University of Minnesota
St. Anthony Falls Hydraulic Laboratory

Project Report No. 266

MEASUREMENTS OF OXYGEN TRANSFER AT SPILLWAYS AND OVERFALLS

by

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and

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Prepared for

LEGISLATIVE COMMISSION ON MINNESOTA RESOURCES
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July 1989
Minneapolis, Minnesota

UNIVERSITY OF MINNESOTA
TWIN CITIES

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September 22, 1989

Mr. Ian Chisholm
Ecological Services
Division of Fish and Wildlife
Department of Natural Resources
500 Lafayette Road
St. Paul, MN 55155

Dear Ian:

Enclosed is a copy of P.R. 266, "Measurements of Oxygen Transfer at Spillways and Overfalls," to be placed in your files (library) for future reference on investigations involving the water quality near hydraulic structures.

Sincerely,

John Gulliver
Associate Professor

UNIVERSITY OF MINNESOTA
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September 27, 1989

Mr. John Velin
Director
Legislative Commission on Minnesota Resources
Room 65, State Office Building
St. Paul, MN 55155

Dear John:

Enclosed is the remaining 9 copies of P.R. 266, "Measurements of Oxygen Transfer at Spillways and Overfalls," for distribution as needed.

Sincerely,

Pat Swanson

Pat Swanson
Editor IV

cc: CA

Reference: 9/22/89 letter

ACKNOWLEDGEMENTS

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John Thene and Judson Woods assisted in data collection, and in the development of field insrumentation. Pat Swanson and Terri Boldischar edited and processed the manuscript. Aaron Gimbel produced the numerous figures described herein.

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I. INTRODUCTION, MEASUREMENT TECHNIQUES, AND DATA REDUCTION

The oxygen transfer across the air–water interface at a spillway or overfall is an important dissolved oxygen source or sink in a river–reservoir system. Normally many river miles are required for a significant air–water transfer of oxygen to occur, but at a spillway this same oxygen transfer may occur in the short residence time at the spillway/weir. The primary reason for this accelerated oxygen transfer is that air is entrained into the flow, producing a large number of bubbles. Air bubbles greatly increase the surface area available for gas transfer. In addition, the bubbles are transported by the flow to various depths downstream of the structure, increasing gas transfer and the possibility of supersaturation due to an increased saturation concentration at higher pressures. This is not a problem with oxygen, but in the case of dissolved nitrogen this supersaturation may cause fish mortality by nitrogen gas bubble disease. The results of this study are limited to oxygen but can be applied to transfer of any chemical for which transport is controlled by the water side of the interface using procedures described in Gulliver, Thene, and Rindels (1989).

Because of the significant influence a hydraulic structure has on the downstream dissolved gas levels, engineers are being required to predict these levels for a particular mode of hydraulic structure operation. In particular, some hydropower developments are being required to improve the downstream dissolved oxygen level, meet pre–project conditions downstream, or show that development will not result in unacceptable downstream dissolved oxygen concentrations. This is not currently possible with the predictive equations available in the literature. Usually the best alternative is to measure the oxygen transfer. However, this is often not possible without employing relatively expensive tracers which require care in sampling and measurement.

The objective of this report is to present as complete of a data set as possible for both a forthcoming analysis of gas transfer at spillways and hydraulic jumps and for use by other researchers. This report documents field measurements collected to determine the oxygen transfer at 14 dams in the vicinity of Minneapolis, Minnesota. It contains data collected from 34 site surveys taken from March 1984 to March 1986. It organizes the data collected on gas transfer at each individual hydraulic structure into separate chapters. Each chapter presents the data collected at a given hydraulic structure and is subdivided into three sections: Physical Description, Discharge Prediction, and Gas Transfer Measurements. The first section presents available data pertaining to the physical structure, e.g. a physical description of the dam, plans and cross sections, etc. The second section describes the means of estimating discharge. The third section describes the gas transfer data collected and the results obtained, i.e. the transfer efficiency with its associated uncertainty.

Oxygen transfer measurements were taken during the winter months to take advantage of the ice cover upstream and downstream of a hydraulic structure. There are two important consequences produced by the ice cover: large upstream dissolved oxygen deficits and ease of sampling. Large upstream dissolved oxygen deficits occur because the ice cover minimizes photosynthesis and surface transfer while there is a net loss of dissolved oxygen due to algae and benthic respiration. There is usually no ice cover on the spillway, and the time of water passage across a hydraulic structure is very short. Dissolved oxygen concentration may then be used directly to determine oxygen transfer. The ice cover also provided an excellent staging area from which dissolved oxygen measurements could be taken. This allowed sampling of D.O. immediately above, below, and at various locations across the crest of a spillway with relative safety. However, continually changing ice thickness upstream and downstream of a dam, especially during a period of thawing, required frequent ice thickness monitoring for safe sampling.

The ice cover did have a detrimental effect on the gas transfer measurements. In some cases the ice would form along the side of retaining walls and grow outward across the structure. This ice would then cap the spillway flow, influencing gas transfer.

A *Standard Methods* [APHA, 1980] type of D.O. sampler, shown in Photo I–1, was used to collect water samples for all the measurements. Meters were not used because the measurements are not as accurate, and cold weather greatly affects their calibration and operation. The azide modification of the Winkler titration method was used to determine D.O. concentration according to *Standard Methods* (APHA, 1980). To minimize the impact of sample degradation, the samples were chemically fixed in the field and typically analyzed within 6 hours of collection. Overall, minimal error was found using this technique, with most upstream and downstream samples having a standard error of less than 0.1 ppm.

Where possible, spillway samples were taken to evaluate the gas transfer which occurred on the spillway face. This was accomplished using a Pitot spillway sampler, fashioned from a U.S. Geological Survey wading rod, a current meter holder and 3/8–inch (9 mm) flexible tubing. The sampler, shown in Photo I–2, was placed in the flow where stagnation pressure head drove the fluid through the tubing. The tubing was placed in the bottom of a 300 $m\ell$ bottle which was flushed at least three times. The deficit ratios obtained at spillways indicate that gas transfer on the spillway face may be significant, even at low head structures. For example, at Kost Dam, up to half of the gas transfer occured before the hydraulic jump when the aerated flow length was 12 ft (3.66 m). For large spillways, it is conceivable that the flow at the bottom of the spillway could be almost fully saturated. Supersaturation, if observed, could typically occur in the stilling basin with adequate tailwater depth.

The oxygen transfer data is reported as the Transfer Efficiency, E, first used by Gameson (1957). For clarity, E is one minus the inverse of the Deficit Ratio, r, as reported by Avery (1978) and is the ratio of total gas transfer at the structure to total potential gas transfer. E is further described by equation 1 as:

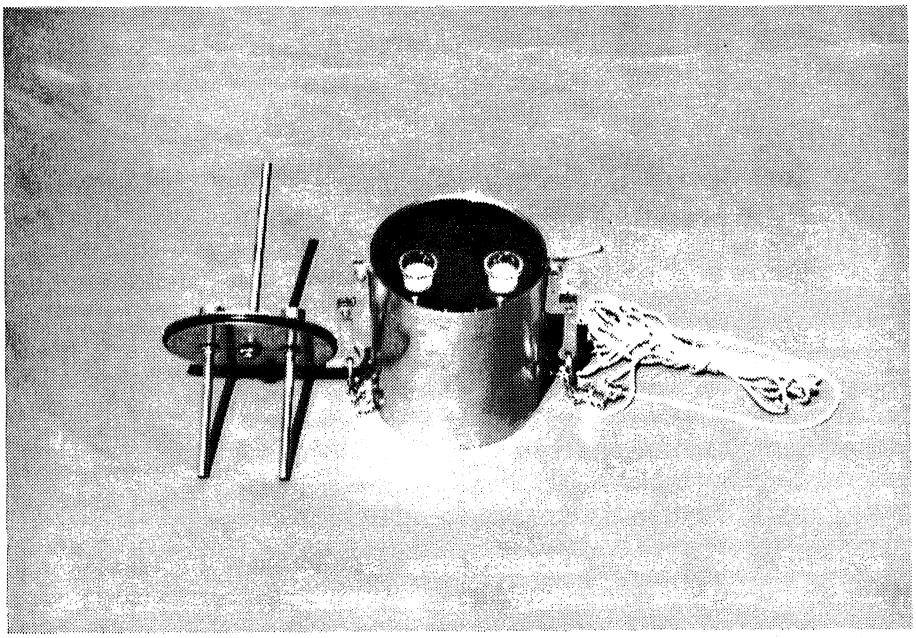


Photo I–1. Standard methods sewage sampler used for water sample collection.

