$$

$$h_{3_{OS}} = 7.96 - 10.62 = -2.66\,ft$$

Because $h_{3_{OS}} / h_{1_{OS}}$ (-2.66/1.24=-2.15) is less than 0.60 and the crest of the hinged-crest gate is the same elevation as the crest of the spillway, free-weir flow exists for the spillway and there is flow over the gate.

Using equation 27 from table 11,

$$Q_S = 683.3 h_{1_{OS}}^{2.046}$$

$$= 683.3(1.24)^{2.046}$$

$$= 1061\,ft^3/s\,.$$

Therefore the total flow is

$$Q_{TOTAL} = Q_S = 1061\,ft^3/s$$

Example 3: The following conditions exist:

Headwater pool stage is 0.78 ft, tailwater pool stage is 8.77 ft, and the hinged-crest gate opening is 4.0 ft.

Flow over the spillway is determined by first converting the stages to depths above the crest of the spillway.

$$h_{1_{OS}} = 0.78 - 0.62 = 0.16\,ft$$

$$h_{3_{OS}} = 8.77 - 10.62 = -1.85\,ft$$

Because $h_{3_{OS}} / h_{1_{OS}}$ (-1.85/0.16=-11.56) is less than -5.0 and the hinged-crest gate is open, free-weir flow exists.

Using equation 24 from table 11,

$$Q_{OS} = 646.1 h_{1_{OS}}^{1.863}$$

$$= 646.1(0.16)^{1.863}$$

$$= 21.26\,ft^3/s\,.$$

Flow over the gate is determined by first converting the stages to depths above the crest of the gate. This is done by subtracting the difference between headwater gage datum (729.48 ft) and the elevation of the gate crest (730.10 ft – $h_{g_{HCG}}$) from the headwater stage and then subtracting the difference between the tailwater gage datum (719.48 ft) and the elevation of gate crest from the tailwater stage.

$$h_{1_{HCG}} = 0.78 - [(730.10 - 4.00) - 729.48] = 4.16\,ft$$

$$h_{3_{HCG}} = 8.77 - [(730.10 - 4.00) - 719.48] = 2.15\,ft$$

Because $h_{3_{HCG}} / h_{1_{HCG}}$ (2.15/4.16=0.52) is less than 0.77, free-weir flow exists. Before calculating flow, the depth from the concrete slab to the crest of the gate must be determined by calculating the difference between the gate crest elevation (730.10 ft – $h_{g_{HCG}}$) and the elevation of the top of the concrete slab (723.58).

$$p_{HCG} = (730.10 - 4.00) - 723.58 = 2.52\,ft.$$

Using equation 32 from table 12,

$$Q_{HCG} = 166.5 h_{1_{HCG}}^{1.348} p_{HCG}^{0.152}$$

$$= 166.5(4.16)^{1.348}(2.52)^{0.152}$$

$$= 1309\,ft^3/s\,,$$

Therefore the total flow is

$$Q_{TOTAL} = 21.26 + 1309 = 1330\,ft^3/s$$

Example 4: The following conditions exist:

Headwater pool stage is 2.45 ft, tailwater pool stage is 12.22 ft, and the hinged-crest gate opening is 6.0 ft.

Flow over the spillway is determined by first converting the stages to depths above the crest of the spillway.

$$h_{1_{OS}} = 2.45 - 0.62 = 1.83\,ft$$

$$h_{3_{OS}} = 12.22 - 10.62 = 1.60\,ft$$

Because $h_{3_{OS}} / h_{1_{OS}}$ (1.60/1.83=0.87) is between -5.0 and 1 and the hinged-crest gate is open, affected flow exists. For affected flow, the values of $h_{1_{HCG}}$, $h_{3_{HCG}}$, and p_{HCG} must be determined.

