TECHNIQUES FOR COMPUTING DISCHARGE AT FOUR NAVIGATION DAMS ON THE ILLINOIS AND DES PLAINES RIVERS IN ILLINOIS

By Dean M. Mades, Linda S. Weiss, and John R. Gray

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CONVERSION FACTORS AND ABBREVIATIONS

For readers who prefer to use metric (International System) units, conversion factors for the inch-pound terms used in this report are listed below:

Multiply Inch-Pound Unit	By	To obtain Metric Unit
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

SYMBOLS USED IN TEXT

Symbol	Description	Unit
B	Width of Tainter gate, headgate, or culvert valve	ft
C	Discharge coefficient for free orifice flow	
C_{gs}	Discharge coefficient for submerged orifice flow	
C_w	Discharge coefficient for free weir flow	
C_{ws}	Discharge coefficient for submerged weir flow	
g	Acceleration due to gravity (32.2)	ft/s^2
h_g	Vertical height of Tainter gate, headgate, or culvert valve opening	ft
h_1	Headwater depth referenced to spillway crest, valve sill, or center of headgate opening	ft
h_3	Tailwater depth referenced to spillway crest, valve sill, or center of headgate opening	ft
i	Index for time, in days	
Q	Discharge	ft^3/s
Δh	Difference between headwater and tailwater depths ($h_1 - h_3$)	ft

TECHNIQUES FOR COMPUTING DISCHARGE AT FOUR NAVIGATION DAMS ON THE ILLINOIS AND DES PLAINES RIVERS IN ILLINOIS

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ABSTRACT

Techniques for computing discharge are developed for Brandon Road Dam on the Des Plaines River and for Dresden Island, Marseilles, and Starved Rock Dams on the Illinois River. At Brandon Road Dam, streamflow is regulated by the operation of Tainter gates and headgates. At Dresden Island, Marseilles, and Starved Rock Dams, only Tainter gates are operated to regulate streamflow. The locks at all dams are equipped with culvert valves that are used to fill and empty the lock. The techniques facilitate determination of discharge at locations along the upper Illinois Waterway where no streamflow-gaging stations exist. The techniques are also useful for computing low flows when the water-surface slope between control structures on the river approaches zero and traditional methods of determining discharge based on slope are unsatisfactory.

Two techniques can be used to compute discharge at the dams--gate ratings and tailwater ratings. A gate rating describes the relation between discharge, gate opening, tailwater stage, and headwater stage. A tailwater rating describes the relation between tailwater stage and discharge.

Gate ratings for Tainter gates at Dresden Island, Marseilles, and Starved Rock Dams are based on a total of 78 measurements of discharge that range from 569 to 86,400 cubic feet per second. Flood hydrographs developed from the gate ratings and Lockmaster records of gate opening and stage compare closely with streamflow records published for nearby streamflow-gaging stations. Additional measurements are needed to verify gate ratings for Tainter gates and headgates at Brandon Road Dam after the dam rehabilitation is completed. Extensive leakage past deteriorated headgates and sluice gates contributed to uncertainty in the ratings developed for this dam.

A useful tailwater rating is developed for Marseilles Dam. Tailwater ratings for Dresden Island Dam and Starved Rock Dam are of limited use because of varying downstream channel-storage conditions. A tailwater rating could not be developed for Brandon Road Dam because its tailwater pool is substantially affected by the headwater pool of Dresden Island Dam.

INTRODUCTION

The Illinois River and lower Des Plaines River compose the downstream 287-mi (mile) reach of the Illinois Waterway. The Waterway extends 327 mi from the mouth of the Illinois River near Grafton, Illinois, to Chicago Harbor in Chicago; it is a navigable link between Lake Michigan and the Mississippi River (fig. 1). The Illinois Waterway is used extensively for commercial transportation and recreation, and conveys wastewater and runoff from the greater Chicago Metropolitan area to the Mississippi River.

The Waterway consists of three connected reaches, each characterized by distinctly different physical features (Kilburn and others, 1984). The lower reach, the Illinois River extending from the Mississippi River to near Utica, Illinois, is a 231-mi-long natural channel that has a relatively gentle slope of 0.18 ft/mi (foot per mile). The middle reach is also a natural channel and includes the upper Illinois River and the most downstream 17 mi of the Des Plaines River. This reach is 56 mi long and falls 1.2 ft/mi. The 40-mi-long upper reach has a slope of 0.10 ft/mi and is composed of 32 mi of the Chicago Sanitary and Ship Canal and 8 mi of the Chicago River and its South Branch.

A minimum Waterway depth of 9.0 ft (feet) is maintained for navigational purposes by operations at eight combination locks and dams. Depths in the upper reach of the Waterway are maintained by Lockport Lock and Dam at Waterway mile 293.0. Depths in the middle reach are maintained by Brandon Road Lock and Dam at mile 285.9, Dresden Island Lock and Dam at mile 271.5, Marseilles Dam at mile 247.0, Marseilles Lock at mile 244.5, and Starved Rock Lock and Dam at mile 231.0. Depths in the lower reach are maintained by Peoria Lock and Dam at mile 157.8, La Grange Lock and Dam at mile 80.2, and Lock and Dam No. 26 on the Mississippi River near Alton, Illinois, 15.1 mi downstream from the mouth of the Illinois River. Make-up water for navigational needs is obtained by diverting water from Lake Michigan to the Illinois River basin at Wilmette Harbor, Chicago Harbor, and the Thomas J. O'Brien Lock and Dam (fig. 1).

Discharge is regulated at the dams to maintain as steady a headwater-pool stage as is possible. No attempt is made to regulate floods when a steady headwater-pool stage cannot be maintained. All Tainter gates are raised out of the water, headgates are fully opened, or Chanoine wickets are completely lowered during floods.

The U.S. Geological Survey (Survey) and the U.S. Army Corps of Engineers (Corps) began a cooperative effort in 1977 to determine discharge ratings for the six most downstream dams on the Illinois Waterway (fig. 1). These relations were needed so that the Corps could more effectively regulate Waterway discharge for navigational purposes.

The study concluded in 1981 with publication of discharge ratings for gated spillways and headgates at Brandon Road Dam; gated spillways at Dresden Island, Marseilles, and Starved Rock Dams; and butterfly valves and Chanoine wickets at Peoria and La Grange Dams (Mades, 1981). The ratings were based on 50 measurements of discharge ranging from 1,730 to 86,400 ft^3/s (cubic feet per second). Mades (1981) concluded that additional measurements were needed at Dresden Island, Marseilles, and Starved Rock Dams because some flow regimes were not rated or the published rating was based on only one or two measurements. He also concluded that additional measurements were needed at Brandon Road Dam because substantial leakage, about 830 ft^3/s, through deteriorated headgate and sluice-gate seals made it difficult to develop accurate ratings for the headgates and Tainter gates at the dam.

Eleven additional measurements were made during Federal fiscal years 1981-82 in an attempt to verify the ratings published in 1981. Interpretation of this information was not published, however, because additional measurements were still needed.

A cooperative study by the Survey and the Corps was begun in 1983 at Brandon Road, Dresden Island, Marseilles, and Starved Rock Dams. The objectives of the study were to (1) define ratings for flow regimes that had not been rated, (2) refine ratings that may have changed because of dam rehabilitation or that were originally defined with very few measurements, (3) define ratings for valves used to fill the lock at each dam, and (4) define tailwater ratings that could be used as an alternative method to estimate discharge at a dam independent of gate settings.

Purpose and Scope

The purpose of this report is to describe discharge ratings for gates, tailwater stage, and lock valves at the Brandon Road, Dresden Island, Marseilles, and Starved Rock Locks and Dams on the Illinois Waterway. Data published by Mades (1981), unpublished information collected in 1981 and 1982, and data collected during the present study from 1983 through 1986 are presented in this report. The gate ratings presented in this report supersede some ratings published in 1981. The tailwater-stage ratings and valve ratings are presented for the first time. No additional work was performed at Peoria and La Grange Dams; therefore, the previously published ratings for these dams have not been changed.

The ratings presented in this report are valid for the hydraulic conditions measured during the period of study.

Description of Dams

Brandon Road Dam

Brandon Road Lock and Dam (fig. 2) is on the Des Plaines River at river mile 13.3 (Illinois Waterway mile 285.9), 14.4 mi upstream from Dresden Island Dam and 41.1 mi downstream from Lake Michigan. Streamflow is regulated at the dam by raising various numbers of the 21 Tainter gates clear of the water to maintain a normal headwater-pool elevation of 538.5 ft. Each gate is 50 ft wide and 2.25 ft high. The ogee spillway crest (hereafter, spillway crest), on which a closed gate rests, is at elevation 536.3 ft. Maps of soundings made in 1978 indicate the streambed on the upstream side of the dam is at an elevation between about 528 and 532 ft.

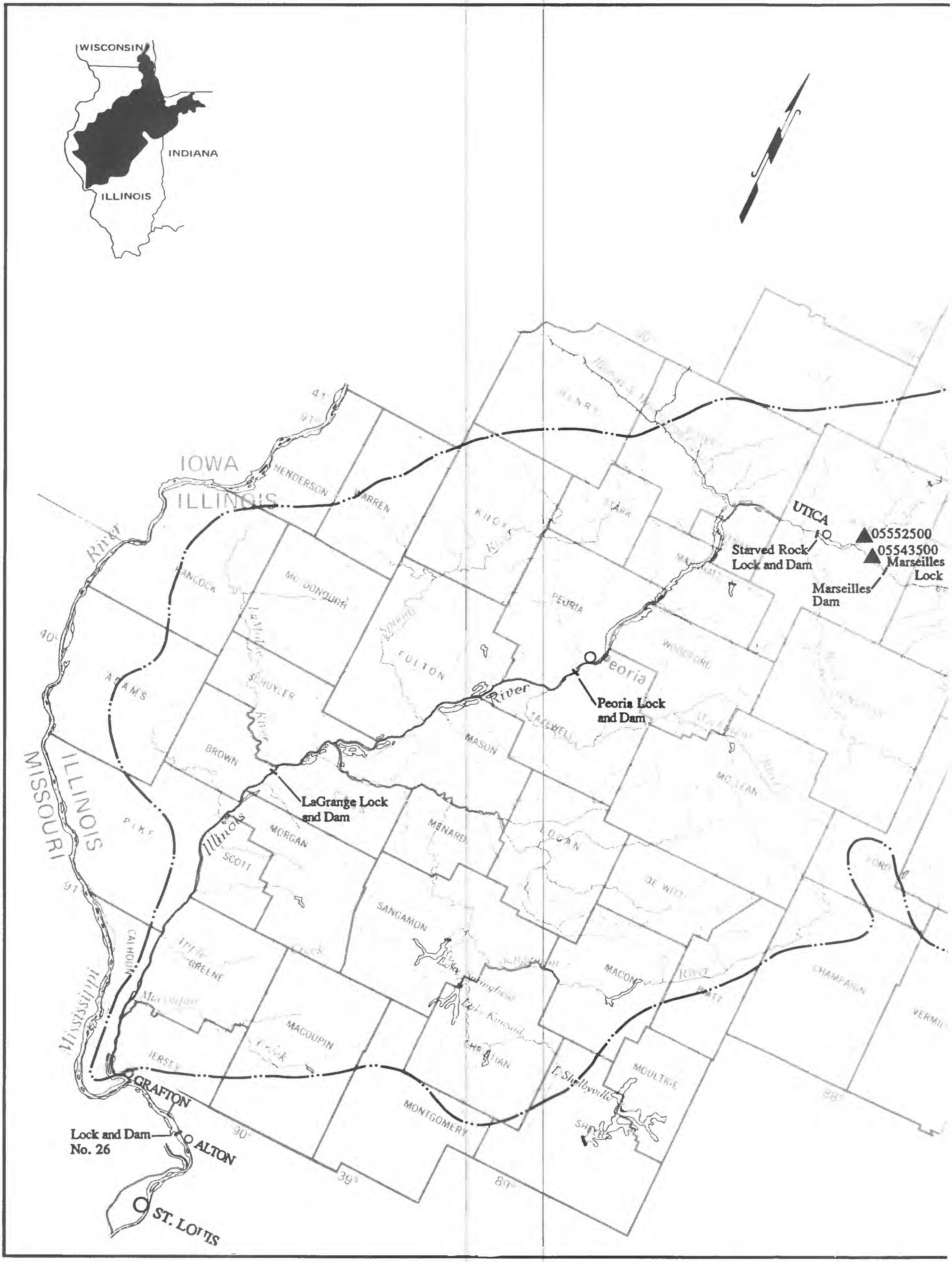
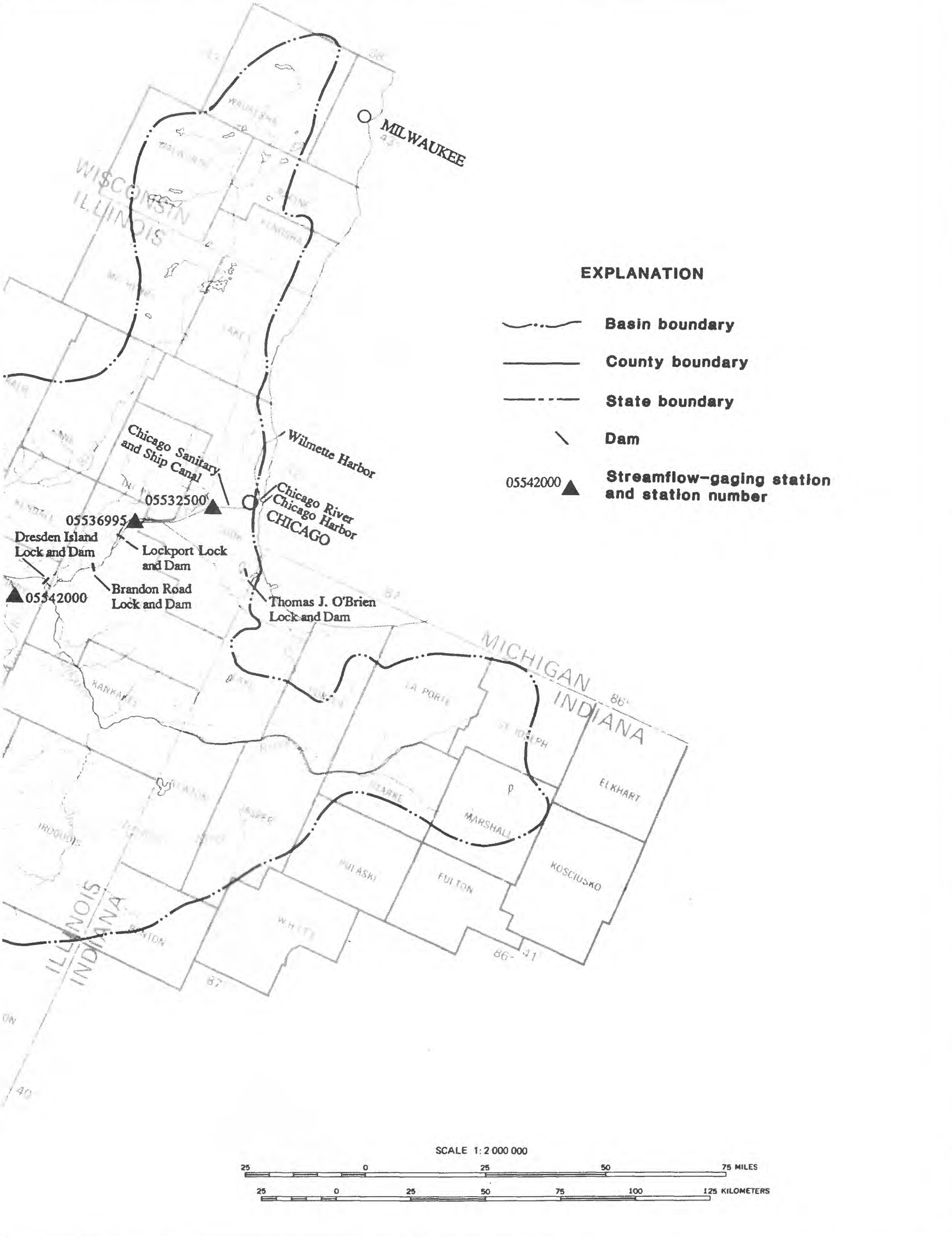
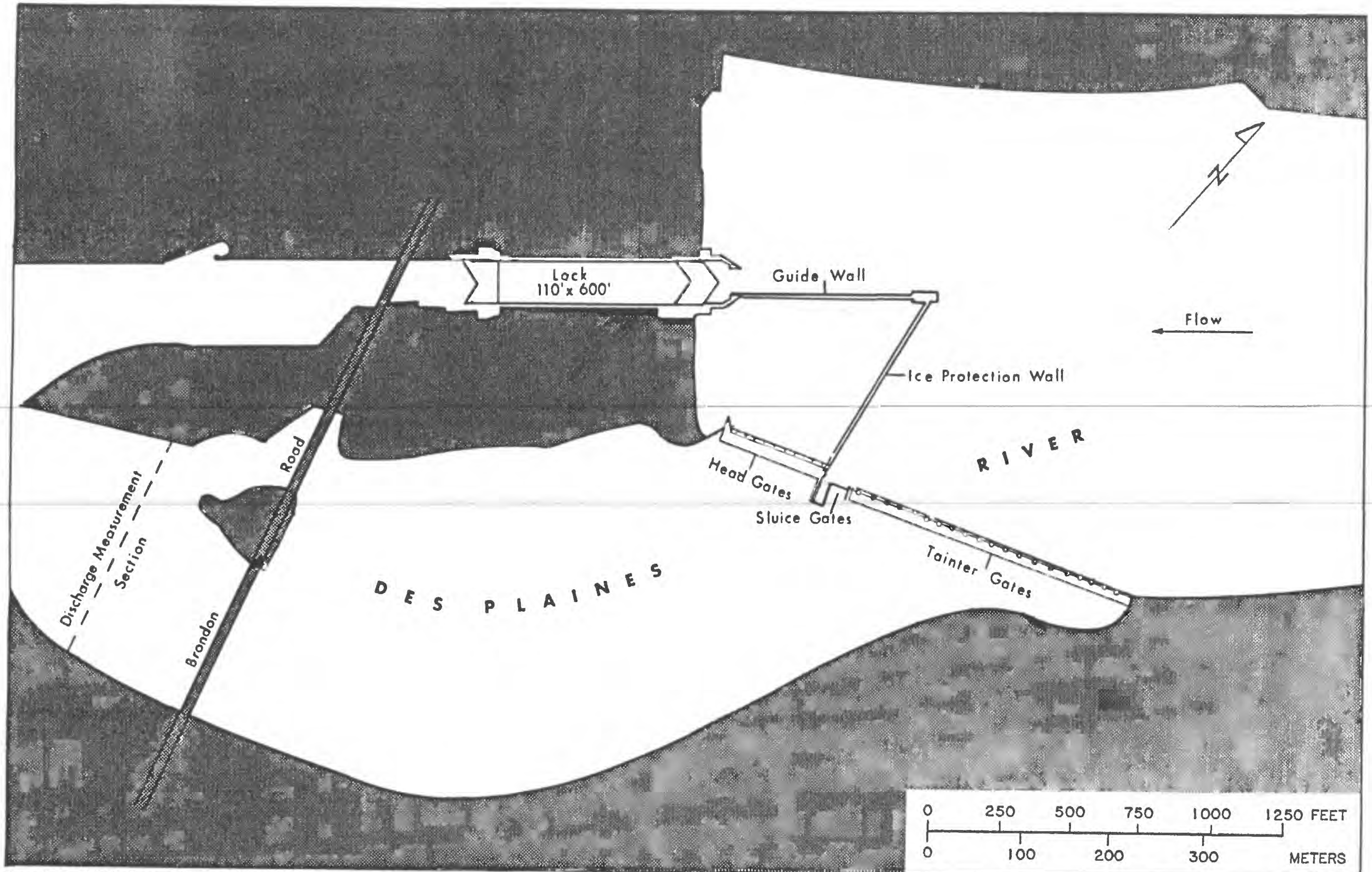


Figure 1.--Location of



Illinois Waterway and dams.



Base from U.S. Army Corps of Engineers,
Chicago, Illinois, September 30, 1978

Figure 2.--Brandon Road Lock and Dam.

The headgate structure adjacent to the Tainter-gate structure originally contained 16 sets of vertical-lift slide gates (hereafter, slide gates). Each of the two slide gates in a set was 10 ft high and 15 ft wide. The upper gates could be raised a maximum of 8.0 ft during regulation of high streamflows. The lower gates were never raised.

The headgate structure is presently (1987) undergoing extensive rehabilitation. Each set of slide gates will be replaced by one slide gate that is 16 ft high and 15 ft wide. The elevation of the concrete sill on which each slide gate will rest is 511.0 ft. The rehabilitation of Brandon Road Dam was nearly completed as of December 1987 (Roy Chapman, U.S. Army Corps of Engineers, oral commun., 1987).

Two lock culvert valves (hereafter, lock valves) are used to fill Brandon Road Lock. Each lock valve is a slide gate, 12 ft wide and 9 ft high. The elevation of the sill on which each gate rests when closed is 489.8 ft.

Dresden Island Dam

Dresden Island Lock and Dam is on the Illinois River at river mile 271.5, 1.5 mi downstream from the confluence of the Des Plaines and Kankakee Rivers. Streamflow is regulated by the operation of nine Tainter gates (fig. 3) to maintain a normal headwater-pool elevation of 504.5 ft. Each gate is 60 ft wide and 16 ft high. The spillway-crest elevation under the Tainter gates is 490.5 ft, and the forebay-floor elevation is 484.4 ft.

The headgate structure located adjacent to the Tainter-gate structure was not used for regulation between 1978 and 1983. All 16 slide gates were removed and the orifices were sealed with concrete in 1984.