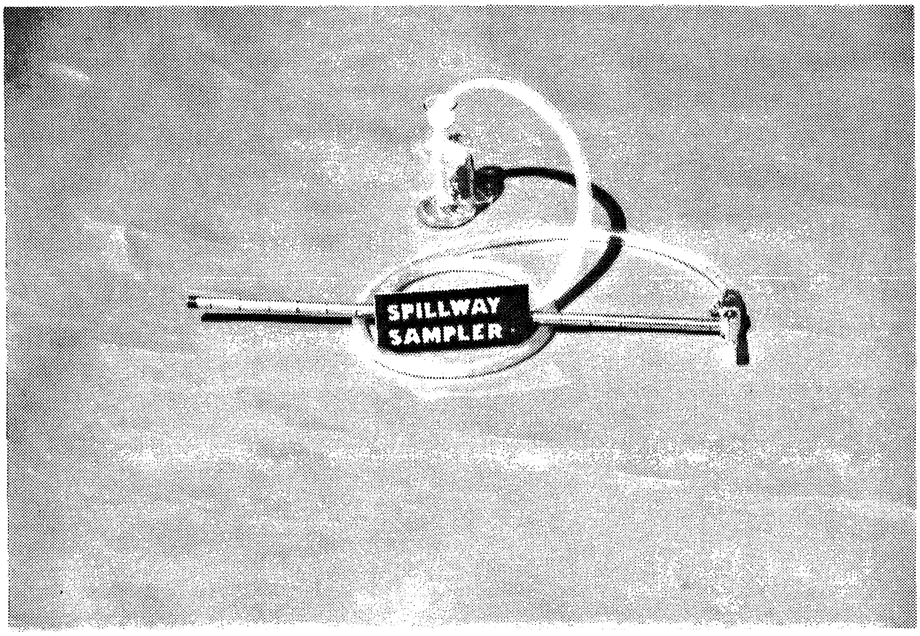


Photo I–2. Pitot tube spillway sampler fashioned from 3/8" tubing, U.S.G.S. wading rod and pygmy meter bracket.

$$E = 1 - \frac{C_s - C_d}{C_s - C_u} = 1 - \frac{1}{r} \quad (1)$$

where C_s, C_d, and C_u are the saturation, upstream, and downstream dissolved oxygen concentration, respectively. The possible range of values are $0 \leq E \leq 1$. $E = 0$ means that no gas transfer has occurred across the structure, and $E = 1$ means that complete transfer has occurred.

Inadvertently, measurement uncertainty occurs due to the inaccuracy of the instruments, of the measurement, or operator error. Attempts were made to quantify all significant measurement uncertainties in the procedures. Investigations were performed during the course of the measurements to identify sources of uncertainty, such as the chemical titrant purity in the Winkler technique or the buret accuracy.

To account for these uncertainties in E, a measure of the total uncertainty of the transfer efficiency, U_E accompanies each measurement.

By definition, the total uncertainty of any measurement is a combination of precision uncertainty, or random error introduced when measurements are repeated, and bias uncertainty, or possible error that would affect each measurement in the same manner (Abernathy et al., 1985). Thus, the total uncertainty of E, U_E can be expressed as

$$U_E^2 = W_E^2 + B_E^2 \quad (2)$$

where W_E = precision uncertainty in the transfer efficiency, and
B_E = bias uncertainty in the transfer efficiency.

All uncertainties will be quoted to the 95% confidence interval. This means that of 20 measurements, 19 should be within this interval.

The precision uncertainty, W_E, is a combination of the sampling uncertainties which result from determining C_u, C_d, and W_{c_u} and W_{c_d}, respectively. W_{c_u} and W_{c_d} are described according to Abernathy et al. (1985) as:

$$W_{c_u} = \left(\frac{t\sigma}{\sqrt{n}} \right)\Big|_{c_u} \text{, and}$$

$$W_{c_d} = \left(\frac{t\sigma}{\sqrt{n}} \right)\Big|_{c_d} .$$

where σ = standard deviation of the measurements

t = Students' t value corresponding to n–1 degrees of freedom, and a 95% confidence interval

n = number of measurements.

When W_{c_u} or W_{c_d} are greater than .05 (the uncertainty associated with reading the buret used for titrations), the above applies, otherwise, W_{c_u} = 0.05 and W_{c_d} = 0.05

The total precision uncertainty is found by the following formula:

$$W_E^2 = \left[\frac{\partial E}{\partial C_d} W_{c_d}\right]^2 + \left[\frac{\partial E}{\partial C_u} W_{c_u}\right]^2 \tag{5}$$

The two bias uncertainties that need to be considered are the chemical titrant purity in the Winkler technique and the uncertainty in the value of saturation concentration. The supplier of the sodium thiosulfate titrant guarantees the purity to within ± 1%. This will be used as the 95% confidence interval.

The saturation concentration of a given hydraulic structure was estimated using the atmospheric pressure, measured before and after sampling, with a barometer at the St. Anthony Falls Hydraulic Laboratory, and the water temperature measured at the site. Since the saturation value is a function of water quality, the value listed has been estimated to be 98% of the distilled water value with an uncertainty of ± 2% (Rindels and Gulliver, 1986).

These two bias uncertainties are added to give the total bias uncertainty in E as follows:

$$B_E^2 = \left[\frac{\partial E}{\partial C_s} B_{c_s}\right]^2 + B_T^2 \tag{6}$$

where B_T is the bias uncertainty in E due to the titrant, and B_{c_s} is the bias uncertainty in C_s. B_{c_s} = 0.02 C_s. B_T however; must be found by a perturbation analysis on E.

$$B_T = E(C_u + \Delta C_u\ ,\ C_d + \Delta C_d) - E(C_u, C_d) \tag{7}$$

or where ΔC_u = .01 C_u and ΔC_d = .01 C_d

$$B_T = 1 - \frac{C_s - 1.01\ C_d}{C_s - 1.01\ C_u} - 1 + \frac{C_s - C_d}{C_s - C_u} \tag{8}$$

or

$$B_T = \frac{0.01\ C_s(C_d - C_u)}{(C_s - 1.01\ C_u)(C_s - C_u)} \tag{9}$$

Finally, Eq. 2 becomes

$$U_E^2 = \left[\frac{W_{c_d}}{C_s - C_u}\right]^2 + \left[\frac{W_{c_u}(1-E)}{(C_s - C_u)}\right]^2 + \left[\frac{0.02\ C_s\ E}{C_s - C_u}\right]^2 + \left[\frac{0.01\ C_s\ (C_d - C_u)}{(C_s - 1.01\ C_u)(C_s - C_u)}\right]^2 \tag{10}$$

Equation 10 indicates the accuracy of the transfer efficiency was strongly dependent on the difference between saturation and the measured upstream dissolved oxygen concentration (the oxygen deficit). Large oxygen deficits lead to an improved accuracy.

II. KOST DAM

A. PHYSICAL DESCRIPTION

The Kost Dam is an earthen dam with a 73.5 ft uncontrolled ogee spillway. The dam is located in Chisago County, Minnesota, on the Sunrise River. Previously the dam was used to maintain a reservoir for hydropower purposes; however, today the dam is primarily used to maintain a small impoundment for recreational purposes.

The uncontrolled ogee spillway shown in Fig. II–1, II–2 and II–3 and also in Photo II–1 through II–2 has a crest length of 73.5 ft and an elevation difference of 13.5 ft from crest to spillway apron. It was completely reconstructed in 1978 to its present condition. To minimize costs during construction, tangents were used to describe the shape of the spillway, as is seen from the horizontal flow discontinuities (white lines parallel to the crest) in Photo II–3. The crest elevation was unknown; a value of 100 ft was assumed.

The dam has also settled, causing the stilling basin floor adjacent to the right abutment (looking downstream) to be about .3 ft higher than the left abutment. This setting resulted in a jet forming along the right abutment, and dissipating downstream off of the stilling basin, downstream of the hydraulic jump.

B. DISCHARGE MEASUREMENTS

Since the dam was rebuilt using a Bureau of Reclamation design, the discharge characteristics published in the *Design of Small Dams* were used to develop the rating curve shown in Figure II–4. In addition, the U. S. Geological Survey maintains a gaging station approximately 3 miles upstream from the dam. Thus, it was possible to calibrate discharge determined from the water surface measurements at the structure to U. S. Geological Survey discharge measurements by assuming discharge is directly proportional to drainage area. As shown in Fig. II–5, the computations using drainage area correspond fairly well to the rating curve developed. Since all the measurements were collected at the site during the winter months with small differences of water surface to crest elevation, the coefficient of discharge was not greatly affected by the approach depth and there was very little error in the results.

C. GAS TRANSFER MEASUREMENTS

Six dissolved oxygen surveys were performed at this site: February 2, 1985, March 12, 1985, December 13, 1985, January 13, 1986, February 21, 1986, and March 10, 1986. The results from these surveys are presented in Tables II–1, through II–6. Spillway aeration and the hydraulic jump characteristics on the six survey dates are shown in all the photos except II–6, II–9, and II–10. Both overall spillway and actual spillway gas transfer was investigated at this structure. Sampling locations for these measurements are shown for each survey in Figs. II–5 through II–13. Spillway sampling in January–March 1986 was performed at the same elevation and are represented by the January 13, 1986, measurement shown in Fig. II–11.