$$h_{1_{HCG}} = 2.45 - [(730.10 - 6.0) - 729.48] = 7.83\,ft$$

$$h_{3_{HCG}} = 12.22 - [(730.10 - 6.0) - 719.48] = 7.60\,ft$$

$$p_{HCG} = (730.10 - 6.0) - 723.58 = 0.52\,ft.$$

Using equation 30 from table 11,

$$Q_{OS} = 285.5 h_{1_{OS}}^{0.933} p_{HCG}^{0.149} \left(h_{1_{OS}} - h_{3_{OS}}\right)^{0.930} \left(\frac{h_{1_{HCG}} - h_{3_{HCG}}}{h_{1_{HCG}}}\right)^{-0.905}$$

$$= 285.5(1.83)^{0.933}(0.52)^{0.149}\left((1.83)-(1.60)\right)^{0.930}\left(\frac{(7.83)-(7.60)}{(7.83)}\right)^{-0.905}$$

$$= 2825\,ft^3/s\,.$$

Because $h_{3_{HCG}} / h_{1_{HCG}}$ (7.60/7.83 = 0.97) is greater than 0.77, submerged-weir flow exists. *Note: there are instances when free-weir flow, rather than submerged-weir flow, exists over the gate while the spillway experiences affected flow. Refer to example 3 for calculations of free-weir flow over the hinged-crest gate.

Using equation 34 from table 12,

$$Q_{HCG} = 146.9 h_{1_{HCG}}^{1.820} h_{3_{HCG}}^{-0.472} p_{HCG}^{0.152}$$

$$= 146.9(7.83)^{1.820}(7.60)^{-0.472}(0.52)^{0.152}$$

$$= 2162\,ft^3/s\,,$$

Therefore the total flow is

$$Q_{TOTAL} = 2825 + 2162 = 4987\,ft^3/s$$

Summary

The Illinois Department of Natural Resources–Office of Water Resources operates control structures on a reach of the Fox River in northeastern Illinois between McHenry and Algonquin. These structures are used to maintain water levels in the river for flood-control and recreational purposes. The McHenry control structure is at river mile 97.8 and has a drainage area of 1,250 square miles (mi^2). The Algonquin control structure is at river mile 81.6 and has a drainage area of 1,403 mi^2. This report documents the effects of the hinged-crest gates, a broad-crested weir, sluice gates, and an ogee spillway on the Fox River control-structure ratings at McHenry and Algonquin.

The Fox River control-structure ratings were determined by measuring headwater and tailwater stage along with streamflow at a wide range of flows at different gate openings. Standard control-structure rating techniques were used to rate each structure.

The control structures at McHenry consist of a 221-feet (ft) broad-crested weir, a 4-ft-wide fish ladder, a 50-ft wide hinged-crest gate, five 13.75-ft-wide sluice gates, and a navigational lock. Sixty measurements were used to rate the McHenry control structures. The flow regime for the broad-crested weir included free weir, and the hinged-crest gate included both free and submerged weir. The flow regimes for the sluice gate included free and submerged weir and free and submerged orifice.

The control structures at Algonquin, consist of a 242-ft ogee spillway and a 50-ft-wide hinged-crest gate. Forty-one measurements were used to rate the Algonquin control structures. The flow regimes for the ogee spillway included both free and affected weir. The flow regimes for the hinged-crest gate included free and submerged weir.

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Appendixes A–F

Appendix A: Fox River near McHenry, Illinois, Headwater and Tailwater Stages for Broad-Crested Weir and Hinged-Crest Gate Measurements.

[USGS, U.S. Geological Survey; ft, foot; BCW, Broad-Crested Weir; HCG, Hinged-Crest Gate; ft^3/s, cubic foot per second; $h_{g_{HCG}}$, hinged-crest gate opening referenced to the broad-crested-weir crest; ---, not applicable]