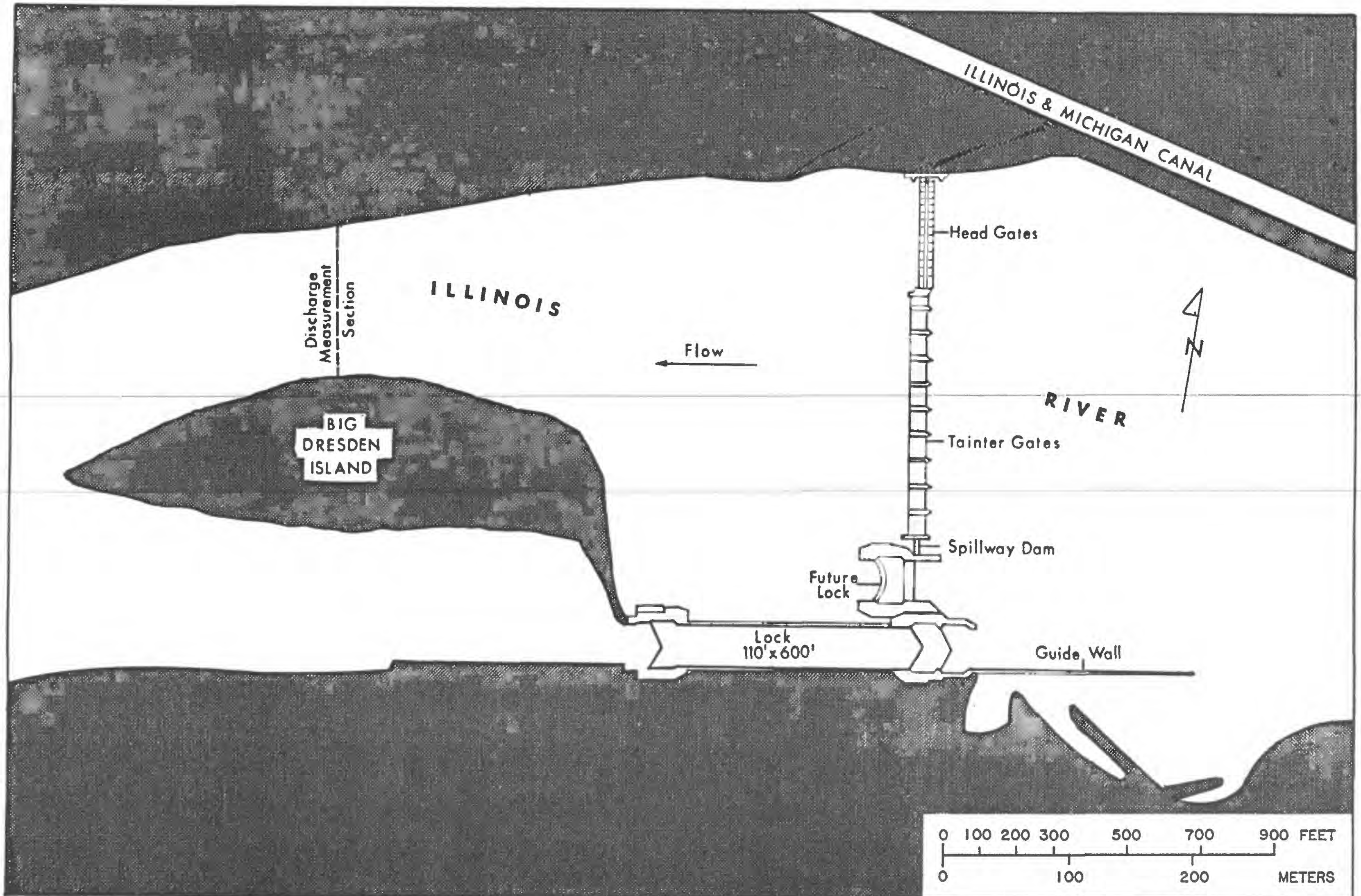
Two lock valves are used to fill Dresden Island Lock. Each lock valve is a slide gate, 12 ft wide and 9 ft high. The elevation of the sill on which each gate rests when closed is 473.0 ft.

Marseilles Dam

Marseilles Dam is on the Illinois River at river mile 247.0 (fig. 4). The lock is 2.5 mi downstream on the Marseilles Canal. Streamflow is regulated by the operation of eight Tainter gates to maintain a headwater-pool elevation of 482.8 ft. Each gate is 60 ft wide and 17 ft high. The spillway-crest elevation under the Tainter gates is 469.8 ft and the forebay-floor elevation is 468.6 ft.

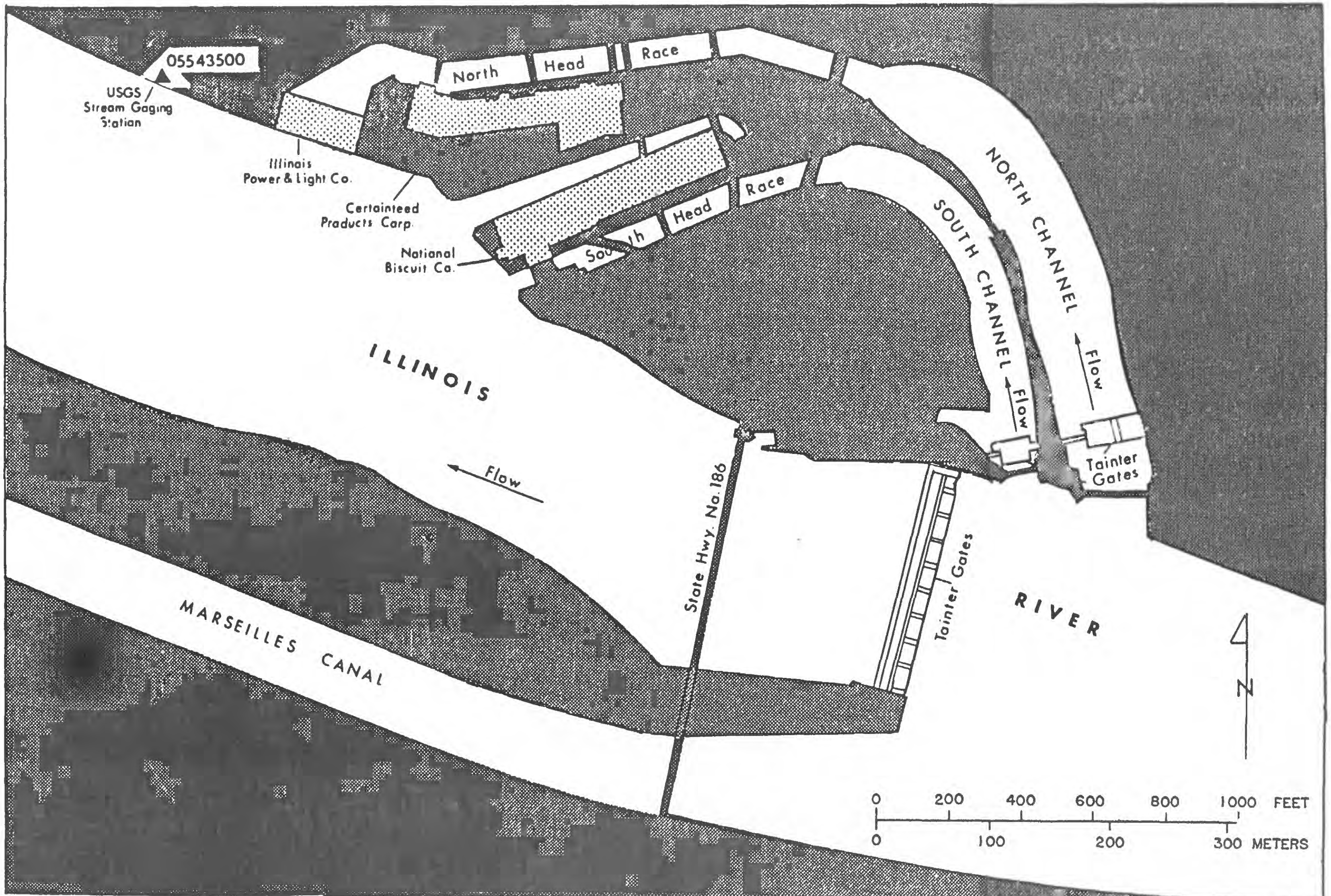
Two lock valves are used to fill Marseilles Lock. Each lock valve is a slide gate, 12 ft wide and 9 ft high. The elevation of the sill on which each gate rests when closed is 447.0 ft.

Illinois Power and Light Company operates a hydroelectric powerplant just downstream from the dam. Water is diverted via Tainter gates from the headwater pool through the north and south channels to turbines near the right



Base from U.S. Army Corps of Engineers, Chicago, Illinois, September 30, 1978

Figure 3.--Dresden Island Lock and Dam.



Base from U.S. Army Corps of Engineers,
Chicago, Illinois, September 30, 1978

Figure 4.--Marseilles Dam.

edge of the tailwater pool. Water diverted to the south channel flows into the north channel about 650 ft downstream from the gates.

Three Tainter gates can be used to regulate diversions to the powerplant (fig. 4). Each gate and the underlying spillway have the same geometry as the main dam. The west gate, across the south channel, is permanently closed, and the middle gate usually is opened 0.5 ft. The east gate, across the north channel, is automatically operated to maintain a steady water-surface elevation of 481.0 ft in the north channel. This gate is infrequently raised more than 4.0 ft.

Starved Rock Dam

Starved Rock Lock and Dam is on the Illinois River at river mile 231.0. Streamflow is regulated by the operation of 10 Tainter gates (fig. 5) to maintain a normal headwater-pool elevation of 458.5 ft. Each gate is 60 ft wide and 19 ft high. The spillway crest on which a closed gate rests is at elevation 441.5 ft and the forebay-floor elevation is 438.4 ft.

The headgate structure adjacent to the Tainter-gate structure contains 28 slide gates that are never used for regulation.

Two lock valves are used to fill Starved Rock Lock. Each lock valve is a slide gate, 12 ft wide and 9 ft high. The elevation of the sill on which each gate rests when closed in 426.5 ft.

Acknowledgments

The U.S. Army Corps of Engineers, Rock Island District, provided some of the data used in this report. Discharge measurements were made for a variety of operating conditions, which the Corps Lockmasters readily arranged. The cooperation of Corps personnel, particularly Mr. Dan Callahan (Lockmaster, Dresden Island Lock and Dam) and Mr. Donald Byczynski (Lockmaster, Starved Rock Lock and Dam), is greatly appreciated.

METHODS OF STUDY

Two techniques for computing discharges at the study dams are developed. The first technique, termed a gate rating or valve rating, describes the relation between discharge under a gate (or through a valve), headwater- and tailwater-pool stages at the dam, and gate (or valve) opening. The second technique, termed a tailwater rating, describes the relation between discharge at the dam and tailwater-pool stage.

Gate and Valve Ratings

The flow of water under a gate, or through a valve, can be categorized by flow regime. Four flow regimes, hydraulic conditions for defining each regime, and equations for computing discharge are listed in table 1. The hydraulic

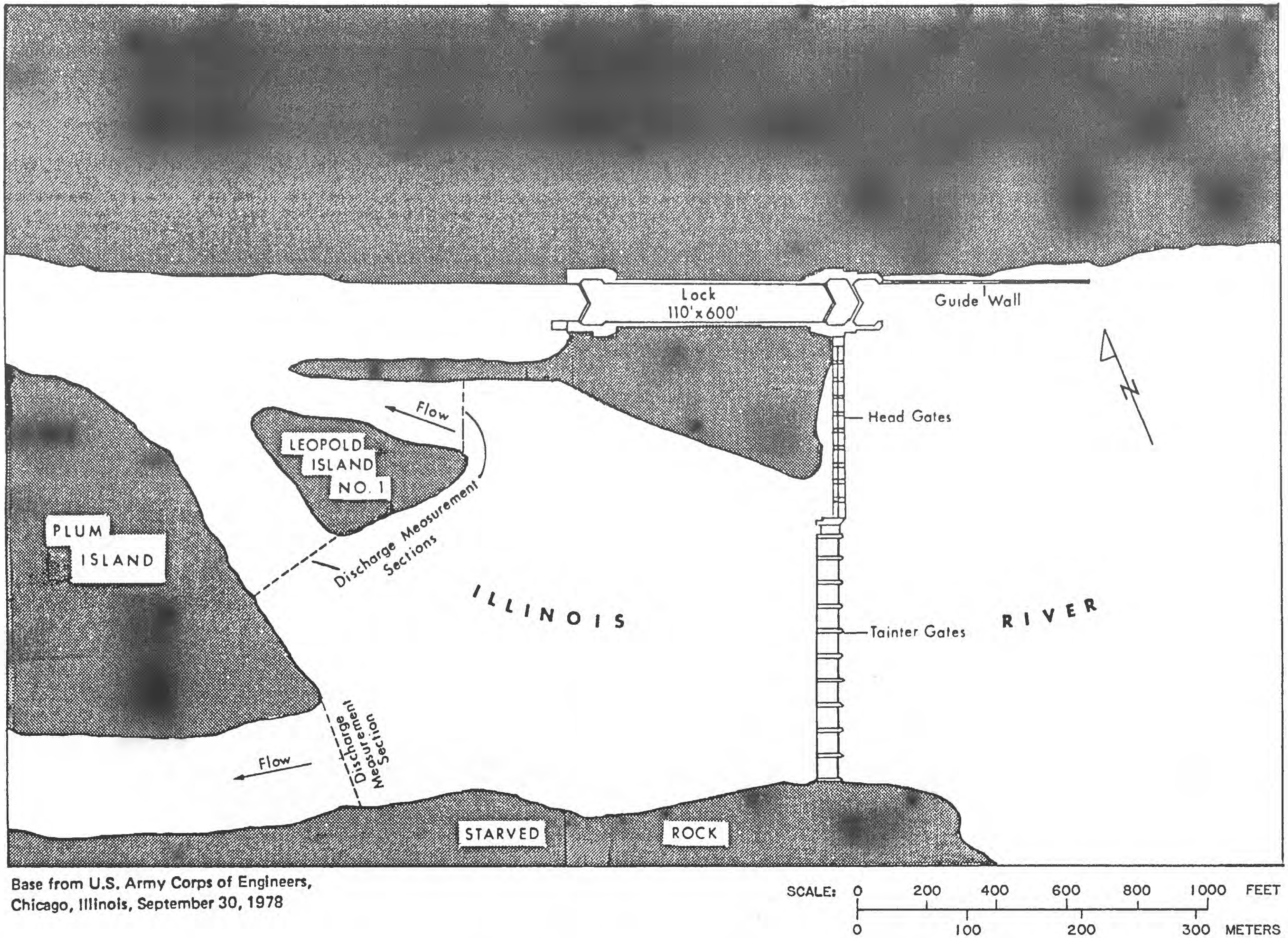


Figure 5.--Starved Rock Lock and Dam.

Table 1.--Equations of flow controlled by a Tainter gate, headgate, or lock valve

[h_1, static headwater depth (ft); h_3, static tailwater depth (ft); h_g, gate opening (ft); Δh, difference between headwater and tailwater depths; g, gravitational constant (32.2 ft/s^2); Q, discharge (ft^3/s); B, width of gate or valve (ft); C, discharge coefficient for free orifice flow (dimensionless); C_{gs}, discharge coefficient for submerged orifice flow (dimensionless); C_w, discharge coefficient for free weir flow (dimensionless); C_{ws}, discharge coefficient for submerged weir flow (dimensionless); ft, foot; ft/s^2, feet per second squared; ft^3/s, cubic feet per second]

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

conditions listed in table 1 are general criteria because they are based on a review of laboratory and field studies (Collins, 1977). Specific criteria for a particular dam must be based on field observations.

Headwater depth, h_1, and tailwater depth, h_3, are referenced to the elevations of specific locations, or reference points, on a cross section of the structure. The reference point for flow under a Tainter gate (fig. 6) and over a free-overflow spillway is the spillway crest. The reference point for a slide gate is the center of the opening through which water discharges (fig. 7). The elevation of this point is the sum of the elevation of the top of the concrete sill on which a closed gate rests and one-half of the gate opening. The reference point for a lock valve is the top of the concrete sill on which a closed lock valve rests. Table 2 is a summary of hydraulic-control characteristics that are frequently mentioned in this report.

Gate ratings and valve ratings were developed using a three-step procedure. Discharge, upstream- and downstream-pool stages, and gate opening were concurrently measured in the first step. The second step was to substitute these measurements into the appropriate equations shown in table 1 and calculate the value of the discharge coefficient (C, C_{gs}, C_w, or C_{ws}). Steps 1 and 2 were repeated for various gate openings, stages, and flow regimes until a wide range of hydraulic and operating conditions were measured.

In the third step, an equation representing the relation between the discharge coefficients for a particular flow regime and gate opening, upstream-pool stage, downstream-pool stage, or a combination of these factors

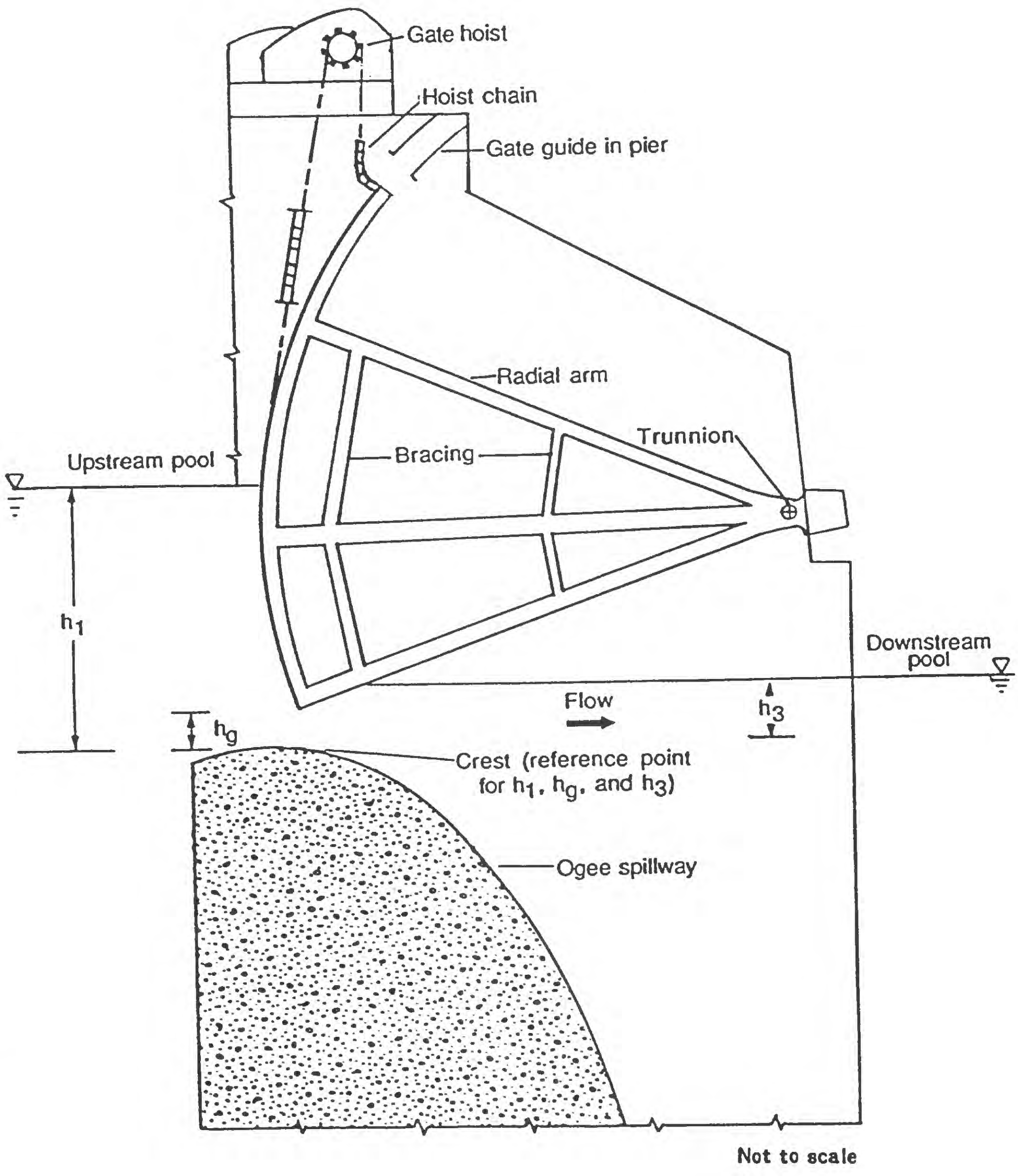


Figure 6.--Construction of a typical Tainter gate.

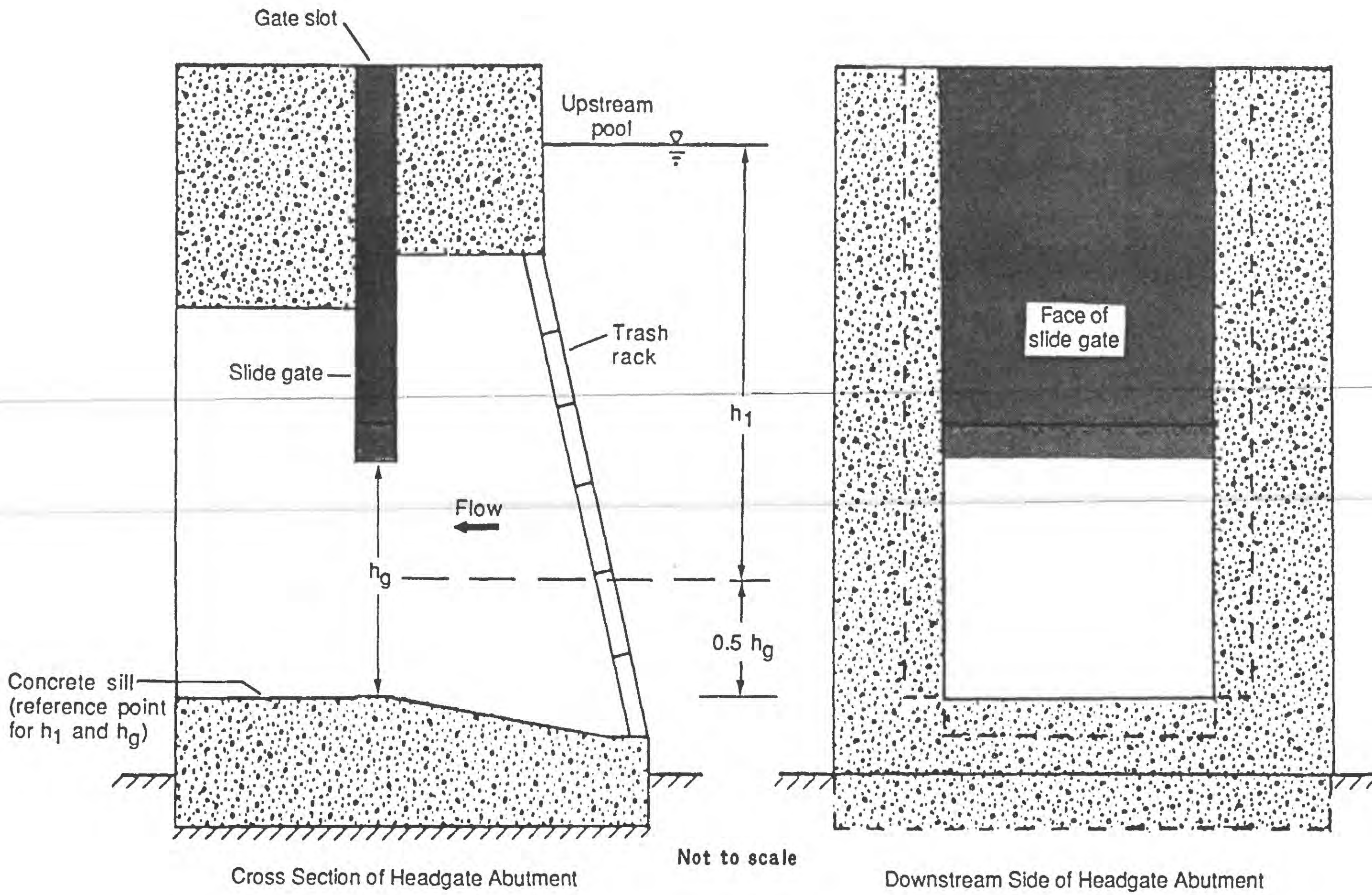


Figure 7.--Construction of a typical headgate abutment.