After the 1985 sampling it was realized that improved accuracy in transfer efficiency could be obtained using a more accurate thermometer. This was used in the 1986 measurements collected at this site, and it indicated a likely winter water temperature of .2° C for the February 2, 1985, data. It was decided that this was a more representative water temperature than the .5° C measured value of the February 1985 sampling. Table II–1 uses a .2° C water temperature to be the representative water temperature for the collected water measurements; .3° C uncertainty was used to account for the discrepancy in thermometers.

In addition to the overall gas transfer data collected, an attempt was made to measure the gas transfer which occurs on the spillway face. The first spillway measurement collected at this site used a piece of tygon tubing positioned in the crotch of a branch shaped like a y. This device was placed into the water flowing down the spillway face. It acted like a pitot tube, and the dynamic pressure drove the water through the tube into a bottle. The apparatus successfully sampled spillway gas transfer for Kost and Fairbault Dam.

The winter 1986 data set focused on collection of a large number of measurements to improve the overall accuracy of the transfer efficiency. Sampling at Kost Dam benefited from a learned experience concerning ice upstream and downstream from a hydraulic structure. In winter 1985 it was first thought that the ice was not safe immediately upstream from a structure. This limited data collection to the left and right abutment and upstream of the crest centerline, as shown in Photos II–1 and II–2. In addition, it was not possible to clear the spillway of ice which caused the thickness of the water flowing over the crest to have a variety of thicknesses. A highly distorted, very three–dimensional jump in the stilling basin resulted. During the winter 1986 as much ice as physically possible was removed from the crest of the spillway, as shown in Photo II–4. The large ice pick, shown in Photo II–4, was found to be most successful in clearing the ice from Kost Dam.

There is a note in the data mentioning natural aeration or biological growth induced aeration. The spillway has at one location a large build–up of biological growth (slime) on the spillway face shown in Photo II–9. It appeared that this growth tripped the spillway flow to start aerating earlier than could have occurred naturally. This allowed a comparison of gas transfer of different lengths for both a longer section of aerated flow to be selected for the measurements and a more accurate estimate of the length of aerated flow.

TABLE II–1. Results from Kost Dam Site Survey, February 2, 1985

Atmospheric Pressure:	745.2 mm of Hg
Water Temperature:	.2 ± .3° C**
Saturation Concentration:	14.21 ± .29 mg O_2/ℓ
Static Head:	.55 ± .03 ft
Energy Loss:	13.16 ± .04 ft (Crest datum)
Upstream Water Surface Elevation:	100.55 ± .03 ft (Crest datum)
Downstream Water Surface Elevation:	87.39 ± .04 ft
Discharge/Unit Crest Width:	1.35 ± .05 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	7.53	2	.035	.31	10.23	2	.035	.31	0.40	.06	.7	
Left Bank	7.18	2	.035	.31	10.10	2	.00	.05	0.42	.03	.9	
	Mean for site:								0.41	.04	.8	~11

**Measured 0.5 °C with a thermometer with an accuracy of ± 0.5° C, water temperature was more correctly described by .2° C as compared to 1986 data

LEGEND:

- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency uncertainty

TABLE II–1 (Cont'd). Data from Kost Dam site survey, February 2, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
7.55	14:00	A1	Upstream right bank
7.50	14:00	A1	Upstream right bank
7.50	14:05	A2	Upstream center of spillway
7.50	14:05	A2	Upstream center of spillway
7.15	14:10	A3	Upstream left bank
7.20	14:10	A3	Upstream left bank
10.20	14:30	A4	Downstream right bank just below spillway
10.25	14:30	A4	Downstream right bank just below spillway
10.15	14:34	A5	Sample taken in hydraulic jump
10.20	14:34	A5	Sample taken in hydraulic jump
10.15	14:45	A6	Sample taken in hydraulic jump just below spillway
10.25	14:45	A6	Sample taken in hydraulic jump just below spillway
10.10	15:15	A7	Downstream left bank off of stilling basin
10.10	15:15	A7	Downstream left bank off of stilling basin
10.25	15:24	A8	Sample taken in jet returning to hydraulic
10.15	15:24	A8	Jump
10.30	15:50	A9	Sample taken in upwelling area in hydraulic
10.50	15:50	A9	Jump

TABLE II–2. Results from Kost Dam Site Survey, March 12, 1985

Atmospheric Pressure:	744.1 ± .1 mm of Hg
Water Temperature:	1.8°C ± .3°C
Saturation Concentration:	13.31 ± .3 mg O_2/ℓ
Static Head:	.60 ft ± .02 ft
Energy Loss:	13.04 ft ± .05 ft
Upstream Water Surface Elevation:	100.60 ft ± .02 ft (Crest datum)
Downstream Water Surface Elevation:	87.56 ft ± .05 ft (Crest datum)
Discharge/Unit Crest length:	1.55 ± .05 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	10.61	4	.075	.12	11.58	4	.05	.08	0.36	.06	0.9	
Left Bank	10.36	4	.048	.08	11.60	2	0	.05	0.42	.05	1.1	
	Mean for site								0.39	.05	1.0	~11

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

TABLE II–2 (Cont'd). Data from Kost Dam Site Survey, March 12, 1985.

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
10.70	8:45	B1	Right bank upstream from crest at depth of 1 ft
10.65	8:45	B1	Right bank upstream from crest at depth of 1 ft
10.55	8:50	B2	Right bank upstream from crest at depth of 1 ft
10.55	8:50	B2	Right bank upstream from crest at depth of 1 ft
11.55	8:55	B3	Right bank just downstream from stilling basin.
11.55	8:55	B3	Right bank just downstream from stilling basin.
11.65	9:00	B4	Just downstream from stilling basin
11.55	9:00	B4	Just downstream from stilling basin
11.60	9:15	B5	Just downstream from stilling basin
11.60	9:15	B5	Just downstream from stilling basin
11.70	9:20	B6	Just downstream from stilling basin
11.70	9:20	B6	Just downstream from stilling basin
11.60	9:25	B7	Left bank just downstream from stilling basin
11.60	9:25	B7	Left bank just downstream from stilling basin
10.30	9:30	B8	Left bank upstream from crest at depth of 2 ft
10.40	9:30	B8	Left bank upstream from crest at depth of 2 ft
10.40	9:35	B9	Left bank upstream from crest at depth of 1 ft
10.35	9:35	B9	Left bank upstream from crest at depth of 1 ft
11.00	9:45	B10	Spillway sample just upstream from Hydraulic jump
11.00	10:25	B11	Spillway sample 2' above horizontal form line
11.20	10:30	B11	Spillway sample 2' above horizontal form line
10.85	10:32	B12	Spillway sample at the form line
11.00	10:35	B13	Spillway sample 2' below last horizontal form line
11.00	10:40	B11	Spillway sample 2' before hydraulic jump
11.05	10:45	B12	Spillway sample at form line
11.10	10:50	B13	Spillway sample 2' below last horizontal form line
11.10	10:55	B14	Spillway sample 4' below last horizontal form line

TABLE II–3. Results from Kost Dam Site Survey, December 13, 1985

Atmospheric Pressure:	746.3 ± .1 mm of Hg
Water Temperature:	.2°C ± .05°C
Saturation Concentration:	13.95 ± .3mg $0_2/\ell$
Static Head:	.64 ft
Energy Loss:	12.97 ft ± .05 ft
Upstream Water Surface Elevation:	100.64 ± .02 ft (Crest Datum)
Downstream Water Surface Elevation:	87.67 ± .05 ft (Crest Datum)
Discharge/Unit Crest Width:	1.75 ± .05 cfs/ft.

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi– ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	8.65	6	.06	.06	10.86	6	.06	.06	.42	.03	1.0	
Left Bank	8.65	6	.06	.06	10.78	6	.06	.06	.40	.03	1.2	
Center	8.70	2	0	.05	10.82	12	.07	.04	.40	.03	1.1	
Spillway	8.68	16	.06	.03	9.64	4	.11	.10	.18	.02		≈ 5'±.5*
	Mean for site								0.41	.02	1.1	~11

*Measured off the photograph.

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table II–3 (Cont'd). Data from Kost Dam Site Survey, December 13, 1985.