USGS measure-ment mumber	Date	Central Standard Time	Water surface				Measured BCW and (or) HCG Flow (ft^3/s)	Gate opening $h_{g_{HCG}}$ (ft)
			Headwater		Tailwater			
			Stage (ft)	Elevation (ft)	Stage (ft)	Elevation (ft)		
5	05/16/1985	1350	4.05	737.05	1.35	731.50	169	---
13	08/28/1986	1500	4.23	737.23	1.05	731.20	342	---
15	09/27/1986	1345	5.34	738.34	6.12	736.27	1,880	---
20	09/30/1986	1120	5.90	738.90	6.98	737.13	2,990	---
44	11/18/2002	1436–1521	4.16	737.16	.93	731.08	565	1.0
45	11/19/2002	0830–0915	3.98	736.98	1.61	731.76	1,012	2.2
46	11/19/2002	1339–1440	3.62	736.62	1.60	731.75	1,345	4.1
47	11/20/2002	0922–1004	3.21	736.21	2.12	732.27	1,775	6.0
[A]48	04/04/2003	1127–1217	4.11	737.11	1.30	731.45	145	0.0
49	05/17/2004	1134–1155	4.30	737.30	3.50	733.65	803	1.0
[B]50	05/17/2004	1509–1537	4.06	737.06	3.78	733.93	1,240	2.0
51	05/17/2004	1703–1728	3.80	736.80	3.99	734.14	2,040	5.0
52	05/24/2004	0800–0838	4.04	737.04	5.85	736.00	1,820	6.0
53	03/17/2006	1033–1048	2.64	735.64	3.77	733.92	1,077	4.0
[C]54	03/17/2006	1551–1628	3.37	736.37	3.31	733.46	401	2.0
[D]55	03/16/2007	1055–1113	2.64	735.64	4.32	734.47	1,132	4.5
56	08/22/2007	1010–1024	3.67	736.67	5.58	735.73	1,710	6.0
57	08/27/2007	1012–1026	4.83	737.83	7.03	737.18	2,550	6.0
58	03/26/2008	1113–1129	2.48	735.48	4.38	734.53	1,440	5.5
59	04/16/2008	1201–1220	4.16	737.16	6.04	736.19	1,930	6.0
60	06/20/2008	0728–0740	4.76	737.76	6.78	736.93	2,450	6.0

[A]No flow over hinged-crest gate. All other measurements from 2002–2008 had flow over the hinged-crest gate.

[B]Hinged-crest gate opening changed 30 minutes before measurement; measurement not used in equation development.

[C]Outlier, measurement not used in equation development.

[D]Total flow (BCW, HCG, and SL) measured without a separate measurement of sluice gate flow. The sluice gate flow is calculated and subtracted from total flow.

Appendix B: Fox River near McHenry, Illinois, Headwater and Tailwater Stages for Sluice Gate Measurements.

[USGS, U.S. Geological Survey; $h_{g_{SL}}$, sluice gate opening; ft, foot; ft³/s, cubic foot per second]

USGS measurement number	Date	Central Standard Time	Gate opening $h_{g_{SL}}$ (ft)	Gates open	Headwater Stage (ft)	Headwater Elevation (ft)	Tailwater Stage (ft)	Tailwater Elevation (ft)	Measured Flow (ft³/s)
1	03/22/1985	1250	4.0	5	3.51	736.51	3.90	734.05	2,790
2	03/22/1985	1400	3.0	5	3.68	736.68	3.70	733.85	1,990
3	03/26/1985	1230	3.8	5	2.64	735.64	3.45	733.60	2,100
4	03/26/1985	1430	3.3	5	2.71	735.71	3.42	733.57	1,850
6	05/16/1985	1350	.6	5	4.03	737.03	1.35	731.50	448
7	10/04/1985	1205	2.5	4	4.05	737.05	2.75	732.90	1,460
8	11/04/1985	1026	3.15	4	3.98	736.98	2.82	732.97	1,830
9	03/17/1986	1350	6.5	5	4.31	737.31	5.03	735.18	3,230
10	04/22/1986	1105	1.2	5	3.23	736.23	1.71	731.86	833
[B]11	04/22/1986	1340	2.0	4	3.13	736.13	1.85	732.00	1,180
[B]11	04/22/1986	1340	1.0	1	3.13	736.13	1.85	732.00	0
12	05/23/1986	115	1.2	5	4.16	737.16	2.25	732.40	967
14	08/28/1986	1500	.2	5	4.22	737.22	1.05	731.20	180
16	09/27/1986	1530	4.0	5	5.35	738.35	6.15	736.30	3,045
17	09/27/1986	1710	7.0	5	5.20	738.20	6.25	736.40	4,054
18	09/27/1986	1805	4.9	5	5.22	738.22	6.25	736.40	3,600
19	09/27/1986	1850	4.5	5	5.26	738.26	6.30	736.45	3,320
21	09/30/1986	1345	4.0	5	5.90	738.90	6.98	737.13	2,600
22	09/30/1986	1505	4.5	5	5.86	738.86	6.98	737.13	2,920
23	10/15/1986	1040	7.0	5	4.25	737.25	5.10	735.25	3,270
24	11/01/1990	936	1.0	5	2.59	735.59	1.32	731.47	636
25	11/01/1990	1137	.1	5	2.67	735.67	1.11	731.26	63.9
26	11/01/1990	1350	.1	5	2.63	735.63	1.05	731.20	74.4
27	11/02/1990	1243	.1	5	2.68	735.68	.58	730.73	73.9
28	11/03/1990	825	.1	5	2.91	735.91	.45	730.60	74.1
29	11/04/1990	815	.1	5	3.17	736.17	.35	730.50	75.0
30	11/04/1990	1355	.1	5	3.17	736.17	.35	730.50	75.9
31	11/05/1990	1024	.1	5	3.56	736.56	.40	730.55	82.6
32	11/05/1990	1812	2.5	5	2.84	735.84	1.74	731.89	1,340
33	11/05/1990	2035	2.5	5	2.76	735.76	1.89	732.04	1,310
34	11/06/1990	230	2.5	5	2.66	735.66	2.19	732.34	1,370
35	11/06/1990	1300	2.5	5	2.60	735.60	2.38	732.53	1,500
36	11/07/1990	1049	2.5	5	2.69	735.69	2.52	732.67	1,360
37	11/07/1990	1430	2.5	5	2.69	735.69	2.52	732.67	1,510