Table 2.--Summary of hydraulic-control characteristics for Brandon Road, Dresden Island, Marseilles, and Starved Rock Locks and Dams

Characteristic	Brandon Road	Dresden Island	Marseilles	Starved Rock
Normal headwater-pool elevation, in feet	538.5	504.5	482.8	458.5
Tainter gates:				
Number of gates	21	9	8	10
Width, in feet	50	60	60	60
Height, in feet	2.25	16	17	19
Elevation of spillway crest, in feet	536.5	490.5	469.8	441.5
Elevation of forebay floor, in feet	506.0	484.4	468.6	438.4
Headgates:				
Number of gates	8	0	0	0
Width, in feet	15	--	--	--
Height, in feet	16	--	--	--
Elevation of top of concrete sill, in feet	511.0	--	--	--
Lock culvert valves:				
Number of valves	2	2	2	2
Width, in feet	12	12	12	12
Height, in feet	9	9	9	9
Elevation of top of concrete sill, in feet	489.8	473.0	447.0	426.5

was developed using least squares regression techniques. The final rating was developed by substituting these equations into equations 1, 2, 3, or 4 (table 1).

Discharge was measured using three different methods. Current-meter measurements were made in main channels, at spillway crests, and in forebays to develop gate ratings. The stage-discharge relation for gaging station 05543500 (Illinois River at Marseilles) was used to determine discharge at Marseilles Dam for gate ratings. Volumetric measurements were made to develop valve ratings.

Current-meter measurements usually were made from a boat or bridge at a main-channel section less than one-half mile downstream from a study dam. Standard Survey measurement equipment and techniques were used (Rantz and others, 1982). Measurements were made when stage at the measuring section was steady or nearly steady so that effects of changes in storage between the dam and measuring section were minimized.

Extremely dangerous conditions exist in the main channel downstream from Dresden Island Dam during floods. High velocities and large floating debris or ice precluded use of main-channel current-meter measurements from a boat. The only nearby bridge was a railroad bridge from which it was extremely difficult and dangerous to make measurements.

An unmanned carrier cableway (figs. 8 and 9) was erected over the forebay of gates No. 2 and No. 6 at Dresden Island Dam to measure discharge in the forebay section during floods when main-channel measurements could not be made. A standard Price AA current meter and sounding weights ranging from 50 to 200 pounds were used to measure discharge in the forebays. Tests were run in the field and in the University of Illinois Hydrosystems Laboratory (Clark, 1985) to determine whether subsurface flow angles caused by pier-induced contraction of flow would significantly affect the accuracy of forebay measurements. Results of these tests indicated that accurate measurements could be made.

At Brandon Road Dam, current-meter measurements were made on the crest of the spillway. Although this is an imperfect measurement section, it is the only section where discharge was unaffected by leakage. Significant leakage through deteriorated gate seals existed at this dam throughout the duration of the study. Attempts to measure this leakage were unsuccessful because it is impossible to lower the upstream pool, close all gates, and measure discharge before water begins to spill over the closed gates.

Discharge at Marseilles Dam was determined from the stage-discharge rating at gaging station 05543500 as defined by about 300 discharge measurements that have been made since 1940. The rating is very stable and does not show any backwater effects. Discharge at the gaging station includes discharge at the dam and return flow from Illinois Power and Light Company's hydroelectric powerplant (fig. 4). Return flow from the powerplant was measured using standard current-meter techniques when it appeared that this flow exceeded 5 percent of the discharge at the gaging station. Discharge at the dam was determined by reading stage at the gaging station, using the stage-discharge rating to compute discharge at the station, and adjusting this value for intervening flow between the dam and gaging station based on a current-meter measurement of return flow if warranted. Total discharge at the dam was then prorated to each gate that was being used.

During gate-rating measurements, a preselected number of gates were set to similar openings, whenever possible, so that similar flow regimes and discharges existed at each gate. Discharge was measured after it appeared that upstream- and downstream-pool stages were steady so that the configuration of gate settings would not have to be changed during a measurement.

Volumetric measurements were made to rate the valves used to fill the locks. These measurements were made by closing both the upstream and downstream lock miter gates and measuring the time-rate-of-change in stage of water inside the lock while it was filled. The volume of water discharged into the lock is the product of the water-surface area and stage inside the lock. The slope of the relation between lock-water volume and time is equivalent to the discharge through the lock valves plus leakage through the closed miter gates. Very little leakage was observed during any measurement.

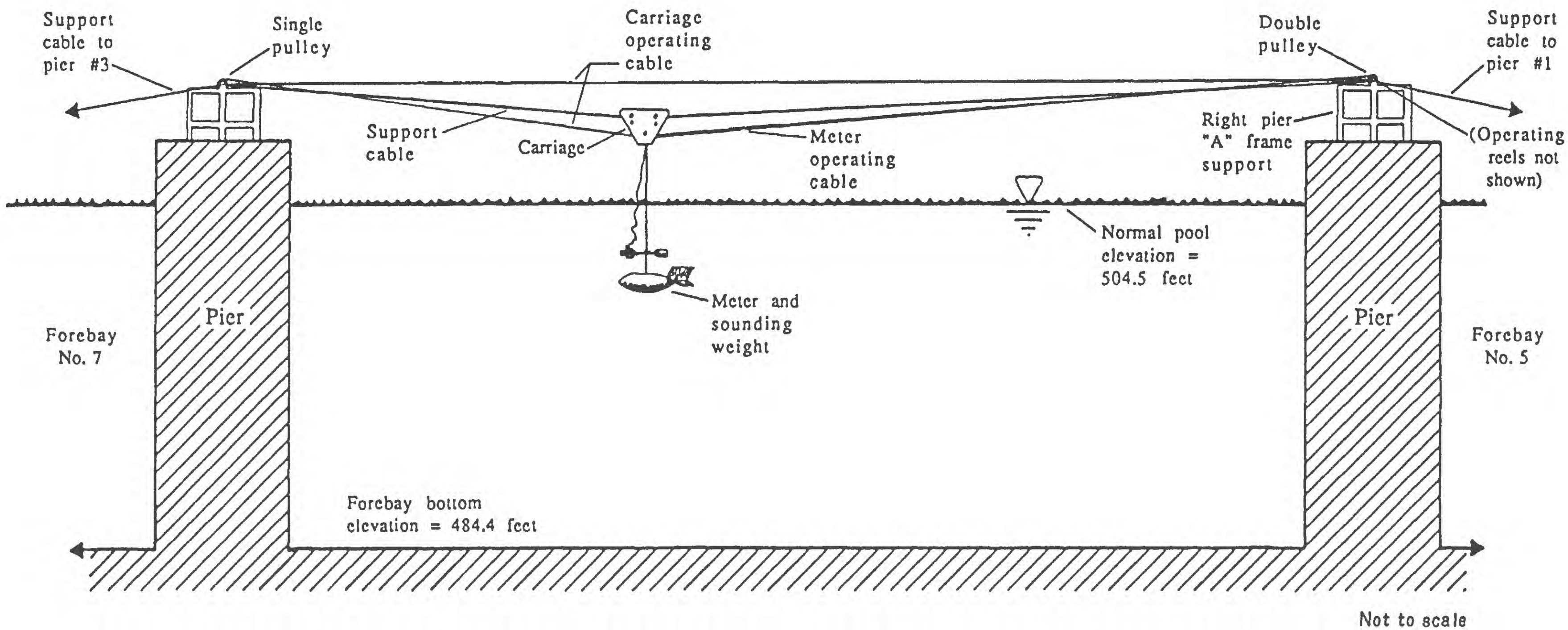


Figure 8.--Upstream view of carrier cableway used to make forebay discharge measurements at Dresden Island Dam.

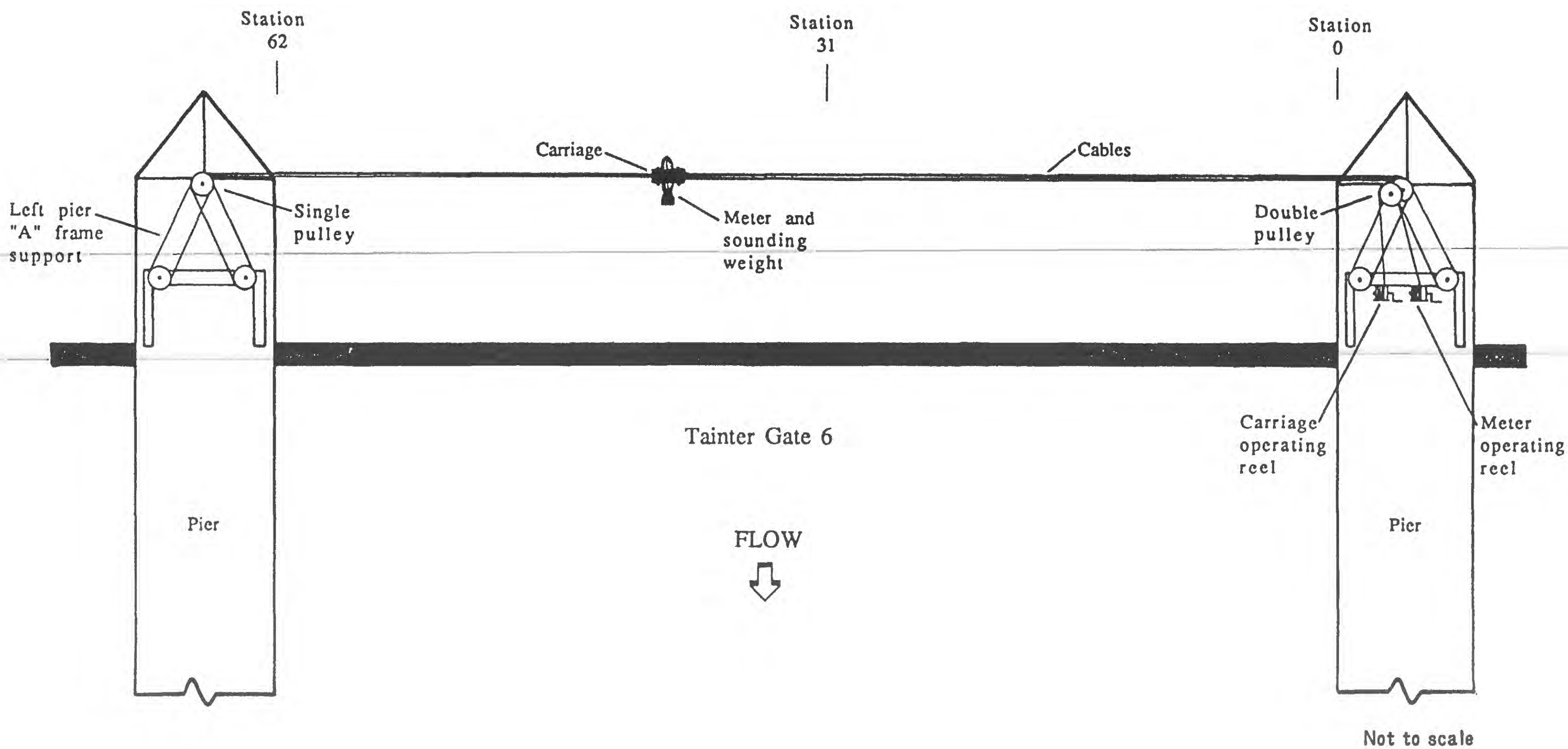


Figure 9.--Overhead view of carrier cableway used to make forebay discharge measurements at Dresden Island Dam.

Upstream- and downstream-pool stages were determined from readings of staff gages or automatic stage recorders. Corps recording gages continuously measure stage at upstream and downstream locations on the lock guide walls. A stilling well and electric-tape gage were installed at the right edge of water in a tailwater section of Marseilles Dam. All gage readings were first recorded as elevations referenced to sea level and later transformed to depths referenced to a spillway-crest elevation or some other fixed reference point (figs. 6 and 7) for which an appropriate value of h_1 and h_3 (table 1) could be determined.

Gate openings for Tainter gates were determined by reading gate scales located on each gate. Each gate scale is graduated in 1-foot intervals. The Tainter gates at Brandon Road Dam do not have gate scales because these gates are either completely lowered or raised out of water when used. Lock-valve openings were not measured but were recorded as fully opened or half opened as informed by the Lockmaster or his assistant during a measurement.

The validity of gate ratings was tested by comparing daily-discharge hydrographs based on the ratings with daily-discharge records from nearby streamflow-gaging stations. A computer program was written to determine the hydrographs based on gate ratings. Equations representing the gate ratings were coded into the program. Hourly observations of headwater-pool elevation, tailwater-pool elevation, and gate settings are used by the program to calculate hourly discharge. The hourly discharges for a day are then averaged as an estimate of daily discharge.

Tailwater Ratings

Discharge in channels with stable streambeds and no obstructions is generally related to stage by an exponential function similar in form to equation 3 (table 1). Simple discharge ratings for such channels are usually defined by concurrent measurements of stage and discharge. Factors such as unstable streambeds and backwater caused by downstream dams, tributaries, or bridges increase the variability in a simple stage-discharge relation (rating). Additional information such as water-surface slope is needed to develop more complex ratings. Rantz and others (1982) describe the theory of discharge ratings and standard Survey methods for developing them.

For Marseilles Dam, a tailwater rating was developed by relating readings of tailwater-pool stage at the dam to concurrent discharges estimated from the rating for station 05543500. During periods of steady or nearly steady flow, stage was measured once daily using the electric-tape gage installed at the right edge of water in the tailwater section. Stage was measured hourly during periods of unsteady flow. Concurrent values of discharge were obtained from the hourly record of stage and discharge recorded for station 05543500. Traveltime and change in storage between the tailwater section and gaging station were not considered because the gaging station is only 1,200 ft downstream from the tailwater section.

For Brandon Road, Dresden Island, and Starved Rock Dams, tailwater ratings are affected by variable backwater effects. Gate ratings were used to develop tailwater ratings because it was impractical to collect a sufficient number of discharge measurements to accurately define the complex discharge ratings that exist at the tailwater sections of these dams. Lockmaster records of headwater- and tailwater-pool elevations and gate settings were obtained for the entire duration of selected floods. The computer program described in the previous section was used to determine an hourly flood hydrograph. The estimated hourly hydrograph was then aggregated into an estimated daily (24-hour mean) discharge hydrograph that was compared to hydrographs from nearby gaging stations to determine if the gate ratings were appropriate. After checking that the estimated daily discharge hydrograph was appropriate, the hourly values of estimated discharge and tailwater-pool stage were plotted to form a tailwater rating.

TECHNIQUES FOR COMPUTING DISCHARGE

Brandon Road Dam

In 1985, the Corps initiated a complete rehabilitation of Brandon Road Dam and its flow-regulation structures. The rehabilitation is presently (December 1987) nearing completion. Tainter gates were repaired or replaced with gates having similar dimensions. A motor was installed to operate each Tainter gate and new seals were installed on the Tainter gates and spillway crest. Eight of the sixteen headgate openings were permanently sealed with concrete. The old slide gates in the eight remaining openings were replaced with 15-ft-wide by 16-ft-high slide gates. Three of these slide gates will be operated by using fixed-position, hydraulic hoists. The other five slide gates will be raised and lowered by means of a movable cable hoist. All sluice-gate passages were permanently sealed with concrete and a 6-ft-wide free-overflow spillway section was also plugged with concrete.

Throughout the period of this study and prior to the recent rehabilitation of the dam, significant leakage hampered attempts to more accurately verify the gate ratings published by Mades (1981). The remainder of this section describes (1) the work that was done to verify the Tainter-gate ratings, (2) a theoretical rating for the recently refurbished headgates, and (3) the lock-valve rating.

Gate and Valve Ratings

Seven additional discharge measurements (table 3) were made between 1981 and 1984 to verify the earlier Tainter-gate ratings. Two measurements were made in the main channel, four were made on the crest of the gated spillway, and one measurement was made on a 6-ft-wide, free-overflow spillway section. Discharges of Hickory Creek, Sugar Run, and the East Side Municipal Treatment Plant enter the Des Plaines River between Brandon Road Dam and the measuring section at Brandon Road bridge, one-third mile downstream from the dam. Measurements of these intervening discharges were used to adjust each main-channel measurement to reflect the discharge past the dam.

Table 3.--Discharge measurements and hydraulic-control data for Brandon Road Dam

Measurement number	Date	Pool elevation, in feet[1]		Tainter gates open	Headgates		Discharge, in cubic feet per second			Deviation from rating (percent)[3]
		Head-water	Tail-water		Number	Opening (feet)	Measured	Adjusted[2]	Rated	
Main Channel										
1	04-29-81	538.25	505.5	11	0	-	7,150	6,680	4,940	35
2	05-11-81	538.55	507.5	21	0	-	14,900	14,000	11,700	20
Gated-Spillway Crest										
1	11-16-83	539.02	([4])	1	-	-	776	776	740	4.9
2	11-16-83	539.00	([4])	1	-	-	746	746	732	1.9
3	11-16-83	538.10	([4])	1	-	-	351	351	398	-12
4	09-28-84	537.45	([4])	1	-	-	200	200	203	-1.5
Free-Overflow Spillway Crest										
1	04-29-81	538.50	505.5	1	-	-	98.7	98.7	97.8	.92

[1]Elevations referenced to National Geodetic Vertical Datum of 1929.
[2]Adjusted discharge equals measured discharge less intervening flow.
[3]Defined as [(Adjusted Discharge/Rated Discharge) - 1.0] x 100%.
[4]Tailwater elevations were not determined for forebay measurements.

The earlier rating for one Tainter gate can be expressed in the form of equation 3 (see table 1). The discharge rating for free weir flow under one Tainter gate or over the free-overflow spillway section at Brandon Road Dam is

$$Q = (3.3)(B)(h_1)^{1.5}, \tag{5}$$

where Q is discharge, in cubic feet per second; 3.3 is the value of the discharge coefficient, C_w, in equation 3 as determined by Mades (1981); B is the gate or overflow section width, in feet; and h_1 is headwater depth, the difference between the headwater-pool elevation and the elevation of the gated-spillway crest (536.5 ft) or overflow-section crest (535.6 ft). Values for B are 50 ft for the gated spillway and 6 ft for the overflow section.

A comparison of rated and measured discharges is included in table 3. The rating (eq. 5) appears reasonable for four of the five spillway-section measurements. The one exception is gated-spillway section measurement 3 that shows a larger deviation. Only two verticals were measured at the measuring section, and more verticals probably were needed because of nonuniform flow past the section. The two main-channel measurements indicate that (1) the rating provides discharges that are too low (meaning the true discharge coefficient is greater than 3.3), (2) the leakage past the dam during these measurements was very large, or (3) a combination of these factors exists.

Two conclusions are offered on the basis of this work. First, the Tainter-gate rating (eq. 5) is still valid. There is a large degree of uncertainty in this conclusion because of the unquantifiable rates of leakage that existed during the two main-channel measurements and the questionable accuracy of measurements made on the spillway crest. The second conclusion is that a brief follow-up to this study is warranted now that the dam is nearly refurbished. Four to six main-channel measurements of discharge would be needed to accurately verify the Tainter-gate rating. Each measurement should be made when all headgates are closed, the headwater-pool elevation is lower than the top edge of a closed Tainter gate, and at least 10 Tainter gates are raised out of water.

The discharge rating for flow regulated by a headgate at Brandon Road Dam can be expressed by equation 1 (see table 1). Historic records of tailwater-pool elevations indicate that flows through the headgate structure should never be submerged. The discharge rating for free orifice flow through one headgate at Brandon Road Dam is

$$\begin{aligned} Q &= (C)(B)(h_g)[(2g)(h_1)]^{0.5} \\ &= (0.78)(15)(h_g)[(64.4)(h_1)]^{0.5} \\ &= (93.9)(h_g)(h_1)^{0.5} \end{aligned} \tag{6}$$

where 0.78 is the value of the discharge coefficient for free orifice flow, C, reported by the U.S. Army Corps of Engineers (1953); 15 is headgate width, B; 64.4 is two times the gravitational constant, g; and h_1 is the headwater depth referenced to the center of the gate opening. All other factors have been previously defined.

Discharge measurements are needed to verify the value of 0.78 shown in equation 6 and to determine if the value of C (eq. 1) varies with gate opening. Six to ten main-channel measurements could be made at gate-opening intervals of 2 ft using one or more headgates set to the same opening. All Tainter gates should be closed and the headwater pool should be maintained at an elevation lower than the top edge of the Tainter gates so that only the discharge through the headgate structure is measured.

The discharge ratings for one Tainter gate (eq. 5) and one headgate (eq. 6) are shown in figure 10. These ratings are not expected to be affected by tailwater-pool stages.

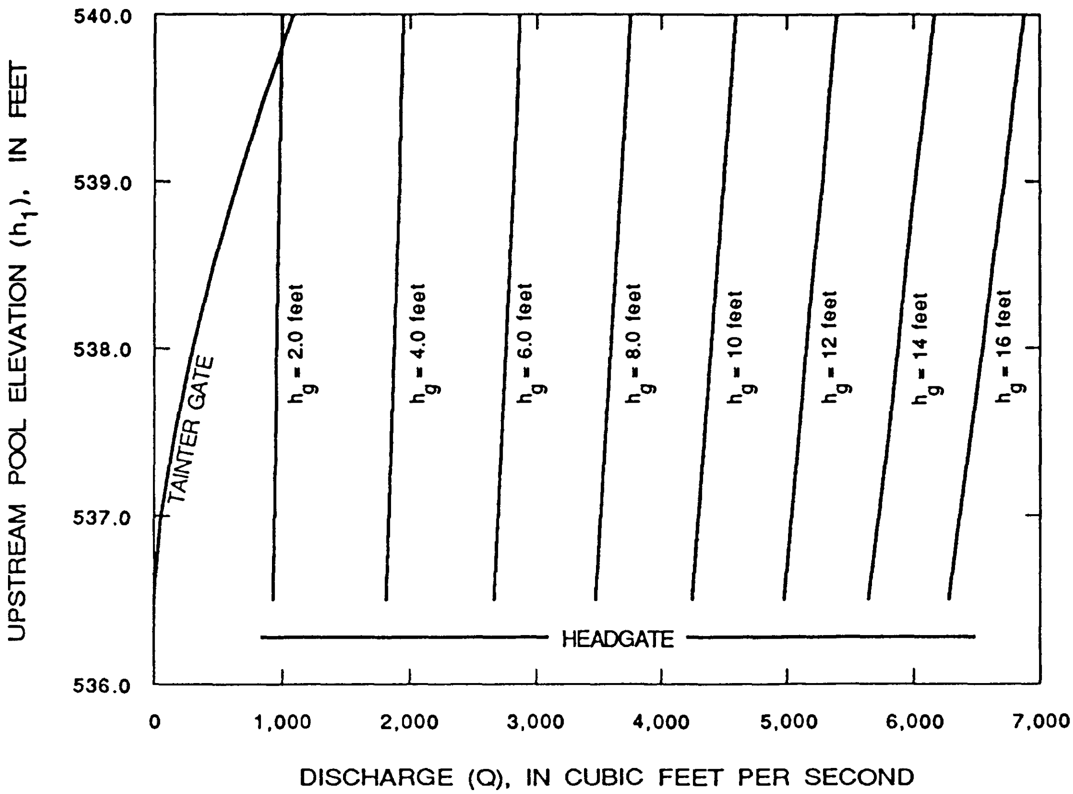


Figure 10.--Discharge ratings for one Tainter gate and one headgate at Brandon Road Dam.