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
8.60	1:45	C1	Upstream Left Bank, on the Crest
8.60	1:45	C1	Upstream Left Bank, on the Crest
8.70	1:50	C1	Upstream Left Bank, on the Crest
8.75	1:50	C1	Upstream Left Bank, on the Crest
8.60	1:55	C1	Upstream Left Bank, on the Crest
8.65	1:55	C1	Upstream Left Bank, on the Crest
10.90	2:05	C4	Downstream Left Bank, just Downstream, of pier
10.85	2:30	C2	Right Bank, Downstream of Pier
10.85	2:30	C2	Right Bank, Downstream of Pier
10.90	2:32	C2	Right Bank, Downstream of Pier
10.95	2:32	C2	Right Bank, Downstream of Pier
10.80	2:34	C2	Right Bank, Downstream of Pier
10.80	2:34	C2	Right Bank, Downstream of Pier
8.75	2:50	C3	Upstream Right Bank, on the Crest
8.75	2:50	C3	Upstream Right Bank, on the Crest
8.65	2:53	C3	Upstream Right Bank, on the Crest
8.60	2:53	C3	Upstream Right Bank, on the Crest
8.75	2:56	C3	Upstream Right Bank, on the Crest
8.70	2:56	C3	Upstream Right Bank, on the Crest
10.75	NR	C4	Downstream off of Left Bank Pier
10.75	NR	C4	Downstream off of Left Bank Pier
10.80	NR	C4	Downstream off of Left Bank Pier
10.80	NR	C4	Downstream off of Left Bank Pier
10.70	NR	C4	Downstream off of Left Bank Pier
10.75	NR	C4	Left bank, Downstream off of Pier
8.60	NR	C1	Upstream Left Bank on the Crest
8.70	NR	C1	Upstream Left Bank on the Crest
8.65	NR	C1	Upstream Center of Spillway on Crest
8.75	NR	C6	Upstream Center of Spillway on Crest
9.60	NR	C6	Downstream on Spillway ~ 5.5 ft from floor of Stilling basin
9.50	NR	C5	Downstream on Spillway ~ 5.5 ft from floor of Stilling basin
9.75	NR	C5	Downstream on Spillway ~ 5.5 ft from floor of Stilling basin
9.70	NR	C5	Downstream on Spillway ~ 5.5 ft from floor of Stilling basin

NR – Not Recorded

TABLE II–4. Results from Kost Dam Site Survey, January 13, 1986

Atmospheric Pressure:	29.42 ± .05 in of Hg
Water Temperature:	.1° C
Saturation Concentration:	13.94 ± .28 mg $0_2/\ell$
Static Head:	.46 ± .02
Energy Loss:	13.04 ± .05
Upstream Water Surface Elevation:	100.46 ± .02 (Crest Datum)
Downstream Water Surface Elevation:	87.42 ± .05 (Crest Datum)
Discharge/Unit Crest Width:	1.05 cfs/ft ± .05 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	7.96	4	.048	.08	10.6	4	.0	.05	.44	.03	0.7	
Left Bank	7.94	4	.085	.14	10.35	4	.10	.16	.40	.04	0.9	
Center	7.95	4	.057	.09	10.63	4	.05	.08	.45	.03	0.8	
Spillway, D7*	7.96	4	.048	.08	8.94	6	.04	.06	.16	.02		11.2'±.2
Spillway, D8*	7.96	4	.048	.08	8.59	5	.09	.14	.11	.02		5.2'±.2
Mean for site									.43	.03	0.8	~11

*Natural spillway aeration.

LEGEND:

- $\bar{x}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- w = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table II-4 (Cont'd). Data from Kost Dam Site Survey, January 13, 1986.

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
8.00	11:30	D1	Upstream Center of Spillway on crest
7.90	11:30	D1	Upstream Center of Spillway on crest.
8.00	11:32	D1	Upstream Center of Spillway on crest
7.90	11:32	D1	Upstream Center of Spellway on crest.
7.95	11:35	D2	Upstream Left Bank on crest
8.05	11:35	D2	Upstream Left Bank on crest
7.90	11:37	D2	Upstream Left Bank on crest
7.85	11:37	D2	Upstream Left Bank on crest
7.90	11:40	D3	Upstream Right Bank on crest
7.95	11:40	D3	Upstream Right Bank on crest
8.00	11:45	D3	Upstream Right Bank on crest
8.00	11:45	D3	Upstream Right Bank on crest
10.60	11:50	D4	Downstream Right Bank on spillway ≃ 6 ft from left bank
10.60	11:50	D4	Downstream Right Bank on spillway ≃ 6 ft from left bank
10.60	11:55	D4	Downstream Right Bank on spillway ≃ 6 ft from left bank
10.60	11:50	D4	Downstream Right Bank on spillway ≃ 6 ft from left bank
10.70	12:00	D5	Downstream Center on spillway
10.60	12:00	D5	Downstream Center on spillway
10.60	12:05	D5	Downstream Center on spillway
10.60	12:05	D5	Downstream Center on spillway
10.50	12:10	D6	Downstream left bank on spillway ≃ 4 ft from left bank
10.30	12:10	D6	Downstream left bank on spillway ≃ 4 ft from left bank
10.30	12:15	D6	Downstream left bank on spillway ≃ 4 ft from left bank
10.30	12:15	D6	Downstream left bank on spillway ≃ 4 ft from left bank
9.00	12:35	D6	Downstream left bank on spillway ≃ 4 ft from left bank
8.90	12:37	D8	On spillway just before hydraulic jump
8.95	12:38	D8	On spillway just before hydraulic jump
8.95	12:40	D8	On spillway just before hydraulic jump
8.90	12:42	D8	On spillway just before hydraulic jump
8.95	12:45	D8	On spillway just before hydraulic jump
8.55	12:20	D9	On spillway 1/2 of aerated zone length
8.70	12:24	D9	On spillway 1/2 of aerated zone length
8.55	12:26	D9	On spillway 1/2 of aerated zone length
8.70	12:28	D9	On spillway 1/2 of aerated zone length
8.45	12:30	D9	On spillway 1/2 of aerated zone length

TABLE II–5. Results from Kost Dam Site Survey, February 21, 1986

Atmospheric Pressure:	29.0 mm of Hg
Saturation Concentration:	13.75 ± .28 mg O_2/ℓ
Water Temperature:	.3° C ± .05° C
Static Head:	.41 ± .02 ft
Energy Loss:	12.93 ± .03 ft
Upstream Water Surface Elevation:	100.41 ± .02
Downstream Water Surface Elevation:	87.48 ± .02 (Crest Datum)
Discharge/Unit Crest Width:	.88 cfs/ft ± .05 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Efficiency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Left Bank	7.33	8	.045	.05	10.75	8	.09	.08	.45	.03	1.0	~11
Spillway, E6*	7.33	8	.045	.05	8.26	8	.06	.05	.14	.01		11.2'±.2
Spillway, E7*	7.33	8	.045	.05	8.13	8	.04	.05	.12	.01		6.5'±.2

*Natural aeration.

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table II–5 (Cont'd). Data from Kost Dam Site Survey, February, 21, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
7.35	11:05	E1	Upstream Left Bank on Crest
7.25	11:05	E1	Upstream Left Bank on Crest
7.30	11:06	E1	Upstream Left Bank on Crest
7.35	11:06	E1	Upstream Left Bank on Crest
7.40	11:10	E2	Upstream 3 ft from left bank on crest
7.35	11:10	E2	Upstream 3 ft from left bank on crest
7.30	11:12	E2	Upstream 3 ft from left bank on crest
7.35	11:12	E2	Upstream 3 ft from left bank on crest
10.15	11:20	E3	Downstream ~ 10 ft from left bank
10.20	11:20	E3	Downstream ~ 10 ft from left bank
10.20	11:20	E3	Downstream ~ 10 ft from left bank
10.15	11:20	E3	Downstream ~ 10 ft from left bank
10.40	11:25	E4	Downstream ~ 25 ft from left bank
10.30	11:25	E4	Downstream ~ 25 ft from left bank
10.30	11:28	E5	Downstream ~ 15 ft from left bank
10.30	11:28	E5	Downstream ~ 15 ft from left bank
8.30	11:45	E6	2 to 3" from beginning of hydraulic jump
8.25	11:45	E6	and 1 ft from beginning of curve in bottom
8.25	11:45	E6	of spillway
8.30	11:45	E6	"
8.35	11:46	E6	"
8.25	11:46	E6	"
8.20	11:47	E6	"
8.30	11:48	E6	"
8.10	12:10	E7	4 ft Upstream from E5 on spillway
8.15	12:10	E7	4 ft Upstream from E5 on spillway
8.15	12:10	E7	4 ft Upstream from E5 on spillway
8.05	12:10	E7	4 ft Upstream from E5 on spillway
8.15	12:10	E7	4 ft Upstream from E5 on spillway
8.16	12:10	E7	4 ft Upstream from E5 on spillway

TABLE II–6. Results from Kost Dam Site Survey, March 10, 1986

Atmospheric Pressure:	735.45 mm of Hg.
Water Temperature:	.2° C ± .05
Saturation Concentration:	13.77 ± 28 mg $0_2/\ell$
Static Head:	.41 ± .02 ft
Energy Loss:	13.0 ± .02 ft
Upstream Water Surface Elevation:	100.51 ± .02
Downstream Water Surface Elevation:	87.51 ± .02
Discharge/Unit Crest Width:	1.22 cfs/ft ± .05 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	9.28	4	.027	.05	11.10	4	.05	.08	.41	.03	0.8	
Left Bank	9.23	4	.119	.19	11.13	4	.05	.08	.42	.04	1.0	
Center	9.10	4	.00	.05	10.89	4	.05	.08	.38	.03	0.9	
Nonaerated	9.28	4	.03	.05	9.33	6	.03	.05	.01	.02		≈ 1.0
Aerated 1*	9.33	6	.03	.05	10.40	6	.06	.06	.24	.02		10.8
Aerated 2**	9.33	6	.03	.05	10.20	6	.06	.06	.20	.02		10.0
					Mean for Site				.40	.03	0.9	~11