[B]Four gates were set to 2.0 ft, and one gate was set to 1.0 ft. Equations developed in this study were used to subtract flow from the gate open to 1.0 ft; a coefficient for a 2.0 ft opening was determined from the measurement.

Appendix B: Fox River near McHenry, Illinois, Headwater and Tailwater Stages for Sluice Gate Measurements.—Continued

[USGS, U.S. Geological Survey; $h_{g_{SL}}$, sluice gate opening; ft, foot; ft³/s, cubic foot per second]

USGS measurement number	Date	Central Standard Time	Gate opening $h_{g_{SL}}$ (ft)	Gates open	Headwater Stage (ft)	Headwater Elevation (ft)	Tailwater Stage (ft)	Tailwater Elevation (ft)	Measured Flow (ft³/s)
38	11/07/1990	1640	2.5	5	2.69	735.69	2.56	732.71	1,480
39	11/08/1990	1202	2.5	5	2.71	735.71	2.60	732.75	1,480
40	11/08/1990	1200	2.5	5	2.71	735.71	2.60	732.75	1,580
41	11/09/1990	947	2.5	5	2.69	735.69	2.58	732.73	1,460
42	04/24/1993	1100	6.0	5	5.17	738.17	3.24	733.39	3,920
43	04/28/1993	845	6.0	5	4.98	737.98	2.78	732.93	3,664
49	05/17/2004	1244–1257	2.2	5	4.29	737.29	3.50	733.65	1,760
50	05/17/2004	1434–1447	2.2	5	4.10	737.10	3.74	733.89	1,690
51	05/17/2004	1759–1811	2.2	4	3.77	736.77	4.00	734.15	1,250
52	05/24/2004	0902–0919	5.7	5	4.04	737.04	5.85	736.00	3,020
53	03/17/2006	1033–1048	3.0	5	2.64	735.64	3.77	733.92	1,664
54	03/17/2006	1536–1546	3.0	5	3.37	736.37	3.31	733.46	1,890
56A	08/22/2007	1122–1130	5.0	5	3.73	736.73	5.59	735.74	2,760
57A	08/27/2007	1107–1116	6.2	5	4.83	737.83	7.03	737.18	3,140
58A	03/26/2008	1248–1258	4.5	5	2.47	735.47	4.36	734.51	1,970
59A	04/16/2008	1306–1319	5.3	5	4.14	737.14	6.02	736.17	2,960
60A	06/20/2008	0848–0854	6.0	5	4.75	737.75	6.76	736.91	3,280

[B]Four gates were set to 2.0 ft, and one gate was set to 1.0 ft. Equations developed in this study were used to subtract flow from the gate open to 1.0 ft; a coefficient for a 2.0 ft opening was determined from the measurement.