Figure 11 shows the relation between the discharge coefficient for submerged orifice flow (C_{gs}) and the submergence ratio (h_3/h_g) for the upstream lock valves at Brandon Road Lock. This relation was developed from one volumetric measurement during which the lock was filled with both valves fully open (h_g equal to 9.0 ft). Tailwater stage (h_3) is the depth of water in the lock relative to the upstream lock-valve-sill elevation of 489.8 ft. This relation is expressed as

$$C_{gs} = 0.433 \, (h_3/h_g)^{-0.907}. \qquad (7)$$

Figure 11 or equation 7 may be used to determine C_{gs} for a known lock-pool elevation and valve opening.

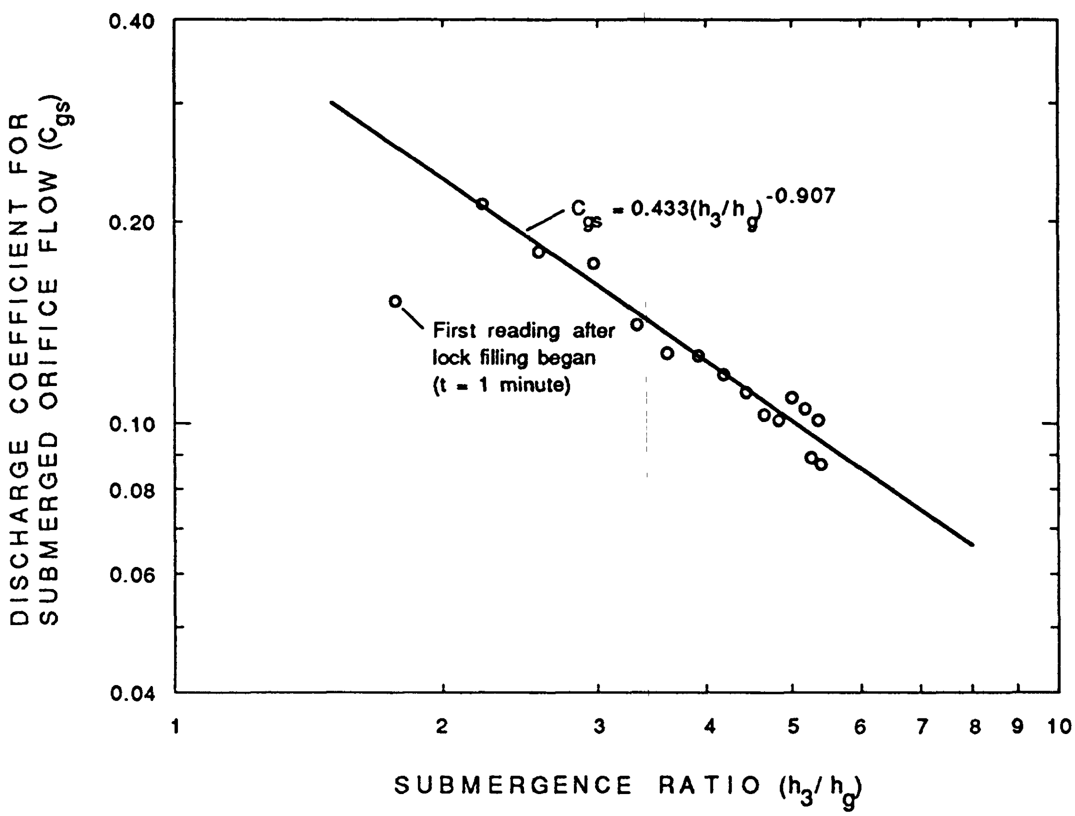


Figure 11.--Relation between the discharge coefficient for submerged orifice flow and submergence ratio for the Brandon Road Lock, upstream culvert valves.

A mathematical expression of the valve rating for Brandon Road Lock was determined by substituting equation 7 into equation 2 (table 1) as follows:

$$Q = (C_{gs})(B)(h_3)[(2g)(\Delta h)]^{0.5}$$

$$= [0.433\ (h_3/h_g)^{-0.907}](12)(h_3)[(64.4)(\Delta h)]^{0.5}$$

$$= 41.7\ (h_3)^{0.093}\ (h_g)^{0.907}\ (\Delta h)^{0.5} \qquad (8)$$

where Δh is the difference between the headwater and tailwater depths relative to the lock-valve sill. Table 4 is provided to facilitate determining discharge through a valve for a normal headwater-pool elevation of 538.5 ft. The table was developed using equation 8.

A flood in August 1987 was selected to test the validity of gate ratings and to define a tailwater rating. This flood was chosen for analysis because the dam rehabilitation was nearly complete and both Tainter gates and headgates were used to regulate discharge. Figure 12 shows two daily discharge hydrographs; one is based on the gate ratings and the other is based on streamflow records from nearby gaging stations. Daily discharges measured at Chicago Sanitary and Ship Canal at Romeoville (05536995) and Des Plaines River at

Table 4.--Discharge rating for one upstream culvert valve at Brandon Road Lock

[Based on a headwater-pool elevation of 538.5 feet]

Lock-pool elevation, in feet	Difference between headwater-pool and lock-pool elevations (Δh), in feet	Discharge, in cubic feet per second	
		One-half open[1]	Fully open[2]
538.5	0	0	0
538.0	.5	165	310
537.5	1	234	438
536.5	2	330	619
535.5	3	403	756
534.5	4	465	871
533.5	5	518	972
532.5	6	567	1,060
530.5	8	651	1,220
528.5	10	725	1,360
523.5	15	876	1,640
518.5	20	997	1,870
513.5	25	1,100	2,050
508.5	30	1,170	2,200
503.5	35	1,230	2,310

[1]Valve opening is 4.5 feet.
[2]Valve opening is 9.0 feet.

Riverside (05532500) were added together as an estimate of the actual streamflow at the dam. The combined drainage area gaged by these stations is 1,369 mi^2 (square miles), or 91 percent of the drainage area of the Des Plaines River at Brandon Road Dam. No adjustments were made to the streamflow records for factors such as intervening flows and lockages.

The results of this analysis were mixed. Differences between estimated and observed discharges were as large as 5,000 ft^3/s (about 20 percent) during the first storm on August 14-17; yet differences during a second storm on August 26-31 were less than 500 ft^3/s (about 3 percent). During August 11-13 and August 23-25, when discharge returned to normal or near-normal conditions, gate-rating discharges were consistently 400 to 1,000 ft^3/s less than discharges derived from the hydrographs.

The hydrograph based on streamflow records is believed to be accurate because field-office personnel have confirmed that all equipment at both streamflow-gaging stations was working properly. However, the erratic shape of the hydrograph based on gate ratings for August 15 and 16 looks peculiar.

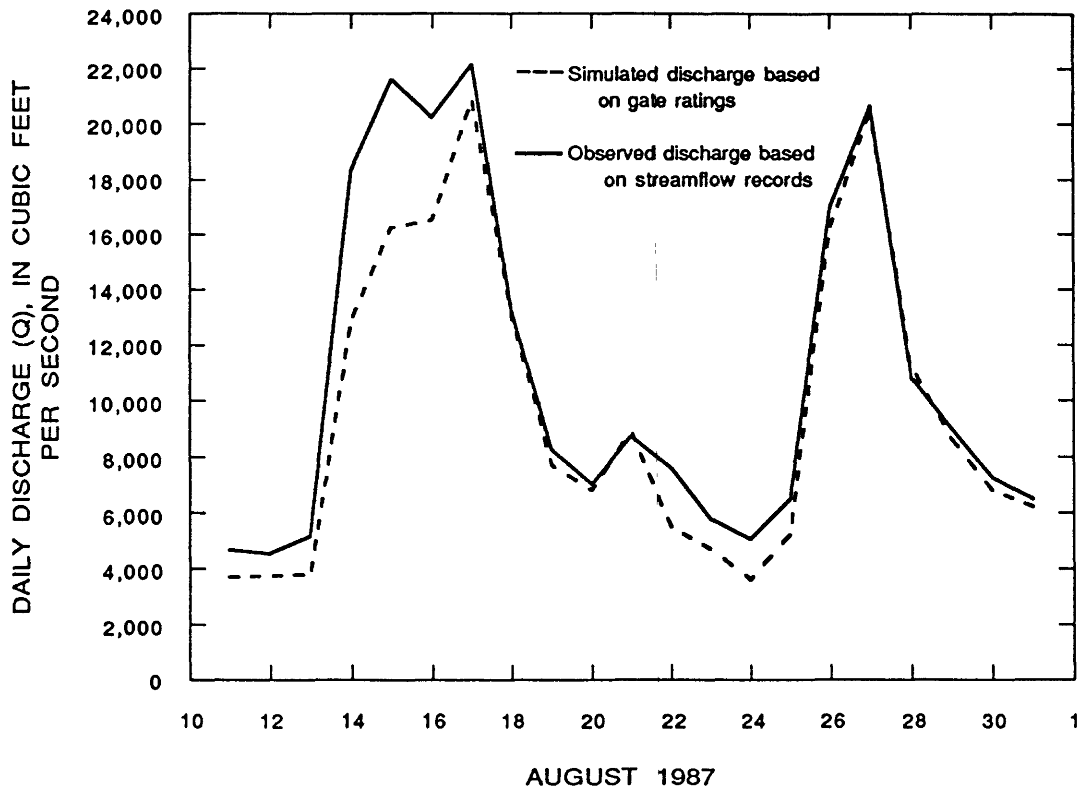


Figure 12.--Simulated and observed flood hydrographs for Des Plaines River at Brandon Road Dam.

One explanation for the large differences during August 14-17 is that recorded gate settings may be in error. The consistent underestimation of discharge, when streamflow was less than about 6,000 ft^3/s and fewer than 12 Tainter gates were raised out of water, may be attributable to one or both of the following factors--not accounting for lockages and errors in the Tainter-gate rating.

Tailwater Rating

Attempts to define a tailwater rating for Brandon Road Dam were not successful. Plots of hourly tailwater stage and concurrent estimated discharge during August 18-31, 1987, showed no distinguishable relation. Daily average values of stage and discharge were calculated to minimize the effects of extremely unsteady flow. Figure 13 illustrates the relation between daily tailwater stage and estimated discharge for the same period in August. Even this relation would seem too poor to use for estimating discharge. The datum of 504.0 ft that was used to calculate stage is 0.5 ft lower than the normal upstream-pool elevation that is maintained at Dresden Island Dam, 14.4 mi downstream.

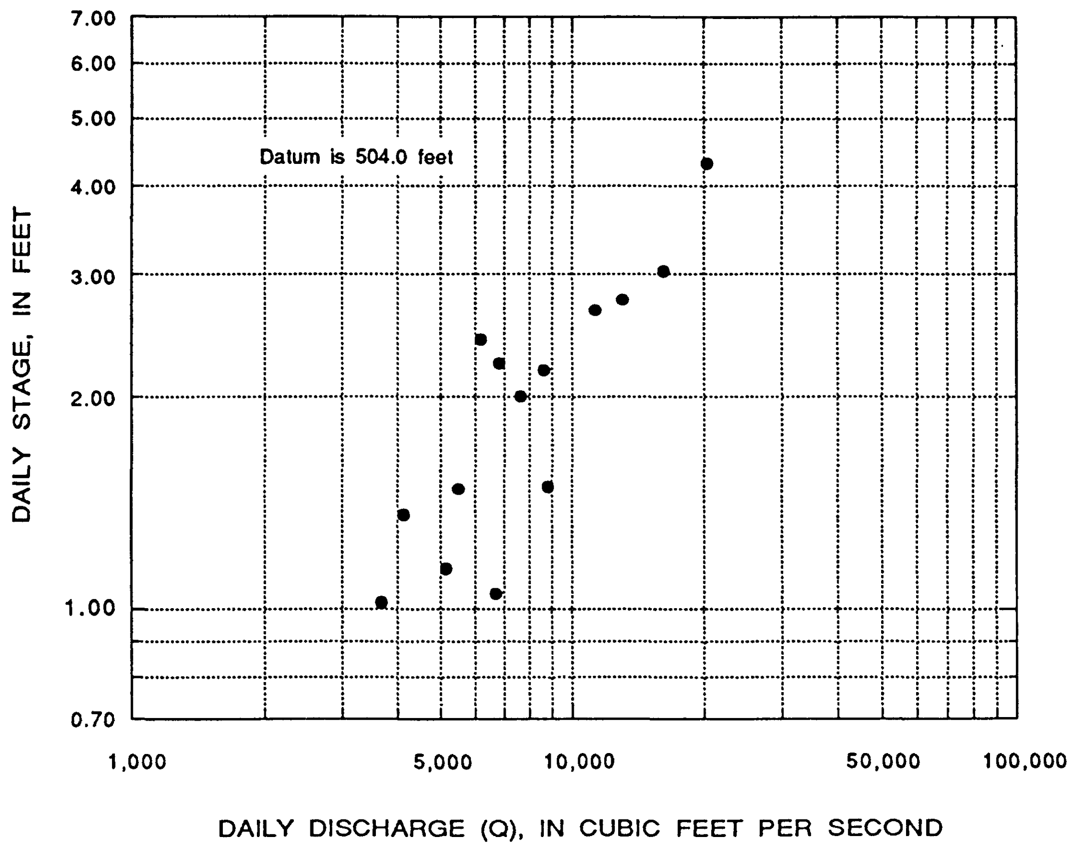


Figure 13.--Relation between tailwater stage and discharge at Brandon Road Dam.

Dresden Island Dam

Gate and Valve Ratings

Thirty-nine discharge measurements were made at Dresden Island Dam to develop gate ratings. Nineteen measurements (table 5) were made on the Illinois River, 0.25 mi downstream from the dam. Eleven measurements were made in forebay No. 2 and nine measurements were made in forebay No. 6 of Dresden Island Dam. Ratings published by Mades (1981) were based on main-channel measurements 1-11.

Measured discharge ranged from 5,450 to 30,600 ft^3/s in the main channel; from 1,310 to 13,200 ft^3/s in forebay No. 2; and from 569 to 5,380 ft^3/s in forebay No. 6. Table 5 summarizes the hydraulic-control conditions during each measurement.

Free orifice flow was measured during main-channel measurements 1, 2, 4-10, and 12-19; during forebay No. 2 mesurements 1-10; and during forebay No. 6 measurements 1-5. Submerged orifice flow was measured during main-channel measurements 9-10 and during forebay No. 6 measurements 6-9. Free

Table 5.--Discharge measurements and hydraulic-control data for Dresden Island Dam

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

Measurement number	Date	Pool elevation, in feet: Headwater	Pool elevation, in feet: Tailwater	Tainter gates: Number open	Tainter gates: Opening (feet)	Flow regime[1]	Measured discharge (ft^3/s)	Discharge coefficient	Rated discharge[2] (ft^3/s)	Deviation[3] (percent)
Main Channel										
1	04-06-76	504.6	([4])	2	4.5	FO	10,900	0.670	10,600	2.8
2	04-06-76	504.6	([4])	3	3.0	FO	11,000	.676	10,900	.92
3	04-07-76	504.7	([4])	1	11.0	FW	10,400	3.24	11,200	-7.1
4	04-07-76	504.7	([4])	1	8.0	FO	[5]9,280	---	10,200	-9.0
				1	1.0	FO		---		
5	04-07-76	504.7	([4])	1	6.0	FO	[5]9,150	---	9,450	-3.2
				2	1.0	FO		---		
6	04-07-76	504.8	([4])	6	1.0	FO	7,770	.711	7,590	2.4
7	04-18-78	504.5	([4])	2	6.0	FO	13,800	.638	13,800	0
8	04-18-78	504.5	([4])	3	4.0	FO	12,200	.564	14,300	-15
9	06-04-80	504.6	494.8	3	3.5	FO	[5]27,200	---	27,500	-1.1
				5	2.5	SO		.451		
10	06-04-80	504.6	494.4	5	3.5	FO	[5]25,900	---	26,600	-2.6
				3	1.5	SO		.267		
11	06-04-80	504.9	494.0	2	11.0	FW	24,500	3.74	22,800	7.5
12	05-23-84	504.7	493.3	4	7.0	FO	30,600	.602	31,700	-3.5
13	05-23-84	504.6	493.9	5	5.0	FO	28,500	.631	29,300	-2.7
14	05-24-84	504.7	493.9	6	4.0	FO	27,300	.627	28,700	-4.9
15	05-24-84	504.7	493.4	7	3.0	FO	24,700	.649	25,600	-3.5
16	05-24-84	504.9	493.3	1	9.0	FO	[5]23,700	---	25,900	-8.5
				2	7.0	FO		---		
17	05-24-84	504.9	493.3	2	6.75	FO	[5]26,300	---	26,900	-2.2
				1	11.0	FW		3.33		
18	08-14-84	504.8	484.2	3	1.5	FO	5,450	.665	5,640	-3.4
19	08-14-84	504.8	([4])	9	.5	FO	5,600	.683	5,740	-2.4

Table 5.--Discharge measurements and hydraulic-control data for Dresden Island Dam--Continued

Measurement number	Date	Pool elevation, in feet: Headwater	Pool elevation, in feet: Tailwater	Tainter gates: Number open	Tainter gates: Opening (feet)	Flow regime[1]	Measured discharge (ft^3/s)	Discharge coefficient	Rated discharge[2] (ft^3/s)	Deviation[3] (percent)
					Forebay No. 2					
1	01-26-84	504.7	([4])	1	1.5	FO	1,980	0.728	1,870	5.9
2	01-26-84	504.7	([4])	1	1.0	FO	1,310	.722	1,260	4.0
3	02-17-84	504.9	493.7	1	8.0	FO	9,090	.621	8,960	1.5
4	05-23-84	504.8	493.0	1	7.0	FO	7,910	.622	7,960	-.63
5	05-23-84	504.7	493.3	1	7.0	FO	8,030	.631	7,940	1.1
6	05-23-84	504.7	493.6	1	5.0	FO	6,050	.667	5,880	2.9
7	05-23-84	504.6	493.9	1	5.0	FO	6,620	.732	5,860	13
8	05-24-84	504.7	493.8	1	4.0	FO	4,790	.660	4,790	0
9	05-24-84	504.7	493.8	1	3.0	FO	3,770	.692	3,650	3.3
10	05-24-84	504.9	493.3	1	9.0	FO	9,910	.603	9,890	.20
11	05-24-84	504.9	493.3	1	11.0	FW	13,200	4.01	11,400	16
					Forebay No. 6					
1	08-14-84	504.8	([4])	1	4.5	FO	5,380	0.657	5,360	0.37
2	08-14-84	504.8	([4])	1	1.5	FO	1,670	.612	1,880	-11
3	08-15-84	504.8	([4])	1	.5	FO	569	.624	638	-11
4	08-15-84	504.8	([4])	1	.5	FO	715	.784	638	12
5	08-15-84	504.8	([4])	1	1.5	FO	2,030	.742	1,880	8.0
6	11-22-85	504.7	497.4	1	.5	SO	1,350	.386	544	150
7	11-22-85	504.7	497.2	1	3.5	SO	3,890	.438	3,660	6.3
8	11-22-85	504.8	497.1	1	2.5	SO	2,640	.306	2,650	-.38
9	11-22-85	504.8	496.9	1	1.5	SO	1,680	.194	1,640	2.4

[1]FO designates free orifice flow; FW designates free weir flow; and SO designates submerged orifice flow.
[2]Discharge based on equations 13-15.
[3]Deviation defined as [(measured discharge/rated discharge) - 1.0] x 100.
[4]Pool elevation is less than ogee spillway crest elevation.
[5]Combined flow through all gate openings.

weir flow was measured during main-channel measurements 3, 11, and 17; and during forebay No. 2 measurement 11. Submerged weir flow was not measured.

The relation between the discharge coefficient for free orifice flow (C) and vertical gate opening (h_g) is shown in figure 14. A least squares regression method was used to determine the parameters in a linear model that relates C to h_g. The equation,

$$C = 0.706 - 0.0116\ h_g, \tag{9}$$

is based on a regression analysis of discharge coefficients and gate openings for 26 main-channel and forebay measurements. Measurements during which free orifice flow existed at multiple gates with different openings were not considered.

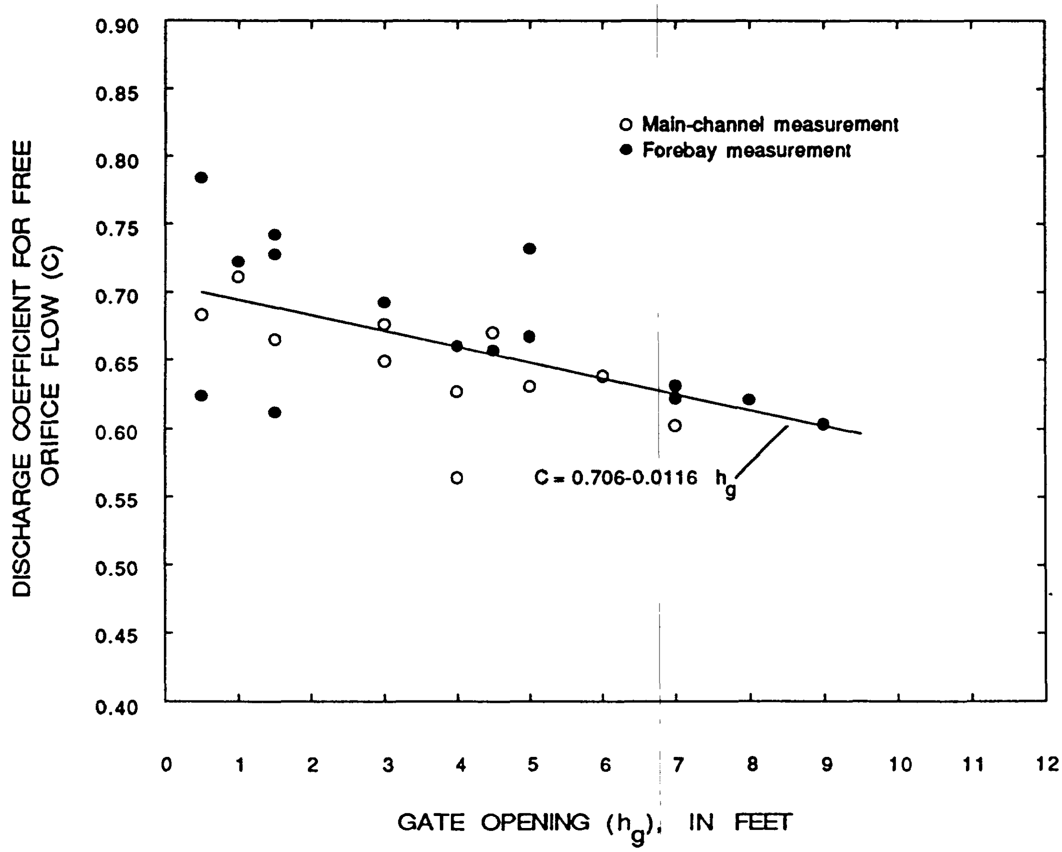


Figure 14.--Relation between the discharge coefficient for free orifice flow and gate opening for Dresden Island Dam Tainter gates.