*Forced aeration by biological growth, 10.8 ft ± .1 ft in length

**Natural spillway aeration, 10.0 ft ± .1 ft in length

LEGEND:
$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table II–6 (Cont'd). Data from Kost Dam Site Survey, March 10, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
9.10	10:15	F1	Upstream Center of Spillway crest
9.30	10:15	F1	Upstream Center of Spillway crest
9.15	10:20	F1	Upstream Center of Spillway crest
9.35	10:20	F1	Upstream Center of Spillway crest
9.10	10:24	F2	Upstream Left Bank on Spillway crest
9.10	10:24	F2	Upstream Left Bank on Spillway crest
9.10	10:27	F2	Upstream Left Bank on Spillway crest
9.10	10:27	F2	Upstream Left Bank on Spillway crest
9.30	10:32	F3	Upstream Right Bank on Spillway crest
9.25	10:32	F3	Upstream Right Bank on spillway crest
9.25	10:35	F3	Upstream Right Bank on Spillway crest
9.30	10:35	F3	Upstream Right Bank on Spillway crest
11.05	10:41	F4	Downstream Right Bank just off stilling basin
11.15	10:41	F4	Downstream Right Bank just off stilling basin
11.10	10:44	F4	Downstream Right Bank just off stilling basin
11.10	10:44	F4	Downstream Right Bank just off stilling basin
10.90	10:46	F5	Downstream Left Bank just off stilling basin
10.85	10:48	F5	Downstream Left Bank just off stilling basin
10.90	10:48	F5	Downstream Left Bank just off stilling basin
11.10	10:53	F6	Downstream Center just off stilling basin
11.20	10:53	F6	Downstream Center just off stilling basin
11.10	10:56	F6	Downstream Center just off stilling basin
11.10	10:56	F6	Downstream Center just off stilling basin
10.40	11:25	F7	Aeration Zone 1 Spillway samples: Aerated flow just prior to hydraulic jump. Longest Aeration zone near center of spillway.
10.50	11:26	F7	"
10.40	11:27	F7	"
10.40	11:28	F7	"
10.40	11:29	F7	"
10.30	11:30	F7	"
9.30	11:55	F8	Non–aerated spillway sample correction
9.35	11:56	F8	Non–aerated spillway sample correction
9.30	11:57	F8	Non–aerated spillway sample correction
9.35	11:58	F8	Non–aerated spillway sample correction
9.30	11:59	F8	Non–aerated spillway sample correction
9.35	12:00	F8	Non–aerated spillway sample correction

Table II–6 (Cont'd). Data from Kost Dam Site Survey, March 10, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
10.10	12:05	F9	Aeration Zone 2 Spillway samples. Aerated flow just prior to hydraulic jump.
10.20	12:06	F9	"
10.30	12:07	F9	"
10.20	12:08	F9	"
10.20	12:09	F9	"
10.20	12:10	F9	"
9.30	12:15	F10	Upstream Right Bank on crest
9.25	12:15	F10	Upstream Right Bank on crest

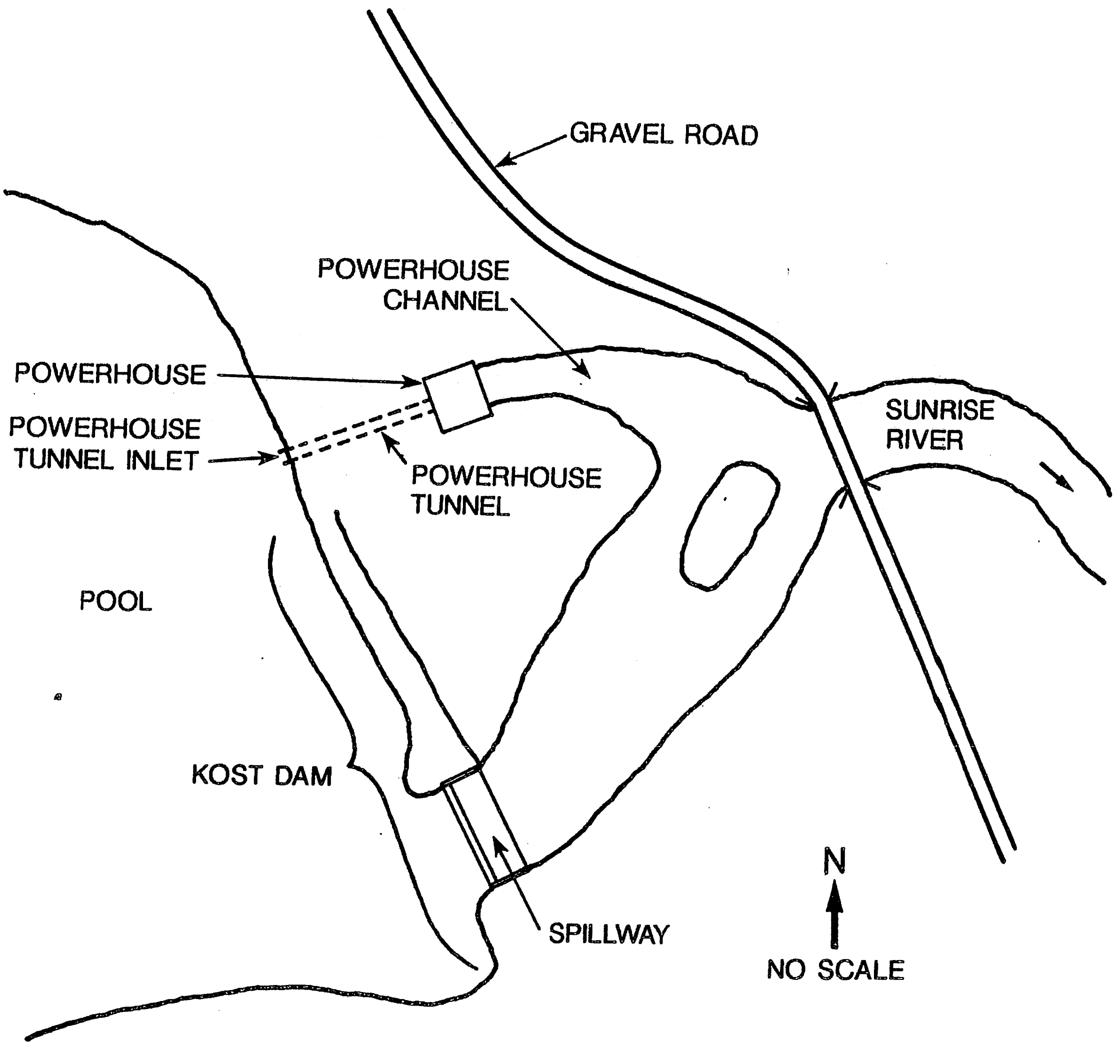


Fig. II–1. Overall plan of the Kost Dam.