Appendix C. Fox River at Algonquin, Illinois, Headwater and Tailwater Stages for Ogee Spillway and Hinged-Crest Gate Measurements with the Hinged-Crest Gate Closed.

[USGS, U.S. Geological Survey; ft, foot; ft³/s, cubic foot per second; measurements in bold indicate that the hinged-crest gate was closed, and no flow was overtopping it; ---, not determined]

USGS measurement number	Date	Time	Water-surface elevation				Measured flow (M) (ft³/s)	Flow over hinged-crest gate
			Headwater (HW)		Tailwater (TW)			
			Stage (ft)	Elevation (ft)	Stage (ft)	Elevation (ft)		
[A]505	**03/26/2002**	**0803–1020**	**2.00**	**731.48**	**---**	**---**	**1,180**	**No**
[A]506	**04/11/2002**	**0845–1015**	**2.76**	**732.24**	**---**	**---**	**2,600**	**No**
[A]507	**06/11/2002**	**0915–1100**	**2.99**	**732.47**	**---**	**---**	**3,260**	**No**
[A]508	**07/23/2002**	**1250–1350**	**1.24**	**730.72**	**---**	**---**	**280**	**No**
509	**09/24/2002**	**1330–1440**	**1.58**	**731.06**	**6.98**	**726.46**	**577**	**No**
510	**11/07/2002**	**1405–1510**	**1.37**	**730.85**	**6.64**	**726.12**	**381**	**No**
511	01/09/2003	1125–1235	1.38	730.86	7.10	726.58	406	Yes
[B]512	03/12/2003	1145–1230	1.17	730.65	6.47	725.95	267	Yes
513	05/05/2003	1040–1140	1.86	731.34	7.96	727.44	1,060	Yes
514	05/07/2003	0950–1140	2.26	731.74	8.81	728.29	1,960	Yes
515	06/18/2003	0800–0900	1.43	730.91	6.88	726.36	473	Yes
516	09/03/2003	1255–1355	.94	730.42	6.05	725.53	76.5	No
517	**10/15/2003**	**0815–0920**	**1.17**	**730.65**	**6.77**	**726.25**	**203**	**No**
518	12/02/2003	1130–1240	1.54	731.02	7.13	726.61	605	Yes
[B]519	02/02/2004	1525–1615	1.34	730.82	6.62	726.10	382	Yes
520	03/23/2004	1300–1450	1.82	731.30	7.77	727.25	989	Yes
[C]525	07/08/2004	1145–1420	1.76	731.24	7.88	727.36	1,240	Yes
526	**09/14/2004**	**1010–1135**	**1.29**	**730.77**	**6.39**	**725.87**	**301**	**No**
527	11/08/2004	1120–1320	1.74	731.22	7.16	726.64	800	Yes
528	03/10/2005	1200–1400	2.11	731.59	8.10	727.58	1540	Yes
529	**06/28/2005**	**1035–1200**	**1.03**	**730.51**	**6.17**	**725.65**	**121**	**No**
530	**10/04/2005**	**0850–1005**	**1.27**	**730.75**	**6.45**	**725.93**	**294**	**No**
535	**07/28/2006**	**0830–0930**	**1.34**	**730.82**	**6.55**	**726.03**	**368**	**No**
536	10/02/2006	1010–1140	1.46	730.94	6.59	726.07	429	Yes
[D]538	06/28/2007	1009–1023	1.65	731.13	7.06	726.54	801	---
[E]541	11/09/2007	1043–1056	1.53	731.01	7.09	726.57	703	---
[E]542	12/17/2007	1354–1409	1.74	731.22	7.59	727.07	1,140	---

[A]Tailwater gage was not yet installed. Flow-regime conditions are considered free weir for computations.

[B]Ice-affected measurement, not used in equation development.

[C]Outlier, measurement not used in equation development.

[D]Hinged-crest gate opening changed 20 minutes before measurement, not used in equation development.

[E]Hinged-crest gate repairs, measurement not used in equation development.

Appendix D. Fox River at Algonquin, Illinois, Headwater and Tailwater Stages for Ogee Spillway and Hinged-Crest Gate Measurements with the Hinged-Crest Gate Open.