A transition from free orifice flow to submerged orifice flow was observed at a submergence ratio (h_3/h_g) of about 1.5. The discharge coefficient for the submerged orifice flow is indirectly proportional to h_3/h_g as shown in figure 15. A least squares regression based on two main-channel measurements and three forebay measurements yielded the logarithmic model,

$$C_{gs} = 0.769\ (h_3/h_g)^{-0.974}. \tag{10}$$

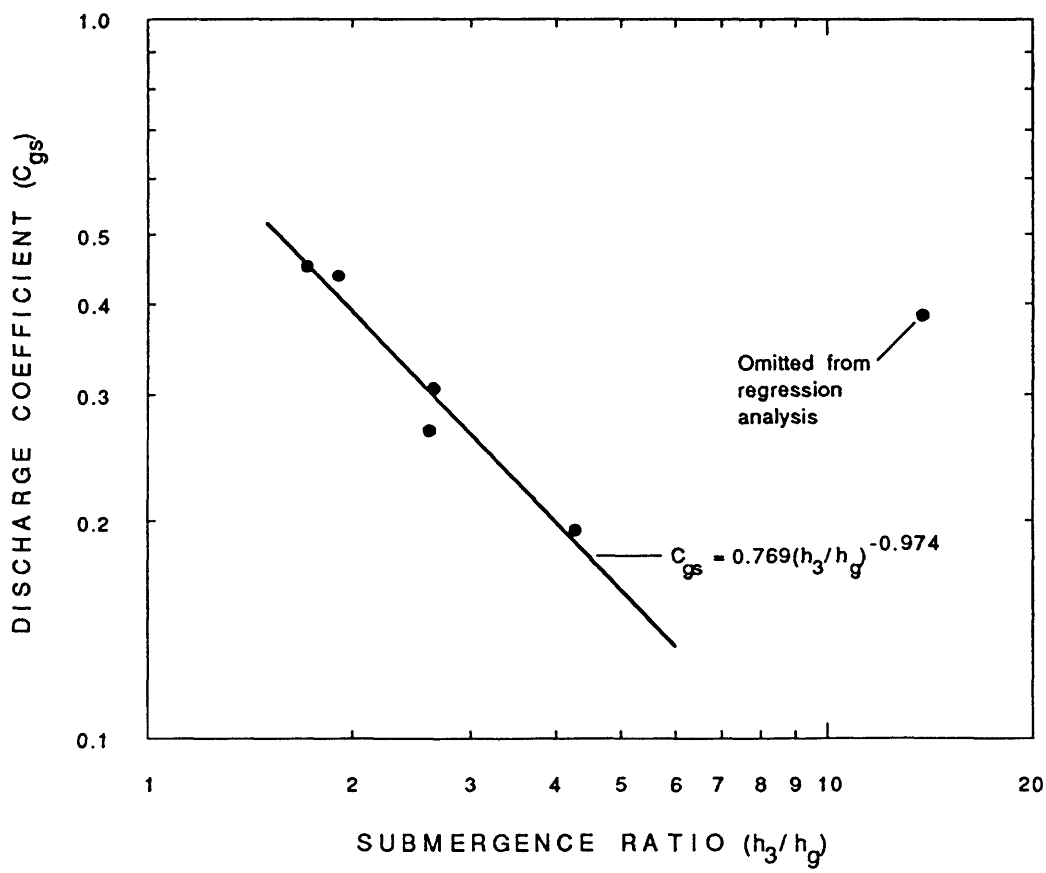


Figure 15.--Relation between the discharge coefficient for submerged orifice flow and submergence ratio for Dresden Island Dam Tainter gates.

The total discharges for main-channel measurements 9 and 10 (table 5) were assumed to be the sum of rated, free orifice flow (calculated using equations 1 and 9) and unrated, submerged orifice flow. Computed free orifice flow was subtracted from measured flow and the difference was used to compute a discharge coefficient for submerged orifice flow. Measurement 6 in forebay No. 6 was excluded from the regression analysis because of apparent measurement error.

A transition to free weir flow occurs as the Tainter gate opening is increased above 9.3 ft. Gates were clear of the water during main-channel measurements 3, 11, and 17, and forebay No. 2 measurement 11. The discharge coefficient for free weir flow, C_w, is estimated to be 3.44, the average of the values based on the main-channel measurements. Measurement 11 in forebay No. 2 was excluded from consideration because it was judged to be a poor measurement with greater than 10-percent error.

Submerged weir flow rarely occurs at Dresden Island Dam. A review of the Lockmaster's log for floods in 1966, 1968, and 1970 indicated that when submerged weir flow conditions did occur, the duration for any period of submerged flow never exceeded 48 hours. Values for the discharge coefficient for submerged weir flow (eq. 4) could not be determined because submerged weir flow was never measured at the dam during the study. The relation,

$$C_{ws} = 3.26 - 2.99\ (h_3/h_1), \qquad (11)$$

is based on measurements made at Starved Rock Dam (see following section, "Starved Rock Dam, Gate and Valve Ratings"). Furthermore, a transition from free to submerged weir flow is assumed to occur when the submergence ratio, h_3/h_1, exceeds 0.76. This relation is believed to be appropriate for Dresden Island Dam because both dams have similar gate, ogee-crest, and approach-section geometries. Although measurements are needed to confirm the validity of this relation for Dresden Island Dam, the infrequent occurrence of submerged weir flow and extremely dangerous measurement conditions lessen the feasibility of obtaining such measurements.

Figure 16 shows the relation between the discharge coefficient for submerged orifice flow (C_{gs} in eq. 2) for the Dresden Island Lock upstream culvert valves and the submergence ratio (h_3/h_g). This relation was developed from three volumetric measurements during which the lock was filled with one valve fully open (h_g equal to 9.0 ft), two valves fully open, and two valves half open (h_g equal to 4.5 ft). Tailwater depth (h_3) is the depth of water in the lock relative to the upstream lock-valve-sill elevation of 473.0 ft. This relation is expressed mathematically as

$$C_{gs} = 0.440\ (h_3/h_g)^{-0.844}. \qquad (12)$$

Figure 16 or equation 12 may be used to determine C_{gs} for a known lock-pool elevation and valve opening.

The following mathematical expressions for the gate and valve ratings for Dresden Island Lock and Dam were determined by substituting equations 9-12 and the discharge coefficient for free weir flow into the appropriate equations listed in table 1. Hydraulic conditions for which the gate ratings are appropriate are enclosed by parentheses.

Gate rating--free orifice flow ($h_3/h_g < 1.5$ and $h_g/h_1 < 0.67$):

$$Q = (C)(B)(h_g)[(2g)(h_1)]^{0.5}$$

$$= (0.706 - 0.0116\ h_g)(60)(h_g)[(64.4)(h_1)]^{0.5}$$

$$= (340\ h_g - 5.59\ h_g^2)\ h_1^{0.5} \qquad (13)$$

Gate rating--submerged orifice flow ($h_3/h_g \geq 1.5$ and $h_g/h_1 < 0.67$):

$$Q = (C_{gs})(B)(h_3)[(2g)(\Delta h)]^{0.5}$$

$$= [(0.769)(h_3/h_g)^{-0.974}](60)(h_3)[(64.4)(\Delta h)]^{0.5}$$

$$= 370\ (h_3)^{0.026}\ (h_g)^{0.974}\ (\Delta h)^{0.5} \qquad (14)$$

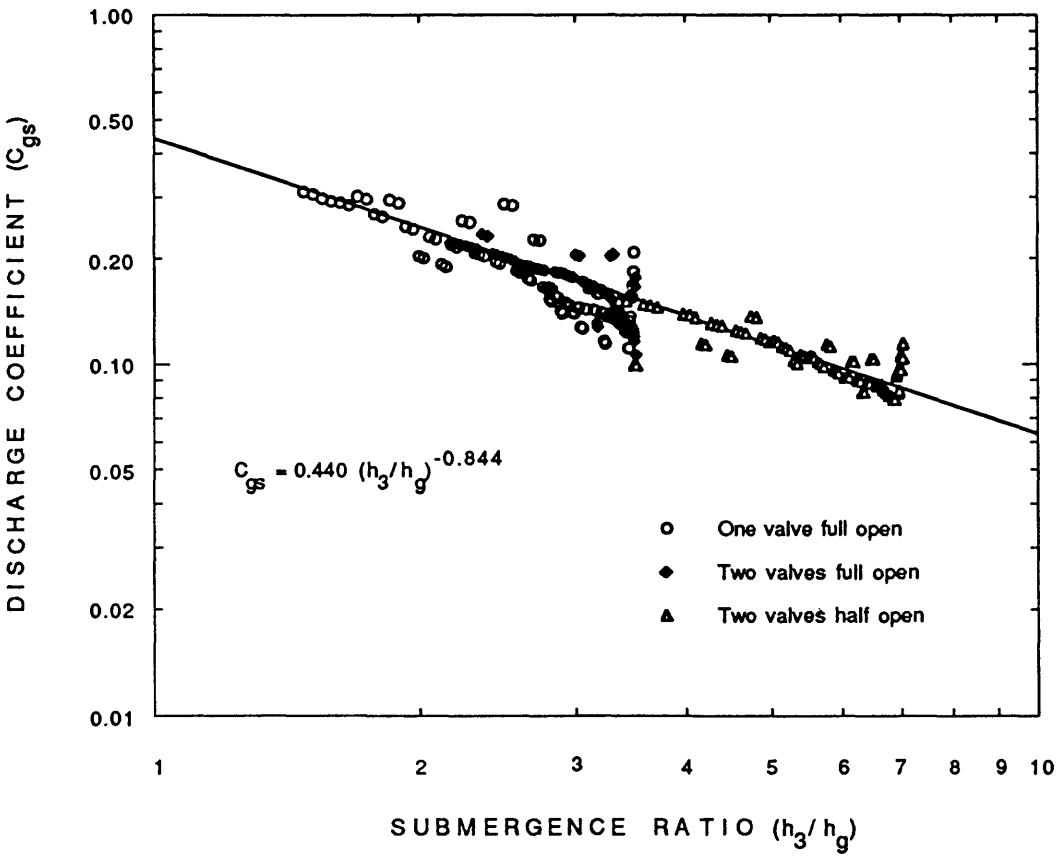


Figure 16.--Relation between the discharge coefficient for submerged orifice flow and submergence ratio for the Dresden Island Lock, upstream culvert valves.

Gate rating--free weir flow ($h_3/h_1 < 0.76$ and $h_g/h_1 \geq 0.67$):

$$Q = (C_w)(B)(h_1)^{1.5}$$

$$= (3.44)(60)(h_1)^{1.5}$$

$$= 206\ h_1^{1.5} \qquad (15)$$

Gate rating--submerged weir flow ($h_3/h_1 > 0.76$ and $h_g/h_1 \geq 0.67$):

$$Q = (C_{ws})(C_w)(B)(h_1)^{1.5}$$

$$= [3.26 - 2.99\ (h_3/h_1)](3.44)(60)(h_1)^{1.5}$$

$$= 673\ (h_1)^{0.5}\ (h_1 - 0.917\ h_3) \qquad (16)$$

Valve rating--submerged orifice flow:

$$Q = (C_{gs})(B)(h_3)[(2g)(\Delta h)]^{0.5}$$

$$= [0.440\ (h_3/h_g)^{-0.844}](12)(h_3)[(64.4)(\Delta h)]^{0.5}$$

$$= 42.4\ (h_3)^{0.156}\ (h_g)^{0.844}\ (\Delta h)^{0.5} \qquad (17)$$

Headwater depth (h_1) and tailwater depth (h_3) for the gate ratings (eqs. 13-16) are the depths, in feet, of the headwater and tailwater pools relative to the spillway-crest elevation of 490.5 ft. The headwater and tailwater depths for the lock-valve rating (eq. 17) are the depths of water in the upstream pool and in the lock, respectively, relative to the valve-sill elevation of 473.0 ft.

Equations 13-16 were used to develop the gate ratings illustrated in figure 17. Figure 17 is based on an assumed headwater-pool elevation of 504.5 ft (h_1 = 14.0 ft) and a range of tailwater-pool elevations and gate openings. Equations 13-16 may be used to determine discharge for headwater-pool elevations other than 504.5 ft or tailwater-pool elevations that are not shown in figure 17.

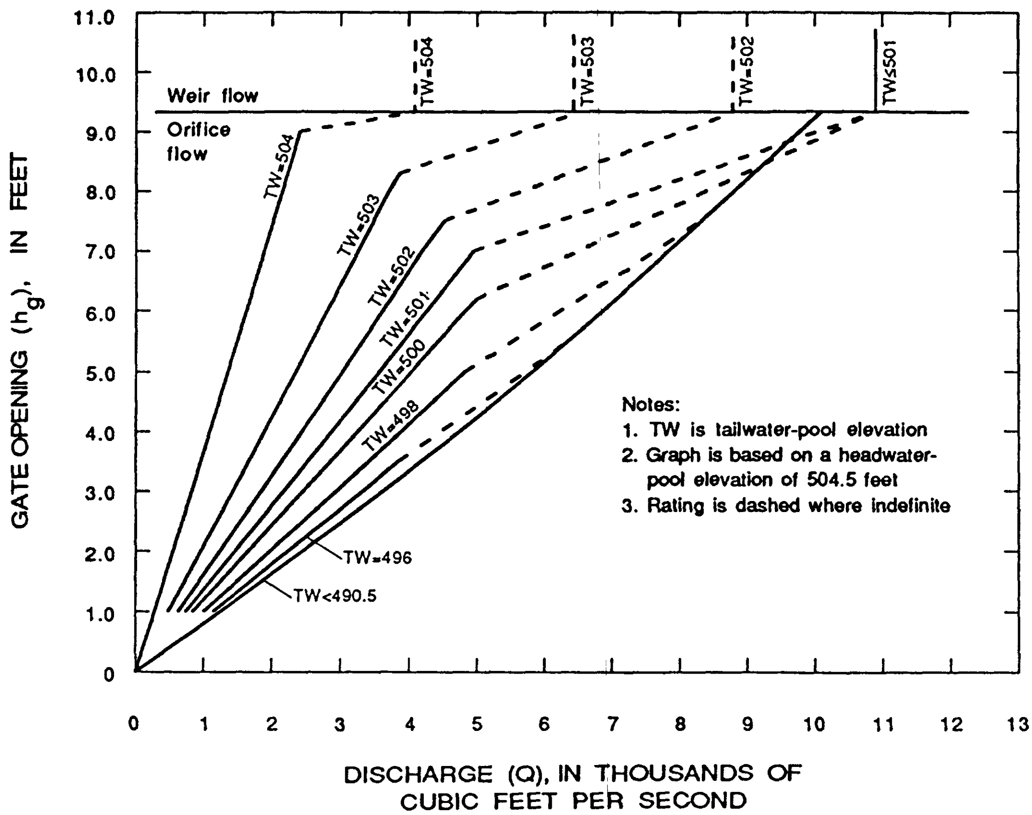


Figure 17.--Discharge rating for one Dresden Island Dam Tainter gate.

The dashed lines in figure 17 indicate an indefinite rating. The transition from submerged orifice flow to free orifice flow (for submergence ratios, h_3/h_g, between 1.5 and 1.0) is represented by the dashed lines below the horizontal line drawn at a gate opening of 9.33 ft. The vertical dashed lines are discharges associated with the submerged weir flow rating that was based on data collected at Starved Rock Dam.

Discharge into the lock has been calculated for values of Δh (difference between the headwater-pool and lock-pool depths) ranging from 0 to 24 ft for one-half and full openings (table 6). The table was developed using equation 17. Table 6 may be used to determine discharge into the lock for a known headwater- and lock-pool elevation.

Table 6.--Discharge rating for one upstream culvert valve at Dresden Island Lock

[Headwater-pool elevation is 504.5 feet]

Lock-pool elevation, in feet	Difference between headwater-pool and lock-pool elevations (Δh), in feet	Discharge, in cubic feet per second: One-half open[1]	Discharge, in cubic feet per second: Fully open[2]
504.5	0	0	0
504.0	.5	182	327
503.5	1	257	461
502.5	2	362	649
501.5	3	440	791
500.5	4	506	908
499.5	5	562	1,010
498.5	6	612	1,100
496.5	8	698	1,250
494.5	10	770	1,380
489.5	15	904	1,620
484.5	20	987	1,770
480.5	24	1,010	1,820

[1]Valve opening is 4.5 feet.
[2]Valve opening is 9.0 feet.

The validity of the gate ratings was checked by comparing discharge hydrographs based on the ratings with streamflow records from nearby streamflow-gaging stations. Figure 18 shows two sets of daily discharge hydrographs for floods that occurred in May 1966 and May 1970. Each set consists of a discharge hydrograph based on the gate ratings and hourly observations of headwater- and tailwater-pool elevation and gate setting recorded in the Lockmaster's log, and a hydrograph based on streamflow records for nearby gaging stations. The floods of 1966 and 1970 were chosen for analysis because the Lockmaster's records indicated that all four flow regimes existed at one time or another during these floods.

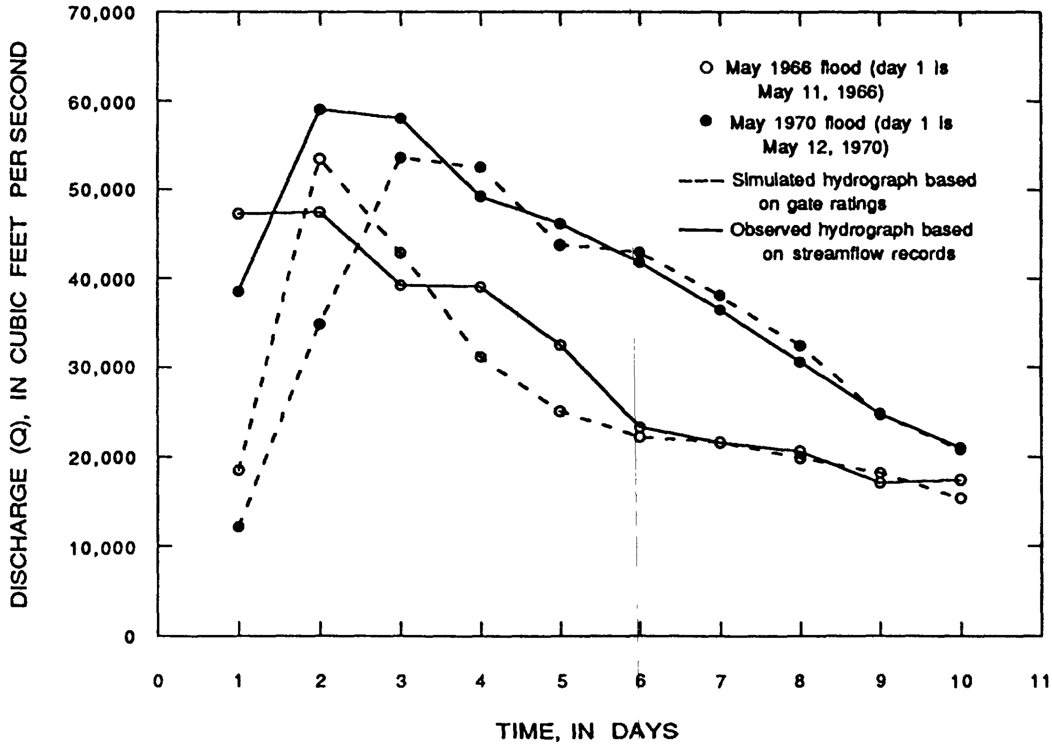


Figure 18.--Simulated and observed flood hydrographs for Illinois River at Dresden Island Dam.

Daily-discharge hydrographs based on streamflow records were calculated using the equation

$$Q_{DI}^{i} = Q_{Mar}^{i+1} - 2.15\ Q_{CC}^{i}, \tag{18}$$

where Q_{DI} is the estimated daily discharge, in cubic feet per second, at Dresden Island Dam;

Q_{Mar} is the observed daily discharge, in cubic feet per second, at Illinois River at Marseilles gaging station;

Q_{CC} is the observed daily discharge, in cubic feet per second, at Mazon River near Coal City gaging station;

i is an index for time, in days; and

2.15 is the ratio between the total intervening drainage area between Dresden Island Dam and Marseilles gaging station, and the area gaged at Coal City.

Streamflow records for Illinois River at Marseilles (station 05543500) and Mazon River near Coal City (station 05542000) have been published (U.S. Geological Survey, 1973).

The peak discharges and recessions for both sets of hydrographs compare well when considering that (1) a very simple routing model, equation 18, was used and (2) the discharge observed at Marseilles is regulated by operations at Marseilles Dam. The effects of regulation on daily discharges are not that great because the dam is operated to maintain a constant headwater-pool elevation.

The poorer comparison of the rise for both flood hydrographs may be attributable to two reasons. First, a 1-day interval is too coarse to accurately account for the timing of runoff from the intervening drainage area, such as the Mazon River basin. Second, the daily discharge on May 12-14, 1970 (days 1-3 in fig. 18), for Illinois River at Marseilles were reported as being estimated because stage-recording equipment at the gaging station had malfunctioned.

Tailwater Rating

Figure 19 shows stage-discharge relations for two floods--one that occurred during May 11-22, 1966, and another during May 12-22, 1970. The figure was developed from the gate ratings developed for Dresden Island Dam (eqs. 13-16) and hourly readings of headwater- and tailwater-pool elevations and gate openings registered in the Lockmaster's log. Tailwater stage is referenced to a datum elevation of 483.0 ft, or 0.2 ft higher than the normal headwater-pool elevation at Marseilles Dam.