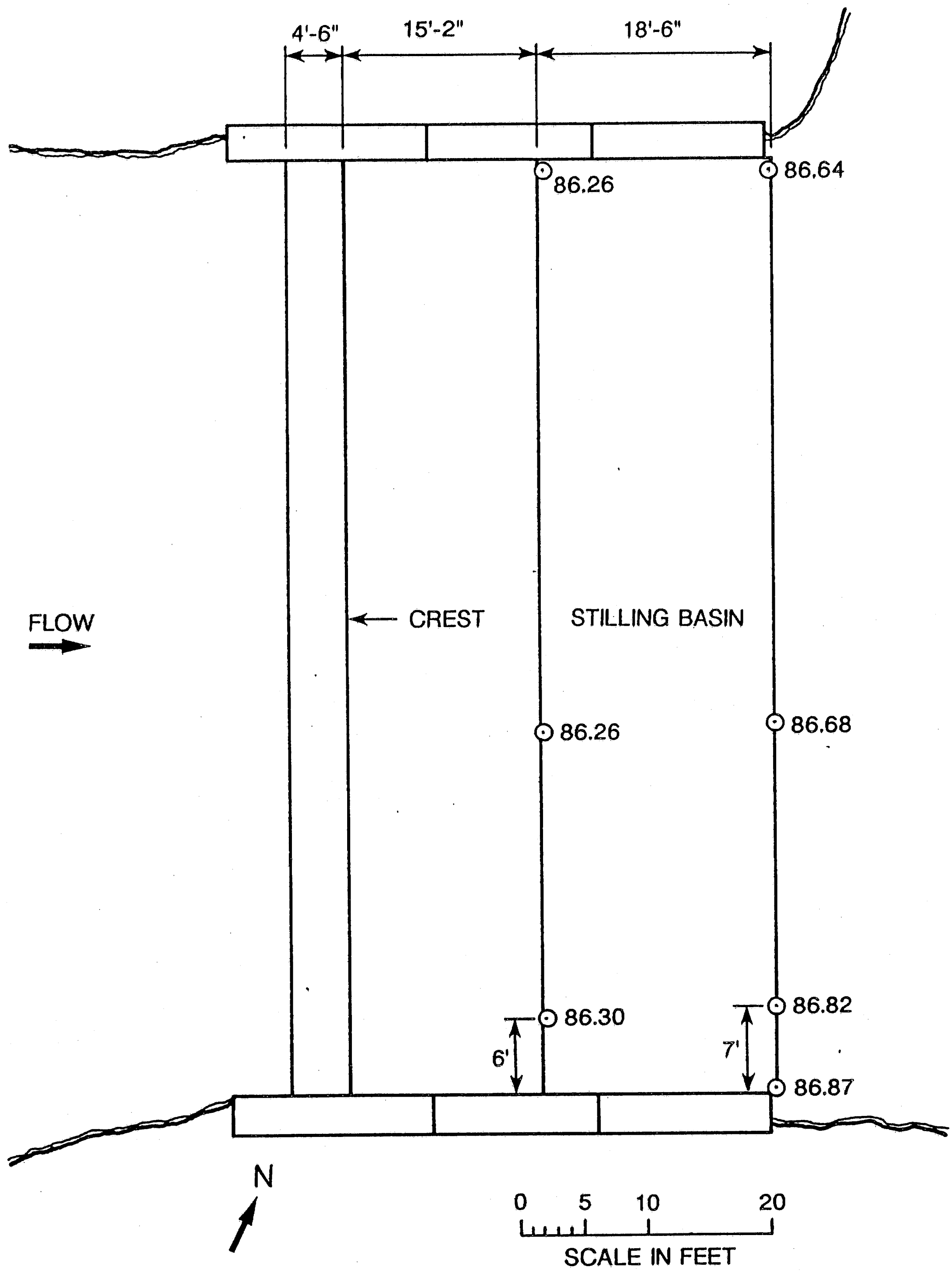


Fig. II–2. Plan of Kost Dam spillway including apron bed elevations.

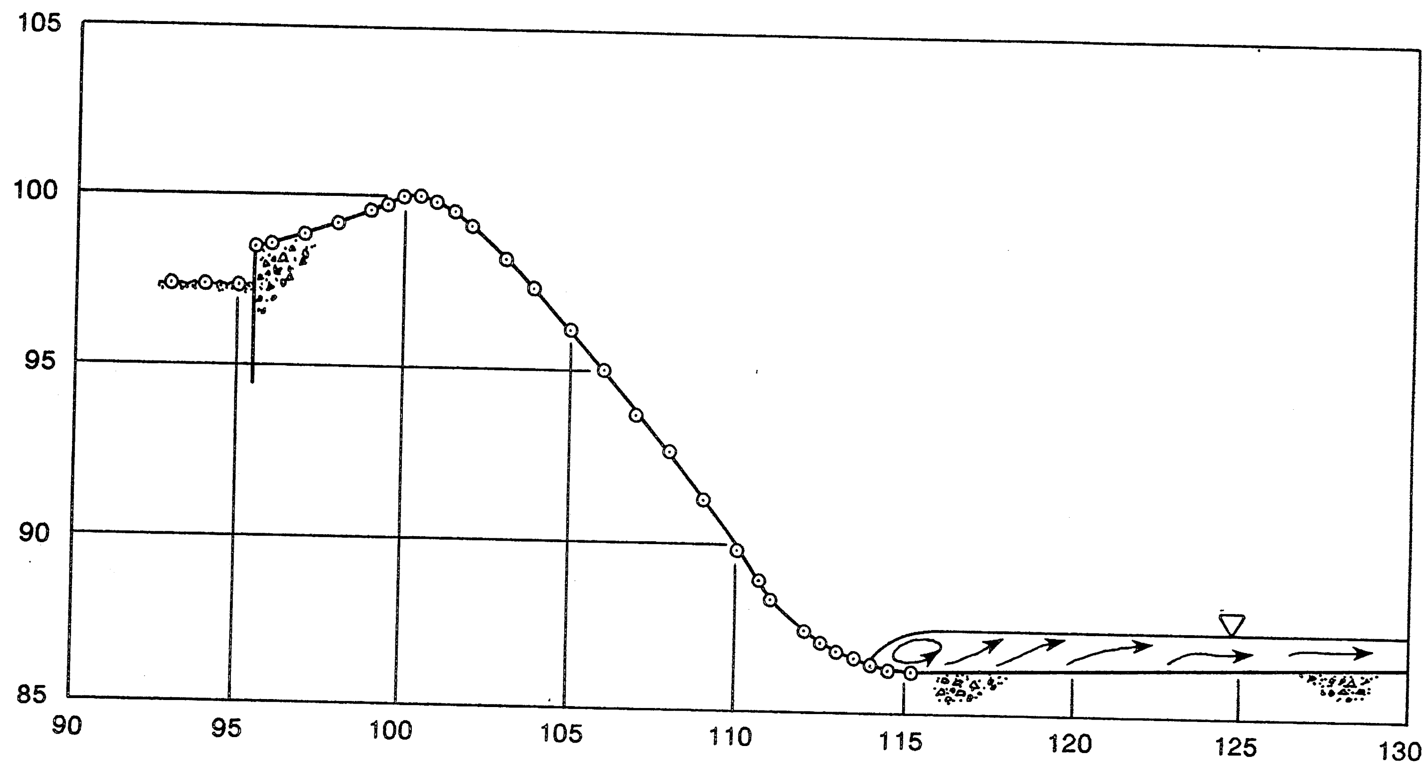


Fig. II–3. Spillway cross section as surveyed on March 15, 1986.

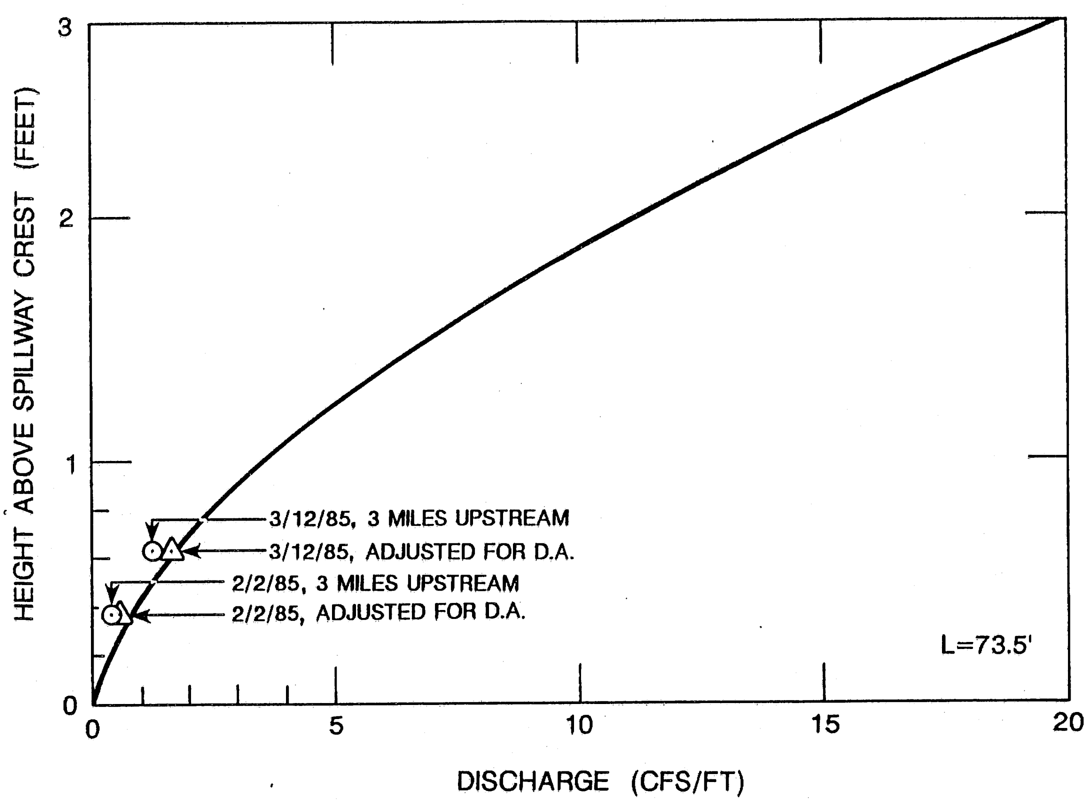


Fig. II–4. Kost Dam spillway rating curve.