[USGS, U.S. Geological Survey; ft,foot; ft^3/s, cubic foot per second; $h_{g_{HCG}}$, hinged-crest gate opening referenced to the broad-crested-weir crest; IDNR, Illinois Department of Natural Resources–Office of Water Resources; ---, not determined]

USGS measurement number	Date	Central Standard Time	Water-surface elevation				Measured OS and (or) HCG flow (ft^3/s)	Gate opening $h_{g_{HCG}}$ (ft)
			Headwater (HW)		Tailwater (TW)			
			Stage (ft)	Elevation (ft)	Stage (ft)	Elevation (ft)		
---	11/19/2002	1118–1200	1.09	730.57	7.77	727.25	868	2.0
---	11/19/2002	1649–1735	.78	730.26	8.77	728.25	1,410	4.0
---	11/20/2002	1220–1310	.60	730.08	9.19	728.67	1,800	6.0
523	05/18/2004	1313–1328	2.86	732.34	10.66	730.14	3,570	1.0
522	05/18/2004	0821–0841	2.66	732.14	11.06	730.54	3,730	1.8
521	05/18/2004	0659–0722	2.56	732.04	11.29	730.77	3,890	2.4
524	05/24/2004	1234–1253	2.66	732.14	12.61	732.09	5,580	6.0
531	02/02/2006	0959–1011	1.48	730.96	8.23	727.71	1,580	2.0
533	03/17/2006	1402–1435	1.69	731.17	10.13	729.61	3,160	4.0
532	03/17/2006	1210–1247	1.55	731.03	10.42	729.90	3,320	5.0
534	05/31/2006	1156–1216	1.66	731.14	8.03	727.51	2,000	2.0
537	03/14/2007	1332–1350	1.88	731.36	10.37	729.85	3,220	4.0
539	08/22/2007	1327–1341	2.47	731.95	12.24	731.72	5,000	6.0
540	08/27/2007	1311–1328	3.45	732.93	13.43	732.91	6,600	6.0
543	01/11/2008	1033–1047	1.76	731.24	10.13	729.61	3,010	3.5
544	02/22/2008	1232–1243	1.60	731.08	8.75	728.23	1,980	2.0
545	03/26/2008	0912–0941	1.87	731.35	10.68	730.16	3,850	4.0
546	04/16/2008	1038–1053	2.62	732.10	12.43	731.91	5,510	6.0
547	06/11/2008	0948–1005	2.28	731.76	11.74	731.22	4,560	6.0
548	06/20/2008	0954–1007	2.95	732.43	12.80	732.28	6,030	6.0
IDNR	09/16/2008	1130	2.22	731.70	10.08	729.56	2,936	2.0

Appendix E: Photographs of Various Flow Conditions, Fox River near McHenry, Illinois

Acronyms

BCW – broad-crested weir
FW – free-weir flow
HCG – hinged-crest gate
NF – no flow
SW – submerged-weir flow

Figure E1. Looking from left to right at tailwater conditions for sluice gates, December 1, 2003.

Figure E2. Looking at the upstream face of open hinged-crest gate, measurement 58, March 26, 2008. HCG flow regime=SW.

Figure E3. Looking at tailwater conditions of open hinged-crest gate, measurement 58, March 26, 2008. HCG flow regime=SW. BCW flow regime=NF.

Figure E4. Looking from right to left at headwater conditions for open hinged-crest gate and weir, measurement 58, March 26, 2008. HCG flow regime=SW. BCW flow regime=NF.

Figure E5. Looking from left to right at tailwater conditions for sluice gates, measurement 58A, March 26, 2008.
Sluice gate flow regime=FW.

Figure E6. Looking from right to left at headwater conditions for sluice gates, measurement 59A, April 16, 2008. Sluice gate flow regime=SW.

Figure E7. Looking from right to left at hinged-crest gate and weir, showing both headwater and tailwater conditions, measurement 59, April 16, 2008. HCG flow regime=SW. BCW flow regime=FW

Appendix F: Photographs of Various Flow Conditions, Fox River at Algonquin, Illinois

Acronyms

AFF – affected flow
FW – free-weir flow
FW-FL – free-weir flow with flow over the hinged-crest gate (crest at elevation of ogee spillway)
FW-NF – free-weir flow with no flow over the hinged-crest gate
HCG – hinged-crest gate
NF – no flow
OS – ogee spillway
SW – submerged-weir flow

Figure F1. Looking at the downstream face of the hinged-crest gate, measurement 506, April 11, 2002. Flow regime=FW-NF.