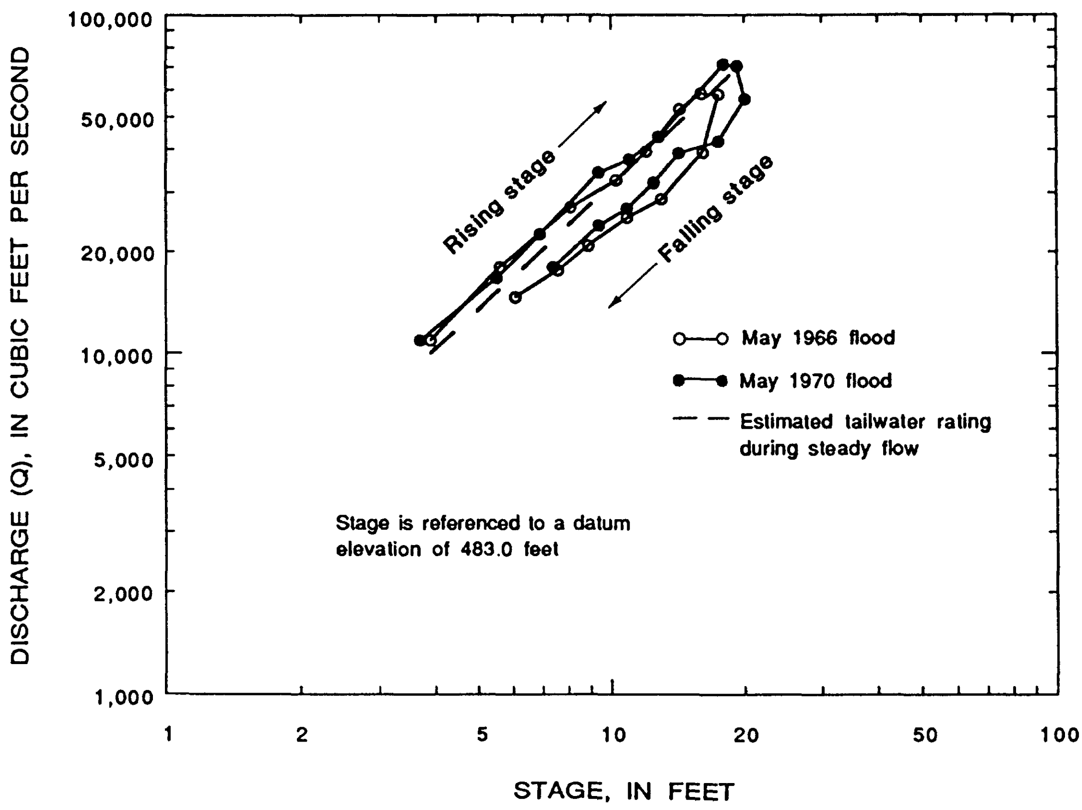


Figure 19.--Tailwater rating for Dresden Island Dam.

Figure 19 also illustrates the effects that variable channel-storage conditions have on the relation between tailwater stage and discharge at Dresden Island Dam. The hysteresis, or loop, in both stage-discharge relations was caused by varying amounts of water in storage downstream from the dam. When tailwater stage was rising, the discharge for a given stage was about 1.5 times the discharge for the same stage when tailwater stage was falling.

The hysteresis in the stage-discharge relations is apparent during unsteady flow when stage, discharge, or both are changing. The tailwater rating for Dresden Island Dam, drawn as a dashed line in figure 19, is an estimate of the relation between tailwater stage and discharge during steady flow. The rating is of limited use because steady conditions seldom exist for the range in discharge and stage for which the rating was drawn. No attempt was made to define a tailwater rating for discharges less than 10,000 ft^3/s because of variable backwater effects caused by Marseilles Dam.

Marseilles Dam

Gate and Valve Ratings

Gaged streamflow and discharge measurements were used to develop gate ratings for Marseilles Dam (table 7). Four measurements of return flow in the Illinois Power and Light Company powerplant north channel (fig. 4) were made. The stage-discharge rating for gaging station 05543500 was used to estimate main-channel discharge adjusted for return flows.

Table 7 summarizes the hydraulic control conditions during each measurement. Headwater- and tailwater-pool elevations and gate openings are from the Lockmaster's log. Main-channel discharge measured at the dam ranged from 3,610 to 86,400 ft^3/s. Discharge measured in the north channel ranged from 1,610 to 3,120 ft^3/s.

Free orifice flow existed during measurements 3-6 and 8-11. Submerged orifice flow existed during measurements 7-15. Measurements 1, 2, and 7-10 were made when free weir flow existed at one or more gates. Submerged weir flow may have existed during measurements 1 and 7; however, the degree of submergence was so little that free weir flow was assumed to have existed.

Multiple flow regimes existed at the dam during 10 measurements. The coefficients for these measurements were determined in a repetitious manner by using information determined from measurements when all gates were set to the same opening.

The relation between discharge coefficient for free orifice flow (C) and vertical gate opening (h_g) is shown in figure 20. A least squares regression method was used to determine the parameters in a linear model that relates C to h_g. The equation,

$$C = 0.748 - 0.0146\ h_g, \qquad (19)$$

is based on a regression analysis of discharge coefficients and gate openings for eight main-channel measurements.

Table 7.--Discharge measurements and hydraulic-control data for Marseilles Dam

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

Measure-ment number	Date	Pool elevation, in feet: Head-water	Pool elevation, in feet: Tail-water	Tainter gates: Number open	Tainter gates: Opening (feet)	Flow regime[1]	Discharge: Gaging station[2] (ft^3/s)	Discharge: North channel (ft^3/s)	Discharge: Dam (ft^3/s)	Discharge coeffi-cient
1	05-15-70	483.2	480.1	8	9+	FW	86,400*	([4])	86,400	3.67
2	04-07-78	483.1	475.8	4	9+	FW	40,100	1,630	38,500	3.31
3	04-12-78	483.2	474.4	2	6.0	FO	[3]25,600	([4])	25,600	.680
				1	5.0	FO				.700
				1	4.0	FO				.720
4	04-20-78	483.2	473.2	4	4.0	FO	20,400	1,860	18,500	.656
5	04-20-78	483.1	473.2	3	5.0	FO	19,000	1,860	17,100	.649
6	08-09-78	483.1	471.2	1	3.0	FO	5,780	2,170	3,610	.685
7	03-07-79	482.8	479.1	2	3.0	SO	[3]62,000*	([4])	62,000	.238
				6	9+	FW				3.43
8	06-03-80	483.0	476.4	1	.5	SO	[3]49,000	([4])	49,000	.037
				1	4.0	SO				.416
				2	5.0	FO				.690
				2	6.0	FO				.650
				2	9+	FW				3.40
9	06-03-80	483.0	476.2	1	.5	SO	[3]47,500	([4])	47,500	.038
				1	2.5	SO				.236
				2	5.0	FO				.675
				2	6.0	FO				.660
				2	9+	FW				3.40

Table 7.--Discharge measurements and hydraulic-control data for Marseilles Dam--Continued

Measurement number	Date	Pool elevation, in feet: Headwater	Pool elevation, in feet: Tailwater	Tainter gates: Number open	Tainter gates: Opening (feet)	Flow regime[1]	Discharge: Gaging station[2] (ft^3/s)	Discharge: North channel (ft^3/s)	Discharge: Dam (ft^3/s)	Discharge coefficient
10	06-03-80	483.0	476.2	1	0.5	SO	[3]45,700	([4])	45,700	.038
				1	1.5	SO				.137
				2	5.0	FO				.670
				2	6.0	FO				.630
				2	9+	FW				3.40
11	06-05-80	483.2	475.4	1	.5	SO	[3]33,800	([4])	33,800	.040
				2	2.0	SO				.339
				2	4.0	FO				.710
				3	5.0	FO				.695
12	04-07-78	483.6	481.0	1	2.9	SO	--	[3]1,610	--	.165
				1	.5	SO				.019
13	04-20-78	483.7	481.0	1	3.0	SO	--	[3]1,860	--	.190
				1	.5	SO				.021
14	04-07-81	483.2	481.0	1	4.5	SO	--	[3]3,120	--	.364
				1	.5	SO				.024
15	04-25-84	483.3	481.0	1	3.25	SO	--	[3]1,940	--	.216
				1	.5	SO				.021

[1]FW designates free weir flow; FO designates free orifice flow; and SO designates submerged orifice flow.
[2]Discharges determined from gaging station stage-discharge relation. Asterisk (*) indicates that discharge was measured.
[3]Combined flow through all gate openings.
[4]Diversion channel discharge not measured because it appeared to be a small percentage of total discharge.

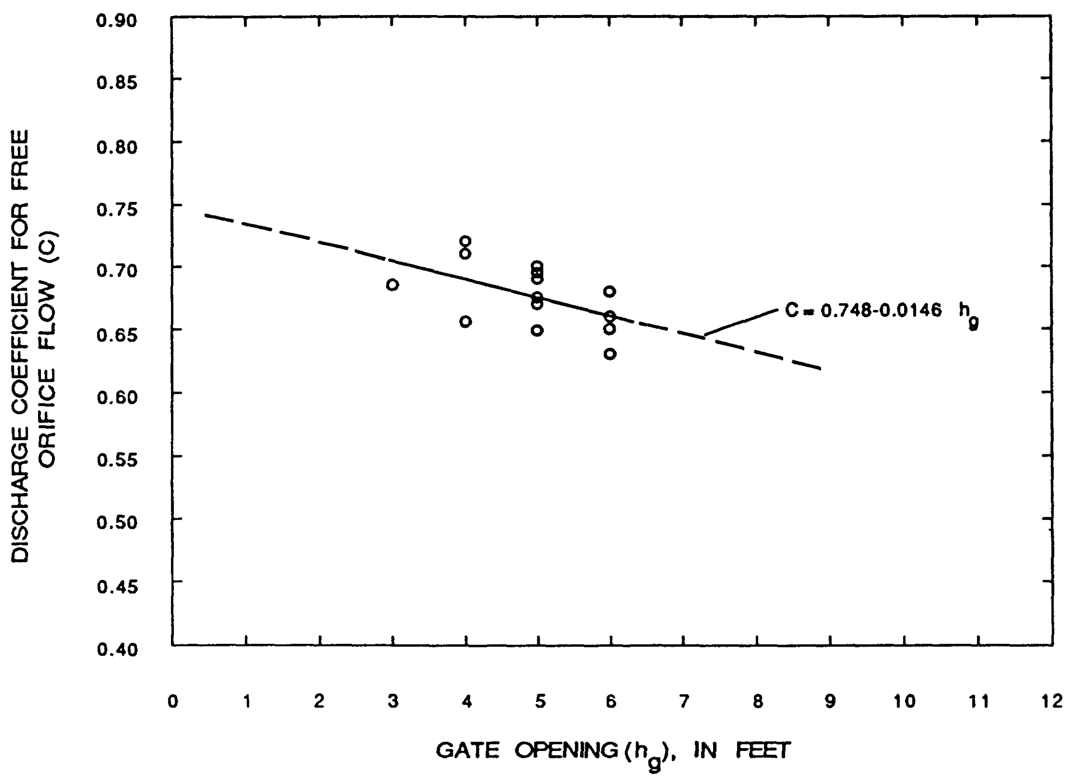


Figure 20.--Relation between the discharge coefficient for free orifice flow and gate opening for Marseilles Dam Tainter gates.

A transition from free orifice flow to submerged orifice flow was observed at a submergence ratio (h_3/h_g) of about 1.5. The discharge coefficient for submerged orifice flow is indirectly proportional to h_3/h_g as shown in figure 21. A least squares regression based on five main-channel measurements and four north-channel measurements yielded the logarithmic model,

$$C_{gs} = 0.918\ (h_3/h_g)^{-1.23}. \qquad (20)$$

A transition to free weir flow occurs as the Tainter-gate opening is increased above 8.7 ft. Gates were clear of the water during main-channel measurements 1, 2, and 7-10. The discharge coefficient for free weir flow, C_w, is estimated to be 3.44, the average of the values based on the main-channel measurements.

Submerged weir flow rarely occurs at Marseilles Dam because very little backwater effect is caused by Starved Rock Dam, 16 mi downstream. Therefore, a gate rating for submerged weir flow was not developed.

Figure 22 shows the relation between the discharge coefficient for submerged orifice flow (C_{gs} in eq. 2) for the Marseilles Lock valves and the submergence ratio (h_3/h_g). This relation was developed from three volumetric measurements during which the lock was filled with one valve fully open (h_g equal to 9.0 ft), two valves fully open, and two valves half open (h_g equal to

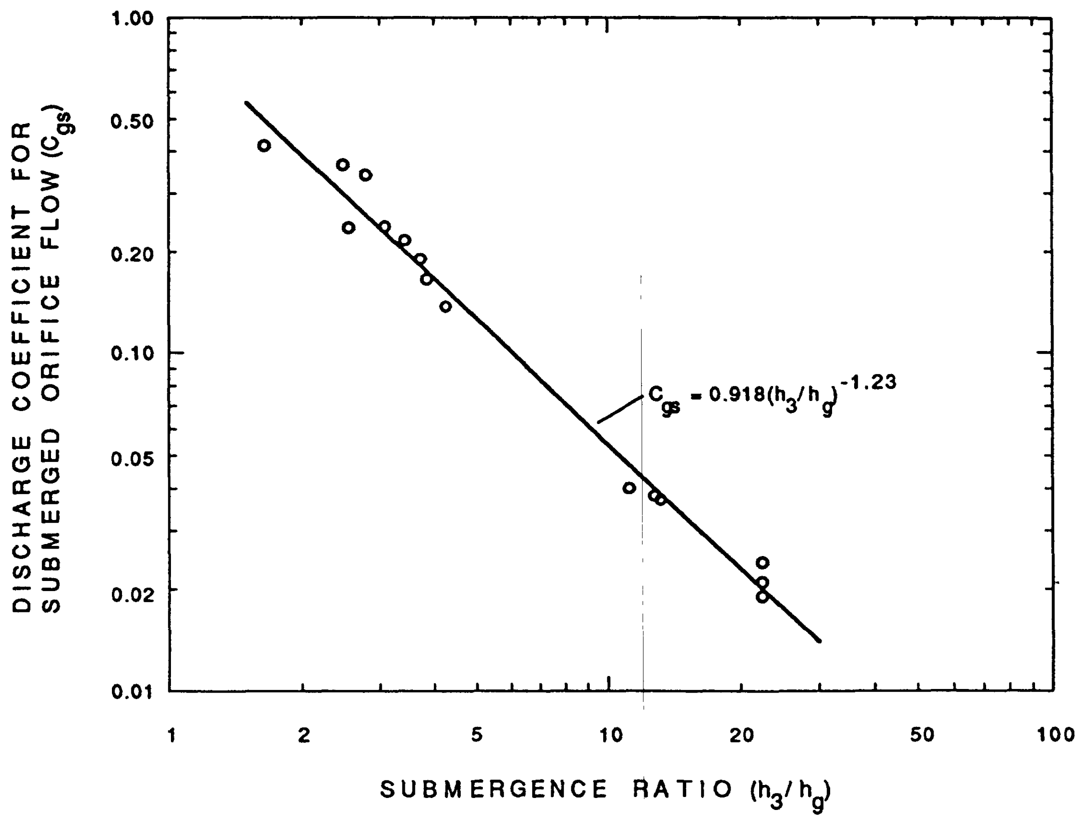


Figure 21.--Relation between the discharge coefficient for submerged orifice flow and submergence ratio for Marseilles Dam Tainter gates.

4.5 ft). Tailwater depth (h_3) is the depth of water in the lock relative to the upstream lock-valve-sill elevation of 447.0 ft. This relation is expressed mathematically as

$$C_{gs} = 0.710\ (h_3/h_g)^{-1.12}. \qquad (21)$$

Figure 22 or equation 21 may be used to determine C_{gs} for a known lock-pool elevation and valve opening.

The following mathematical expressions for the gate and valve ratings for Marseilles Lock and Dam were determined by substituting equations 19-21 and the discharge coefficient for free weir flow into the appropriate equations listed in table 1. Hydraulic conditions for which the gate ratings are appropriate are enclosed by parentheses.

Gate rating--free orifice flow (h_3/h_g <1.0 and h_g/h_1 <0.67):

$$Q = (C)(B)(h_g)[(2g)(h_1)]^{0.5}$$

$$= (0.748 - 0.0146\ h_g)(60)(h_g)[(64.4)(h_1)]^{0.5}$$

$$= (360\ h_g - 7.03\ h_g^2)\ h_1^{0.5} \qquad (22)$$

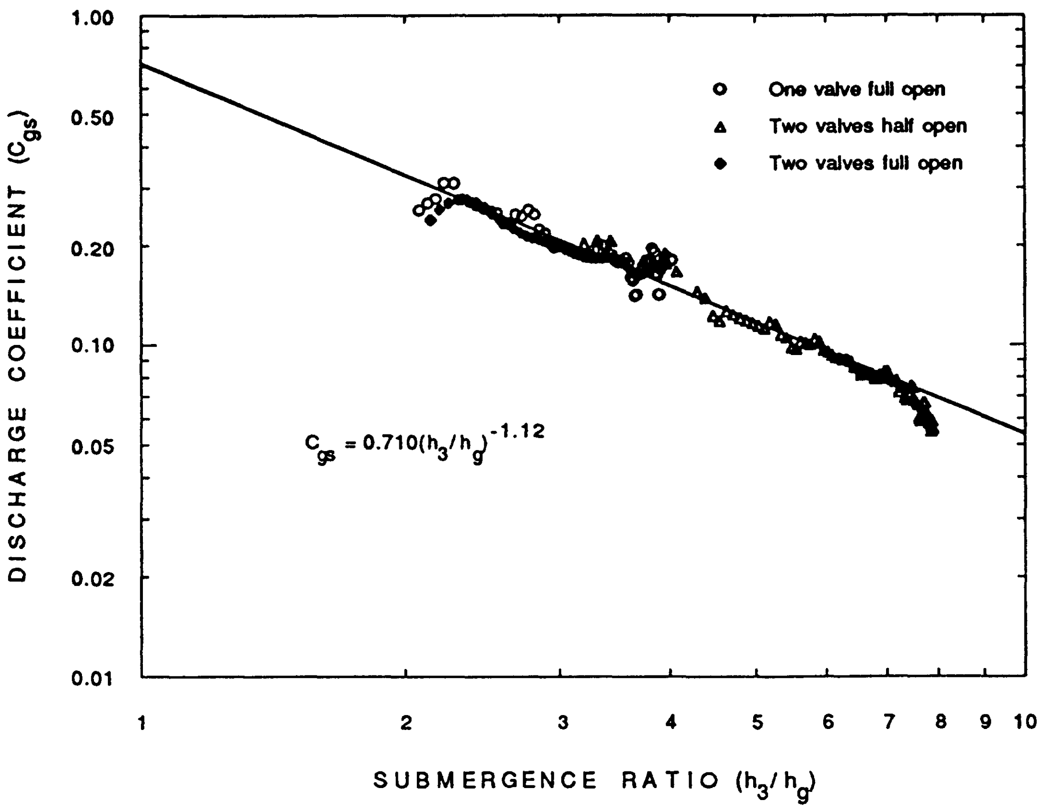


Figure 22.--Relation between the discharge coefficient for submerged orifice flow and submergence ratio for the Marseilles Lock, upstream culvert valves.

Gate rating--submerged orifice flow ($h_3/h_g \geq 1.5$ and $h_g/h_1 < 0.67$):

$$\begin{aligned} Q &= (C_{gs})(B)(h_3)[(2g)(\Delta h)]^{0.5} \\ &= [(0.918)(h_3/h_g)^{-1.23}](60)(h_3)[(64.4)(\Delta h)]^{0.5} \\ &= 442\ (h_3)^{-0.23}\ (h_g)^{1.23}\ (\Delta h)^{0.5} \end{aligned} \tag{23}$$

Gate rating--free weir flow ($h_3/h_1 < 0.70$ and $h_g/h_1 \geq 0.67$):

$$\begin{aligned} Q &= (C_w)(B)(h_1)^{1.5} \\ &= (3.44)(60)(h_1)^{1.5} \\ &= 206\ h_1{}^{1.5} \end{aligned} \tag{24}$$

Valve rating--submerged orifice flow:

$$\begin{aligned} Q &= (C_{gs})(B)(h_3)[(2g)(\Delta h)]^{0.5} \\ &= [0.710\ (h_3/h_g)^{-1.12}](12)(h_3)[(64.4)(\Delta h)]^{0.5} \\ &= 68.4\ (h_3)^{-0.12}\ (h_g)^{1.12}\ (\Delta h)^{0.5} \end{aligned} \tag{25}$$

Headwater depth (h_1) and tailwater depth (h_3) for the gate ratings (eqs. 22-24) are the depths, in feet, of the headwater and tailwater pools relative to the spillway-crest elevation of 469.8 ft. The headwater and tailwater depths for the lock-valve rating (eq. 25) are the depths of water in the upstream pool and in the lock, respectively, relative to the valve-sill elevation of 447.0 ft.

Equations 22-24 were used to develop the gate ratings illustrated in figure 23. Figure 23 is based on an assumed headwater-pool elevation of 482.8 ft (h_1 = 13.0 ft) and a range of tailwater-pool elevations and gate openings. Equations 22-24 may be used to determine discharge for headwater-pool elevations other than 482.8 ft or tailwater-pool elevations that are not shown in figure 23.

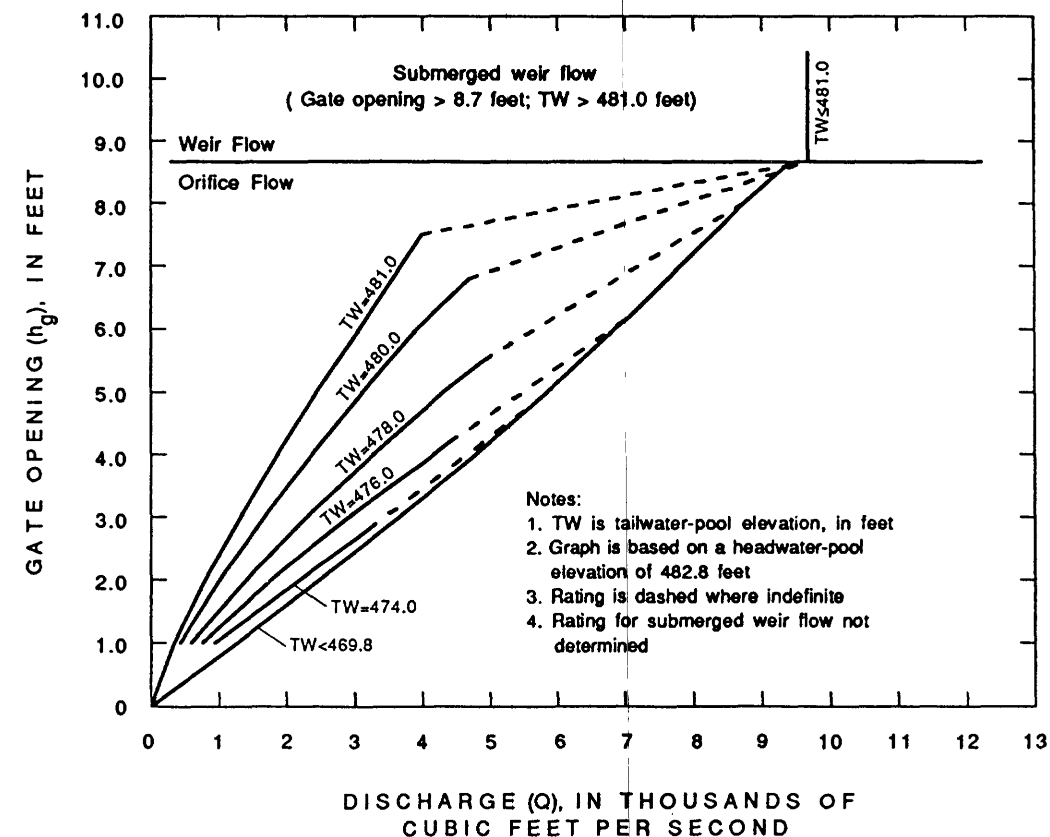


Figure 23.--Discharge rating for one Marseilles Dam Tainter gate.