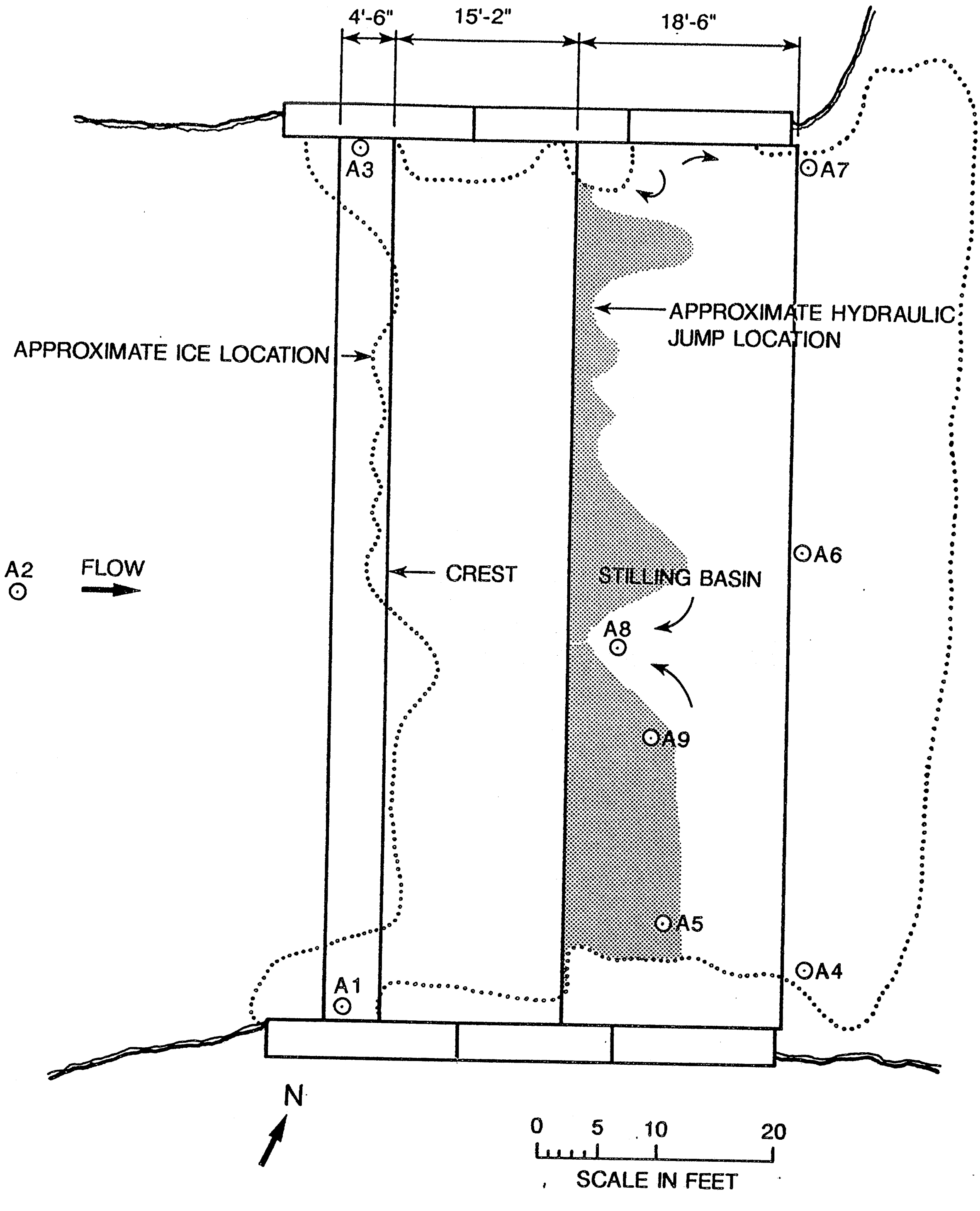


Fig. II–5. Plan view, February 2, 1985, sampling locations.

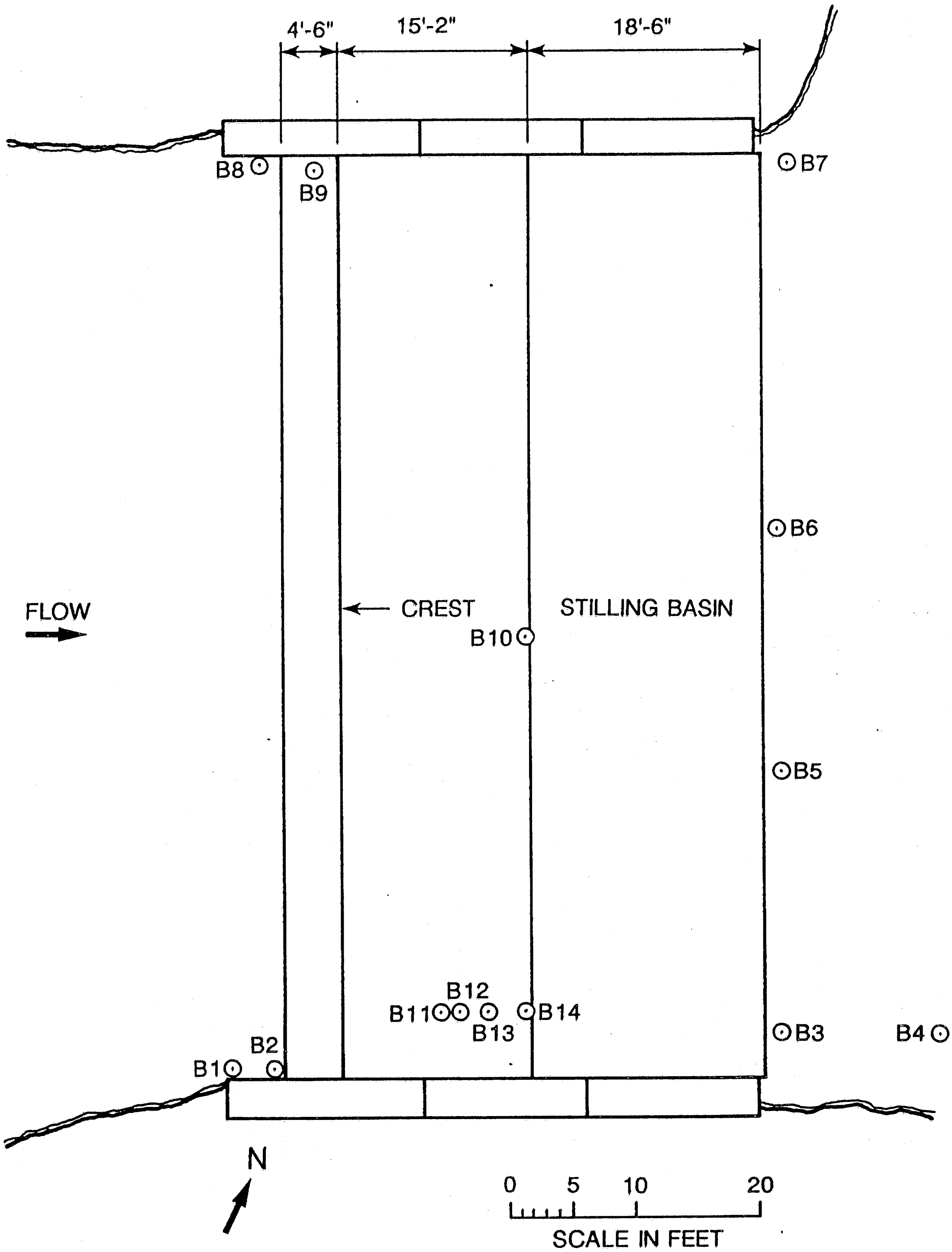


Fig. II–6. Plan view of March 12, 1985, sampling locations.