Figure F2. Looking from right to left at both headwater and tailwater conditions, measurement 506, April 11, 2002. Flow regime=FW-NF.

Figure F3. Looking from right to left at tailwater conditions, measurement 506, April 11, 2002. Flow regime=FW-NF.

Figure F4. Looking downstream at hinged-crest gate and spillway from bridge, measurement 506, April 11, 2002.
Flow regime=FW-NF.

Figure F5. Looking from right to left at headwater and tailwater conditons while gate is fully open, November 20, 2002.
HCG flow regime=FW.
OS flow regime=NF.

Figure F6. Looking downstream at headwater and tailwater conditions when gate is fully open, November 20, 2002.
HCG flow regime=FW.
OS flow regime=NF.

Figure F7. Looking downstream of gate at tailwater conditions, November 20, 2002.
HCG flow regime=FW.
OS flow regime=NF.

Figure F8. Looking upstream from riprap at tailwater conditions, November 20, 2002.
HCG flow regime=FW.
OS flow regime=NF.

Figure F9. Looking downstream at headwater conditions from upstream side of bridge, November 20, 2002.
HCG flow regime=FW.
OS flow regime=NF.

Figure F10. Looking upstream at spillway, measurement 511, January 9, 2003.
Flow regime=FW-FL.

Figure F11. Looking downstream along new rock deposition, measurement 511, January 9, 2003.
Flow regime=FW-FL.

Figure F12. Looking upstream at gate and spillway, measurement 511, January 9, 2003. Flow regime=FW-FL.

Figure F13. Looking downstream of gate and spillway, measurement 511, January 9, 2003. Flow regime=FW-FL.

Figure F14. Looking at conditions of hinged-crest gate, measurement 515, June 18, 2003. Flow regime=FW-FL.

Figure F15. Looking downstream from gate, measurement 516, September 3, 2003. Flow regime=FW-NF.

Figure F16. Looking from right to left at tailwater conditions, measurement 518, December 2, 2003. Flow regime=FW-FL.

Figure F17. Looking at upstream side of hinged-crest gate as well as tailwater conditions during flood, measurement 521 May 18, 2004.
HCG flow regime=SW.
OS flow regime=AFF.

Figure F18. Looking right to left at tailwater conditions, measurement 525, July 8, 2004.
Flow regime=FW-FL.

Figure F19. Looking at downstream face of gate, measurement 527, November 8, 2004.
Flow regime=FW-FL.

Figure F21. Looking right to left at dam crest with ice, February 15, 2007.

Figure F20. Looking downstream of gate and spillway at tailwater conditions, February 15, 2007.

Figure F22. Looking right to left at headwater conditions, February 15, 2007.

Figure F23. Looking downstream of gate and spillway at tailwater conditions, measurement 537, March 14, 2007. HCG flow regime=FW. OS flow regime=AFF.

Figure F24. Looking right to left at headwater conditions, measurement 537, March 14, 2007. HCG flow regime=FW. OS flow regime=AFF.

Figure F25. Looking right to left at tailwater conditions, measurement 543, January 11, 2008. HCG flow regime=FW. OS flow regime=AFF.

Figure F26. Looking downstream, measurement 543, January 11, 2008. HCG flow regime=FW. OS flow regime=AFF.

Figure F27. Looking right to left at tailwater conditions, measurement 545, March 26, 2008. HCG flow regime=SW. OS flow regime=AFF.

Figure F28. Looking downstream of gate at tailwater conditions, measurement 545, March 26, 2008. HCG flow regime=SW. OS flow regime=AFF.

Figure F29. Looking downstream of gate at tailwater conditions, measurement 546, April 16, 2008. HCG flow regime=SW. OS flow regime=AFF.

Figure F30. Looking right to left at headwater and tailwater conditions, measurement 546, April 16, 2008. HCG flow regime=SW. OS flow regime=AFF.

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