The dashed lines in figure 23 indicate an indefinite rating. The transition from submerged orifice flow to free orifice flow (for submergence ratios, h_3/h_g, between 1.5 and 1.0) is represented by the dashed lines below the horizontal line drawn at a gate opening of 8.67 ft. A discharge rating for submerged weir flow was not developed.

Discharge into the lock has been calculated for values of Δh (difference between the headwater-pool and lock-pool depths) ranging from 0 to 25 ft for one-half and full openings (table 8). The table was developed using equation 25. Table 8 may be used to determine discharge into the lock for known headwater- and lock-pool elevations.

Table 8.--Discharge rating for one upstream culvert valve at Marseilles Lock

[Headwater-pool elevation is 482.8 feet]

Lock-pool elevation, in feet	Difference between headwater-pool and lock-pool elevations (Δh), in feet	Discharge, in cubic feet per second	
		One-half open[1]	Fully open[2]
482.8	0	0	0
482.3	.5	168	367
481.8	1	238	520
480.8	2	338	737
479.8	3	416	906
478.8	4	482	1,050
477.8	5	541	1,180
476.8	6	595	1,300
474.8	8	693	1,510
472.8	10	782	1,700
467.8	15	983	2,140
462.8	20	1,170	2,560
457.8	25	1,370	2,990

[1]Valve opening is 4.5 feet.
[2]Valve opening is 9.0 feet.

The validity of the gate ratings was checked by comparing a discharge hydrograph based on the ratings with streamflow records from gaging station 05543500. Figure 24 shows a set of daily-discharge hydrographs for a flood that occurred in May 1970. The set consists of a discharge hydrograph based on the gate ratings and hourly observations of headwater- and tailwater-pool elevations and gate settings recorded in the Lockmaster's log and a hydrograph based on streamflow records for the gaging station. The flood of 1970 was chosen for analysis because the Lockmaster's records indicated that all three flow regimes existed at one time or another during the flood and a fourth regime, submerged weir flow, may have existed.

The peak discharges and recessions of both hydrographs compare well. The actual discharges on May 14 and 15 probably were somewhat lower than the reported values. Only two discharge measurements were available in 1970 to define the high end of the stage-discharge relation. Three additional measurements have been made since then, and the present stage-discharge relation indicates a discharge about 5,000 ft^3/s lower than indicated by the relation used in 1970. The poorer comparison on the rise of the flood is probably because the daily discharges on May 12-14, 1970, were estimated due to malfunctioning stage-recording equipment at the gaging station.

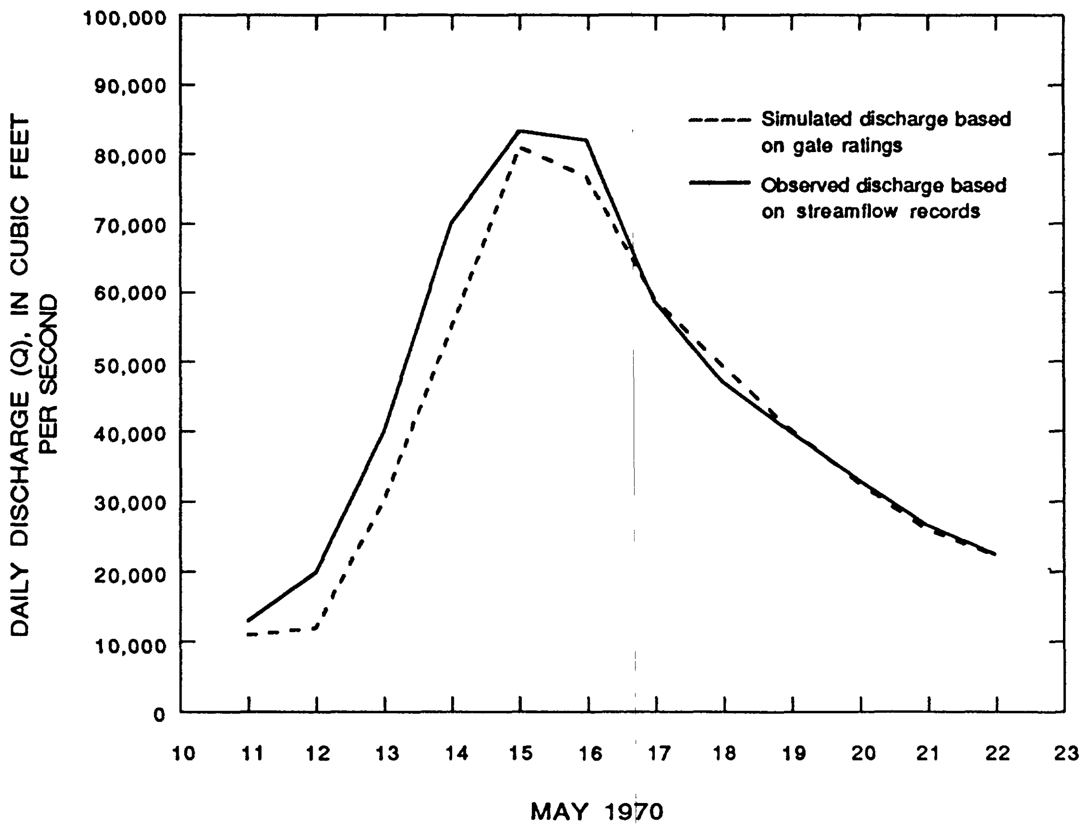


Figure 24.--Simulated and observed flood hydrographs for Illinois River at Marseilles Dam.

Tailwater Rating

Figure 25 shows the tailwater rating for Marseilles Dam. The rating is based on 626 measurements of stage at the dam and stage at gaging station 05543500 from April 12, 1984, through November 18, 1985. During this period of time, stage ranged from 1.0 ft when only two gates were open 0.5 ft, to 13.6 ft when seven gates were completely raised out of water. A rating for stages less than 2.7 ft is not shown in figure 25 because stage varied as much as 1.3 ft due to powerplant return flows and to the proximity of the gates in operation at the dam to the tailwater-stage gage. Tailwater stage is referenced to a datum of 467.2 ft, 8.7 ft higher than the normal headwater-pool elevation at Starved Rock Dam.

The rating represents conditions at the tailwater section of Marseilles Dam upstream from where return flows from the Illinois Power and Light Company powerplant are discharged to the river. The tailwater rating should not be used to estimate total discharge of the Illinois River when tailwater stage is below 4.0 ft because return flow from the powerplant can exceed 15 percent of the total discharge.

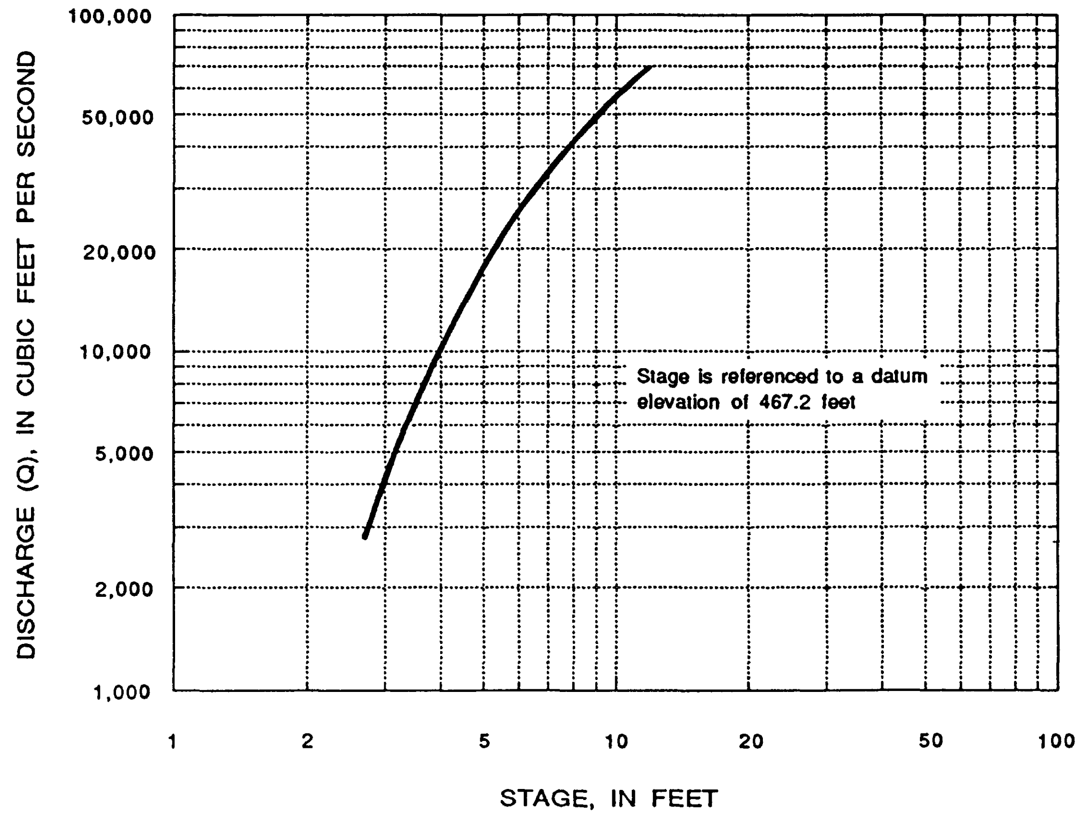


Figure 25.--Tailwater rating for Marseilles Dam.

Starved Rock Dam

Gate and Valve Ratings

Twenty-four measurements were made on the Illinois River to obtain data for determining discharge coefficients for equations 1 through 4 (table 1). Measurements 1-6 (table 9) were made about one-fourth mile downstream from the dam. The remaining measurements were made at Starved Rock State Park, about three-fourths mile downstream from the dam.

Measured discharges ranged from 4,800 to 71,900 ft^3/s. Table 9 summarizes the hydraulic control conditions during each measurement. Free orifice flow was measured during measurements 5, 6, 9, 12-16, 20, 23, and 24. Submerged orifice flow was measured during measurements 1-4, 8-11, 19, and 22. Free weir flow was measured during measurements 7 and 23. Submerged weir flow was measured during measurements 17-19, 21, and 22.

The relation between the discharge coefficient for free orifice flow (C) and Tainter-gate opening (h_g) is shown in figure 26. A least squares regression method was used to determine the parameters in a linear model that relates

Table 9.--Discharge measurements and hydraulic-control data for Starved Rock Dam

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

Measurement number	Date	Pool elevation, in feet		Tainter gates		Flow regime[1]	Measured discharge (ft^3/s)	Discharge coefficient
		Headwater	Tailwater	Number open	Opening (feet)			
1	04-19-78	459.2	450.9	7	3.0	SO	23,800	0.261
2	04-19-78	459.2	450.9	3	7.0	SO	26,400	.675
3	05-24-78	458.8	448.2	4	3.0	SO	15,600	.371
4	05-24-78	458.6	448.1	6	2.0	SO	14,600	.236
5	08-30-78	458.3	442.1	4	1.0	FO	6,220	.787
6	08-30-78	458.4	442.0	5	1.0	FO	7,810	.790
7	06-17-80	459.0	447.8	1	12.0	FW	15,300	3.48
8	06-17-80	458.8	448.0	2	6.0	SO	16,800	.817
9	06-17-80	458.9	447.7	1	9.0	FO	[2]13,000	.656
				1	1.0	SO		[3].118
10	04-14-81	458.9	454.6	7	7.0	SO	[2]54,400	.479
				2	6.0	SO		.403
11	04-15-81	459.0	456.5	2	11.0	SO	[2]59,300	.650
				4	10.0	SO		.584
				3	9.0	SO		.519
12	11-28-83	458.9	449.0	3	8.0	FO	29,600	.614
13	11-28-83	459.2	449.0	2	11.0	FO	25,200	.565
14	08-01-84	458.8	441.1	2	2.0	FO	6,260	.781
15	08-01-84	458.8	441.1	1	3.0	FO	[2]6,250	.761
				2	.5	FO		.840
16	08-01-84	458.7	441.1	1	3.0	FO	4,800	.801
17	02-26-85	462.0	461.0	9	12+	SW	71,900	.443
18	03-01-85	458.6	457.2	7	12+	SW	47,300	.489
19	03-02-85	458.8	456.3	4	12+	SW	[2]39,600	.683
				1	4.0	SO		[3].210
20	05-28-85	458.8	441.9	2	2.0	FO	[2]7,720	.767
				1	1.0	FO		.788
21	11-23-85	459.0	458.4	10	12+	SW	54,300	.378
22	11-27-85	458.6	455.0	2	12+	SW	[2]31,800	.923
				1	8.0	SO		[3].507
23	12-05-85	459.0	453.6	1	12+	FW	[2]26,000	3.02
				1	11.0	FO		[3].580
24	05-30-86	459.0	445.0	2	5.0	FO	[2]12,800	.635

[1]SO designates submerged orifice flow; FO designates free orifice flow; FW designates free weir flow; and SW designates submerged weir flow.

[2]Combined flow through all gate openings.

[3]Coefficient is obtained from equation 27.

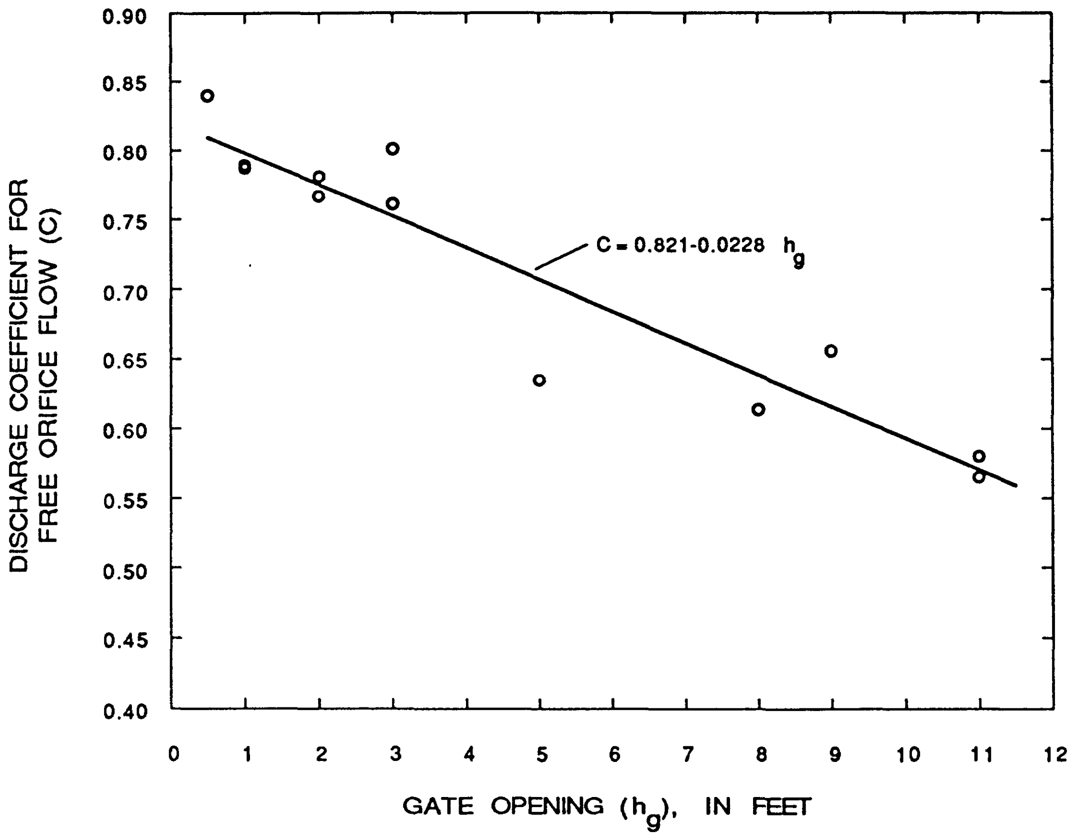


Figure 26.--Relation between the discharge coefficient for free orifice flow and gate opening for Starved Rock Dam Tainter gates.

C to h_g. The equation,

$$C = 0.821 - 0.0228\ h_g, \tag{26}$$

is based on a regression analysis of discharge coefficients and gate openings for 11 main-channel measurements.

A transition from free orifice flow to submerged orifice flow was observed at a submergence ratio (h_3/h_g) of about 1.5. The discharge coefficient for submerged orifice flow is indirectly proportional to h_3/h_g as shown in figure 27. A least squares regression based on 10 main-channel measurements yielded the logarithmic model,

$$C_{gs} = 0.923\ (h_3/h_g)^{-1.12}. \tag{27}$$

A transition to weir flow occurs as the Tainter-gate opening is increased above 11.3 ft. Gates were clear of the water during main-channel measurements 7, 17-19, and 21-23. The discharge coefficient for free weir flow, C_w, is estimated to be 3.25, the average of the values based on main-channel measurements 7 and 23. Submerged weir flow occurs when the headwater submergence

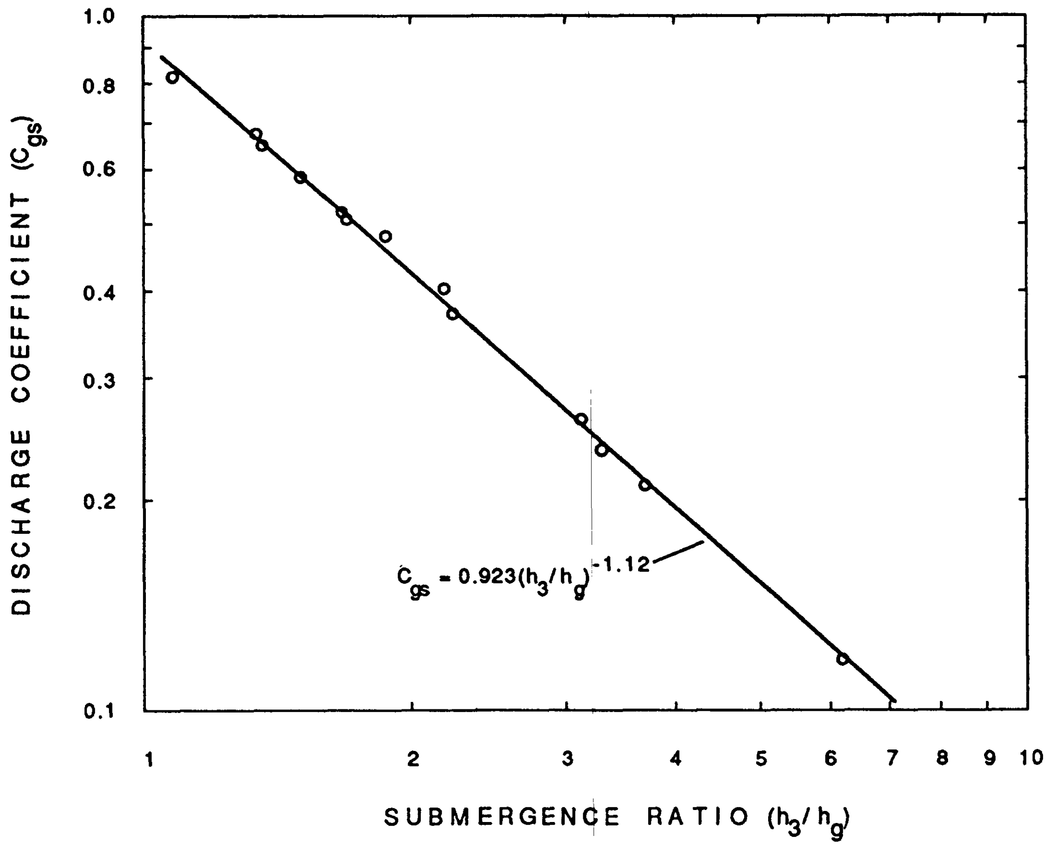


Figure 27.--Relation between the discharge coefficient for submerged orifice flow and submergence ratio for Starved Rock Dam Tainter gates.

ratio (h_3/h_1) exceeds 0.76. Figure 28 shows the relation between the discharge coefficient for submerged weir flow (C_{ws}) and h_3/h_1. The equation,

$$C_{ws} = 3.26 - 2.99 \ (h_3/h_1), \qquad (28)$$

is based on five main-channel measurements.

Figure 29 shows the relation between the discharge coefficient for submerged orifice flow (C_{gs} in eq. 2) for the Starved Rock Lock upstream lock valves and the submergence ratio (h_3/h_g). This relation was developed from two volumetric measurements during which the lock was filled with two valves fully open (h_g equal to 9.0 ft) and two valves half open (h_g equal to 4.5 ft). Tailwater depth (h_3) is the depth of water in the lock relative to the upstream lock-valve-sill elevation of 426.5 ft. This relation is expressed mathematically as

$$C_{gs} = 0.565 \ (h_3/h_g)^{-0.947}. \qquad (29)$$

Figure 29 or equation 29 may be used to determine C_{gs} for a known lock-pool elevation and valve opening.

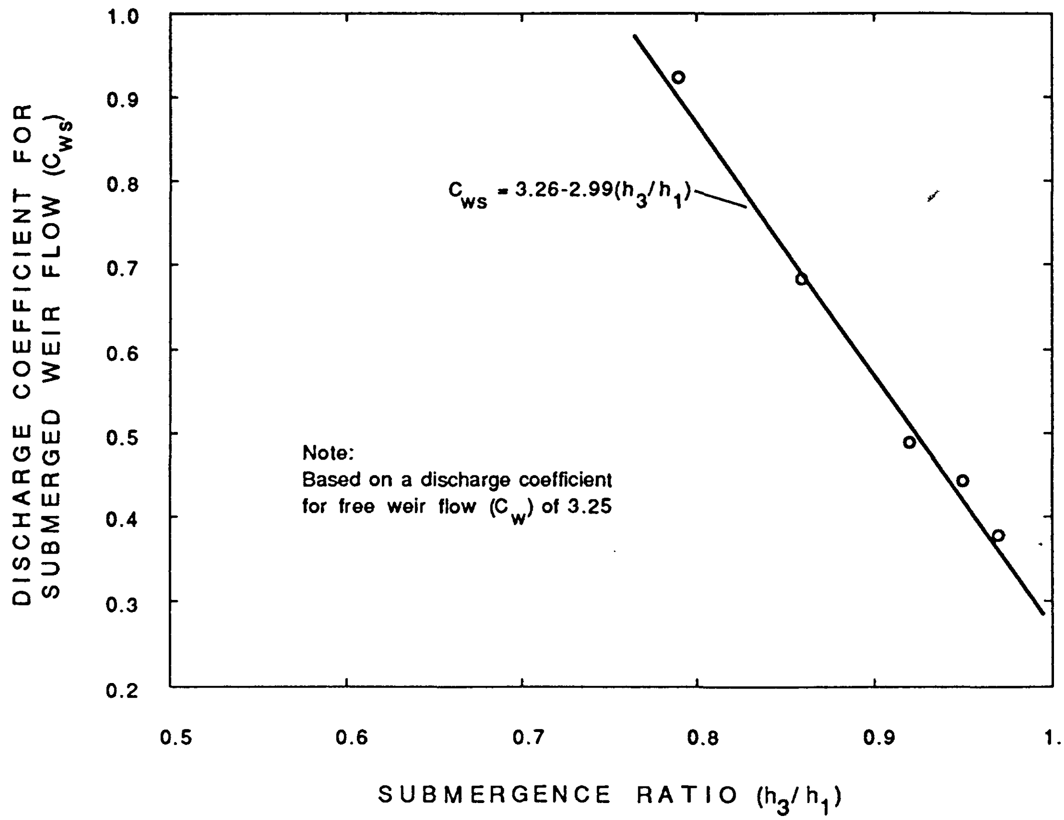


Figure 28.--Relation between the discharge coefficient for submerged weir flow and submergence ratio for Starved Rock Dam Tainter gates.

The following mathematical expressions for the gate and valve ratings for Starved Rock Lock and Dam were determined by substituting equations 26-29 and the discharge coefficient for free weir flow into the appropriate equations listed in table 1. Hydraulic conditions for which the gate ratings are appropriate are enclosed by parentheses.

Gate rating--free orifice flow (h_3/h_g <1.0 and h_g/h_1 <0.67):

$$Q = (C)(B)(h_g)[(2g)(h_1)]^{0.5}$$
$$= (0.821 - 0.0228\ h_g)(60)(h_g)[(64.4)(h_1)]^{0.5}$$
$$= (395\ h_g - 11.0\ h_g^2)\ h_1^{0.5} \qquad (30)$$

Gate rating--submerged orifice flow (h_3/h_g ≥1.5 and h_g/h_1 <0.67):

$$Q = (C_{gs})(B)(h_3)[(2g)(\Delta h)]^{0.5}$$
$$= [(0.923)(h_3/h_g)^{-1.12}](60)(h_3)[(64.4)(\Delta h)]^{0.5}$$
$$= 444\ (h_3)^{-0.12}\ (h_g)^{1.12}\ (\Delta h)^{0.5} \qquad (31)$$

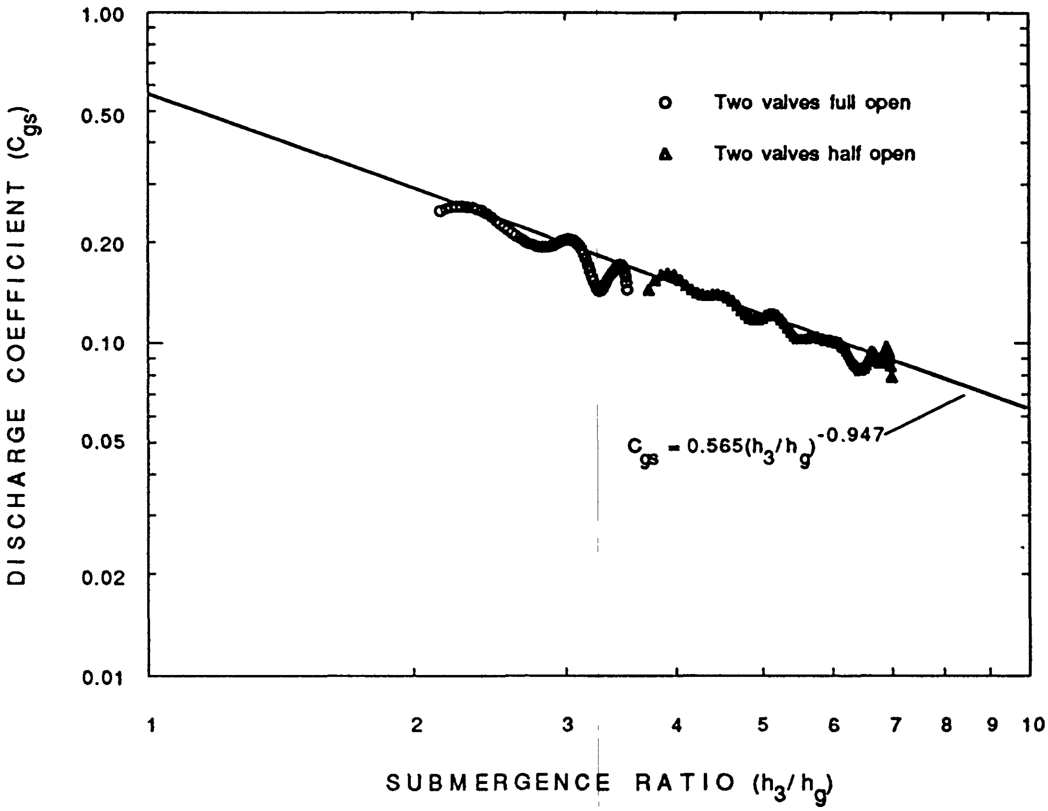


Figure 29.--Relation between the discharge coefficient for submerged orifice flow and submergence ratio for the Starved Rock Lock, upstream culvert valves.

Gate rating--free weir flow (h_3/h_1 <0.76 and $h_g/h_1 \geq 0.67$):

$$\begin{aligned} Q &= (C_w)(B)(h_1)^{1.5} \\ &= (3.25)(60)(h_1)^{1.5} \\ &= 195\ h_1^{1.5} \end{aligned} \quad (32)$$

Gate rating--submerged weir flow ($h_3/h_1 \geq 0.76$ and $h_g/h_1 \geq 0.67$):

$$\begin{aligned} Q &= (C_{ws})(C_w)(B)(h_1)^{1.5} \\ &= [3.26 - 2.99\ (h_3/h_1)](3.25)(60)(h_1)^{1.5} \\ &= 636\ (h_1)^{0.5}\ (h_1 - 0.917\ h_3) \end{aligned} \quad (33)$$

Valve rating--submerged orifice flow:

$$\begin{aligned} Q &= (C_{gs})(B)(h_3)[(2g)(\Delta h)]^{0.5} \\ &= [0.565\ (h_3/h_g)^{-0.947}](12)(h_3)[(64.4)(\Delta h)]^{0.5} \\ &= 54.4\ (h_3)^{0.053}\ (h_g)^{0.947}\ (\Delta h)^{0.5} \end{aligned} \quad (34)$$

Headwater depth (h_1) and tailwater depth (h_3) for the gate ratings (eqs. 30-33) are the depths, in feet, of the headwater and tailwater pools relative to the spillway-crest elevation of 441.5 ft. The tailwater depth for the lock-valve rating (eq. 34) is the depth of water in the lock relative to the valve-sill elevation of 426.5 ft.

Equations 30-33 were used to develop the gate ratings illustrated in figure 30. Figure 30 is based on an assumed headwater-pool elevation of 458.5 ft (h_1 = 17.0 ft) and a range of tailwater-pool elevations and gate openings. Equations 30-33 may be used to determine discharge for headwater-pool elevations other than 458.5 ft or tailwater-pool elevations that are not shown in figure 30.

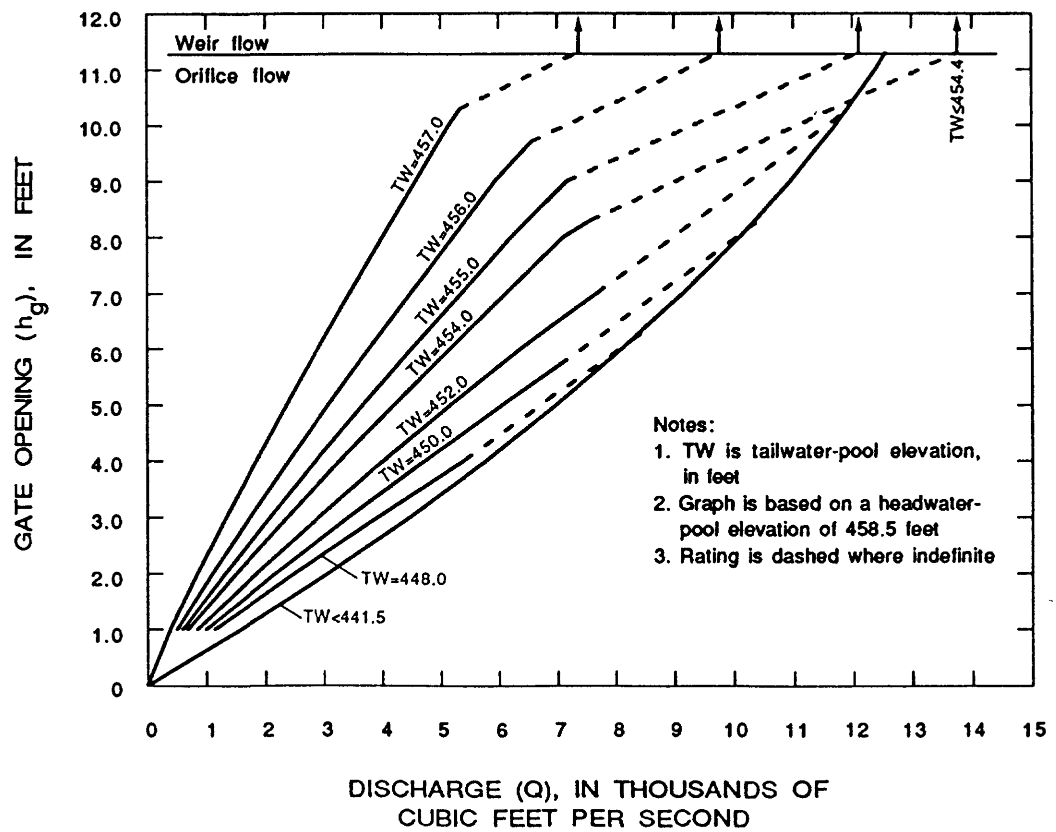


Figure 30.--Discharge rating for one Starved Rock Dam Tainter gate.

The dashed lines in figure 30 indicate an indefinite rating. The transition from submerged orifice flow to free orifice flow (submergence ratios, h_3/h_g, between 1.5 and 1.0) or submerged weir flow (submergence ratios, h_3/h_1, greater than 0.76) is represented by the dashed lines below the horizontal line drawn at a gate opening of 11.3 ft.

Discharge into the lock has been calculated for values of Δh (difference between the headwater-pool and lock-pool depths) ranging from 0 to 28 ft for one-half and full openings (table 10). The table was developed using equation 34. Table 10 may be used to determine discharge into the lock for known headwater- and lock-pool elevations.

Table 10.--Discharge rating for one upstream culvert valve at Starved Rock Lock

[Headwater-pool elevation is 458.5 feet]

Lock-pool elevation, in feet	Difference between headwater-pool and lock-pool elevations (Δh), in feet	Discharge, in cubic feet per second: One-half open[1]	Discharge, in cubic feet per second: Fully open[2]
458.5	0	0	0
458.0	.5	192	370
457.5	1	271	523
456.5	2	383	738
455.5	3	468	902
454.5	4	540	1,040
453.5	5	602	1,160
452.5	6	658	1,270
450.5	8	757	1,460
448.5	10	842	1,620
443.5	15	1,020	1,960
438.5	20	1,150	2,220
434.5	24	1,240	2,380
430.5	28	1,290	2,480

[1]Valve opening is 4.5 feet.
[2]Valve opening is 9.0 feet.

The validity of the gate ratings was checked by comparing discharge hydrographs based on the ratings with streamflow records from nearby streamflow-gaging stations. Figure 31 shows two sets of daily-discharge hydrographs for floods that occurred in May 1966 and June 1968. Each set consists of a discharge hydrograph based on the gate ratings and hourly observations of headwater- and tailwater-pool elevation and gate setting recorded in the Lockmaster's log, and a hydrograph based on streamflow records for nearby gaging stations. The floods of 1966 and 1968 were chosen for analysis because the Lockmaster's records indicated that all four flow regimes existed at one time or another during these floods.

The hydrographs based on streamflow records were determined by summing the concurrent daily discharges reported for Illinois River at Marseilles (05543500) and Fox River at Dayton (05552500). Streamflow records for both stations have been published (U.S. Geological Survey, 1973).

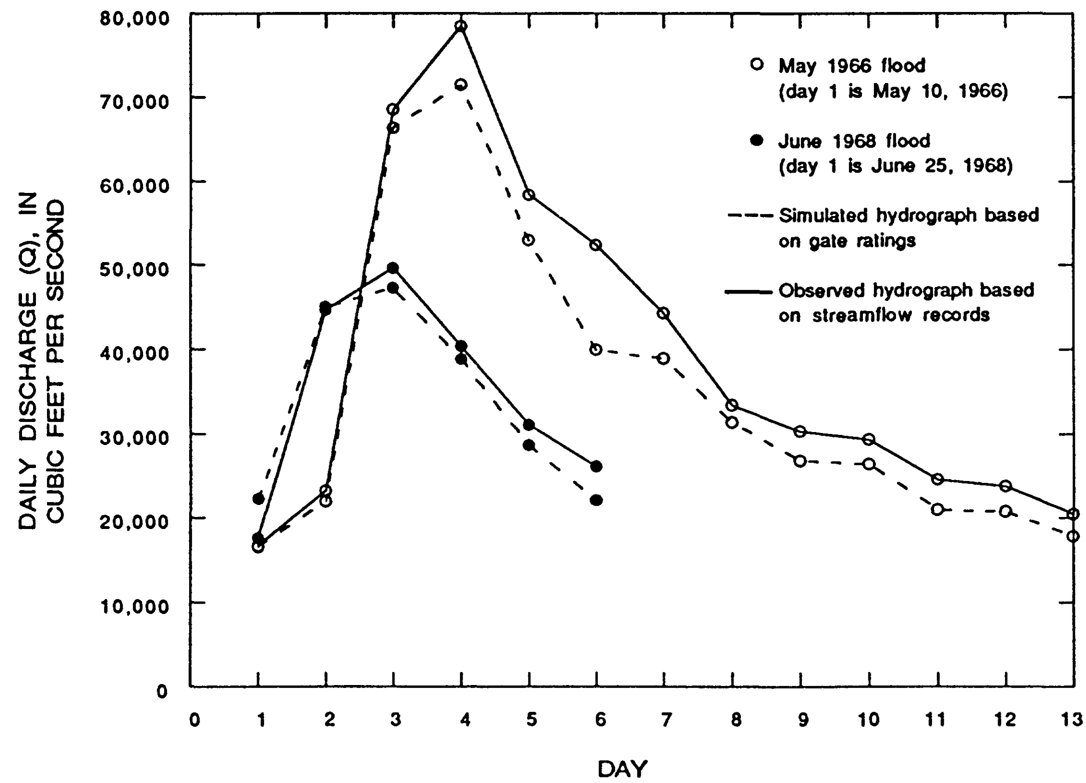


Figure 31.--Simulated and observed flood hydrographs for Illinois River at Starved Rock Dam.

The rise of both sets of hydrographs compare quite well. However, the gate ratings for weir flow and submerged orifice flow appear to underestimate discharge as illustrated by the recessions of both sets of hydrographs shown in figure 31. The poorer comparison of peak discharges and recessions cannot be explained. Records of stage and gate opening were checked, and the discharge coefficients for free weir, submerged weir, and submerged orifice flows were adjusted beyond the range of values determined using discharge measurements. Streamflow records for both gaging stations were checked. The effects of lockages, which were not considered in this analysis, may explain some of the differences when daily discharge was less than 40,000 ft^3/s.

Tailwater Rating

Figure 32 shows stage-discharge relations for two floods--one that occurred May 10-22, 1966, and another that occurred June 25-30, 1968. The figure was developed from the gate ratings developed for Starved Rock Dam (eqs. 30-33) and hourly readings of headwater- and tailwater-pool elevations and gate openings registered in the Lockmaster's log. Tailwater stage is referenced to a datum of 440.0 ft, the normal headwater-pool elevation at Peoria Dam.

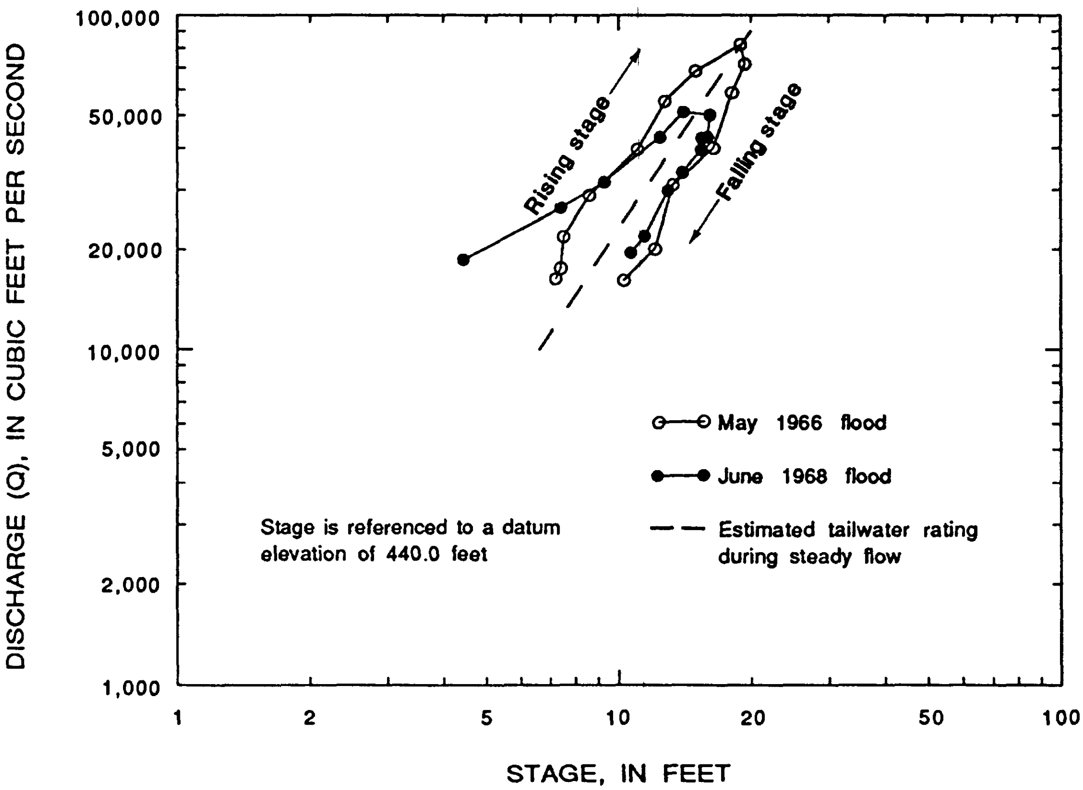


Figure 32.--Tailwater rating for Starved Rock Dam.

Figure 32 also illustrates the effects that variable channel-storage conditions have on the relation between tailwater stage and discharge at Starved Rock Dam. The hysteresis, or loop, in both stage-discharge relations was caused by varying amounts of water in storage downstream from the dam. When tailwater stage was rising, the discharge for a given stage was about 1.3 to 2.0 times the discharge for the same stage when stage was falling. The stage-discharge relation can also be affected by antecedent conditions in downstream Peoria Lake when discharge is less than 30,000 ft^3/s. Figure 32 illustrates how the May 1966 flood began when lake levels were about 5 ft higher than a similar flood in June 1968.

The dashed line shown in figure 32 is an estimate of the relation between tailwater stage and discharge during steady flow. The rating is of limited use because steady flow seldom exists for the range of stage and discharge for which the rating was drawn and antecedent conditions of Peoria Lake can have pronounced effects on the rating when discharge is less than 30,000 ft^3/s. Further refinement of the tailwater rating was beyond the scope of this study.

SUMMARY

Techniques for computing discharge are developed for the Brandon Road Dam on the Des Plaines River and the Dresden Island, Marseilles, and Starved Rock Dams on the Illinois River. The techniques facilitate computation of discharge at locations having no nearby streamflow-gaging stations. The techniques are also useful for computing low flows when the water-surface slope between control structures on the river approaches zero and traditional methods of determining discharge based on slope are unsatisfactory.

Hydraulic equations based on the assumption of steady flow were used to develop relations between discharge, stage, and gate openings (termed gate or valve ratings) for Tainter gates at the dams and culvert valves at the locks. Discharge measurements are used to determine discharge coefficients for the free orifice, submerged orifice, free weir, and submerged weir flow regimes that may occur at the gates and valves. Relations between tailwater stage and discharge, termed tailwater ratings, were determined using Lockmaster records of gate settings and headwater- and tailwater-pool elevations in conjunction with the developed gate ratings. Flood hydrographs determined using the gate ratings were compared to daily discharges reported for nearby streamflow-gaging stations. Discharge hydrographs computed using the gate ratings compare favorably with measured data.

Brandon Road Dam was being rehabilitated during the period of study. Accurate ratings for the Tainter-gate sections could not be determined because of substantial leakage through deteriorated headgates and sluice gates. A rating for the newly constructed headgates is developed using discharge coefficients reported by the Corps for geometrically similar headgates. Additional discharge measurements should be made after rehabilitation is completed. The Tainter-gate and headgate ratings developed in this study should be verified by additional measurements after rehabilitation is completed. A rating for discharge ranging from 0 to 2,310 ft^3/s through the upstream lock valves is developed from one volumetric measurement. A tailwater rating could not be determined for Brandon Road Dam because of variable backwater effects caused by Dresden Island Dam and extremely unsteady flow.

The gate rating for nine Tainter gates at Dresden Island Dam is based on 39 measurements of discharge that ranged from 569 to 30,600 ft^3/s; 20 of these measurements were made in gate forebays. Ratings of free weir, free orifice, and submerged orifice flow regimes are based on these 39 measurements; however, the rating of submerged weir flow is based on results for Starved Rock Dam. A rating for discharge ranging from 0 to 1,820 ft^3/s through the upstream lock valves is developed from three volumetric measurements. The tailwater rating developed for Dresden Island Dam is of limited use because of hysteresis in the stage-discharge relation that is caused by unsteady flow and variable downstream channel-storage conditions.

Gate ratings for eight Tainter gates at Marseilles Dam are based on gaged and measured discharges that range from 1,610 to 86,400 ft^3/s. A gate rating for the submerged weir flow regime was not developed because this regime rarely, if ever, exists at the dam. A rating for discharge ranging from 0 to 2,990 ft^3/s through the upstream lock valves is developed from three volumetric

measurements. A tailwater rating for stages between 2.7 and 12 ft is based on 626 measurements of tailwater stage and concurrent stage and discharge at a nearby streamflow-gaging station.

Gate ratings for 10 Tainter gates at Starved Rock Dam are based on 24 measurements of discharge that range from 4,800 to 71,900 ft^3/s. Ratings for each of four flow regimes that occur at the dam are based on discharge measurements. A rating for discharge ranging from 0 to 2,480 ft^3/s through the upstream lock valves is developed from two volumetric measurements. The tailwater rating developed for Starved Rock Dam is of limited use because of hysteresis in the stage-discharge relation that is caused by unsteady flow and variable downstream channel-storage conditions, notably Peoria Lake.

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