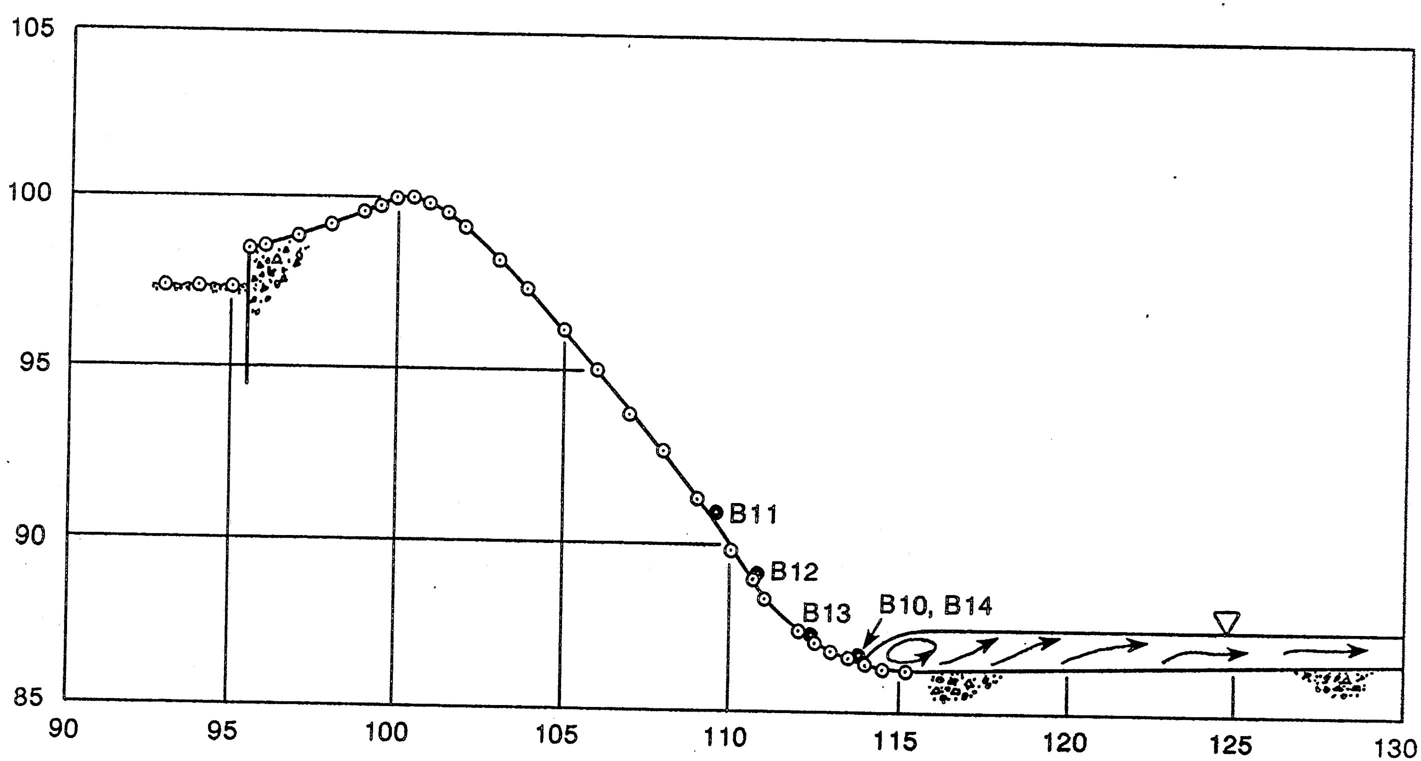


Fig. II–7. Section view of March 12, 1985, spillway sampling locations.

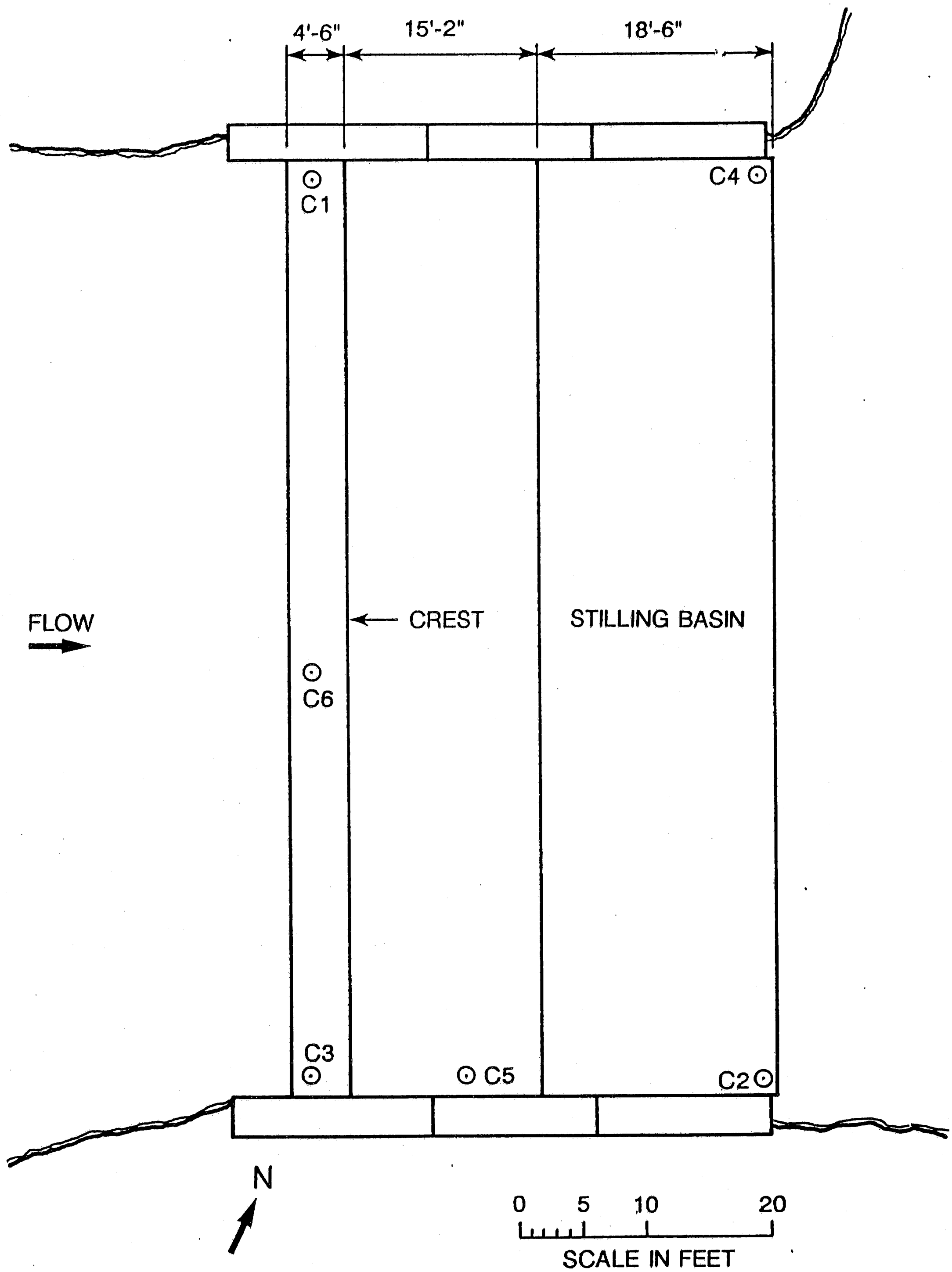


Fig. II–8. Plan view of December 13, 1985, sampling locations.

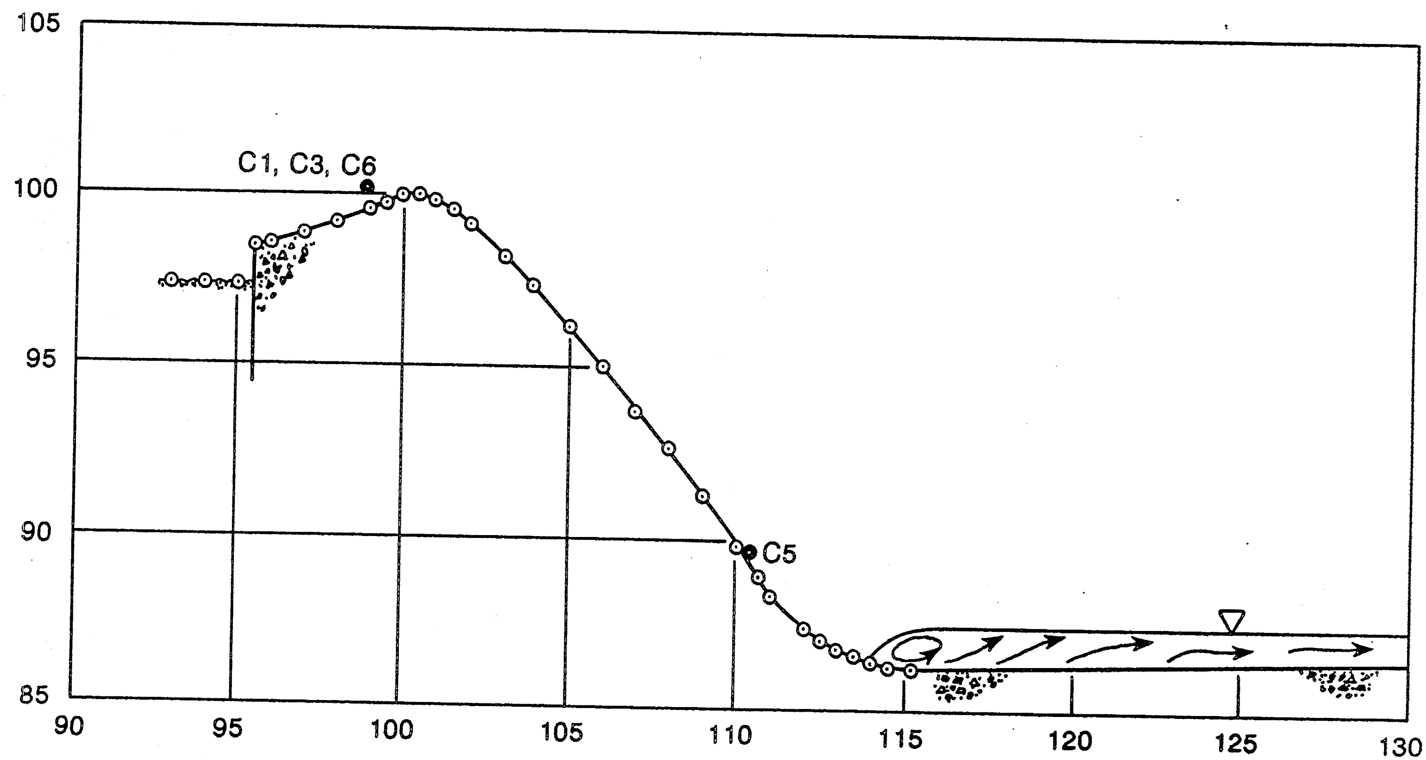


Fig. II–9. Section view of December 13, 1985, sampling locations.

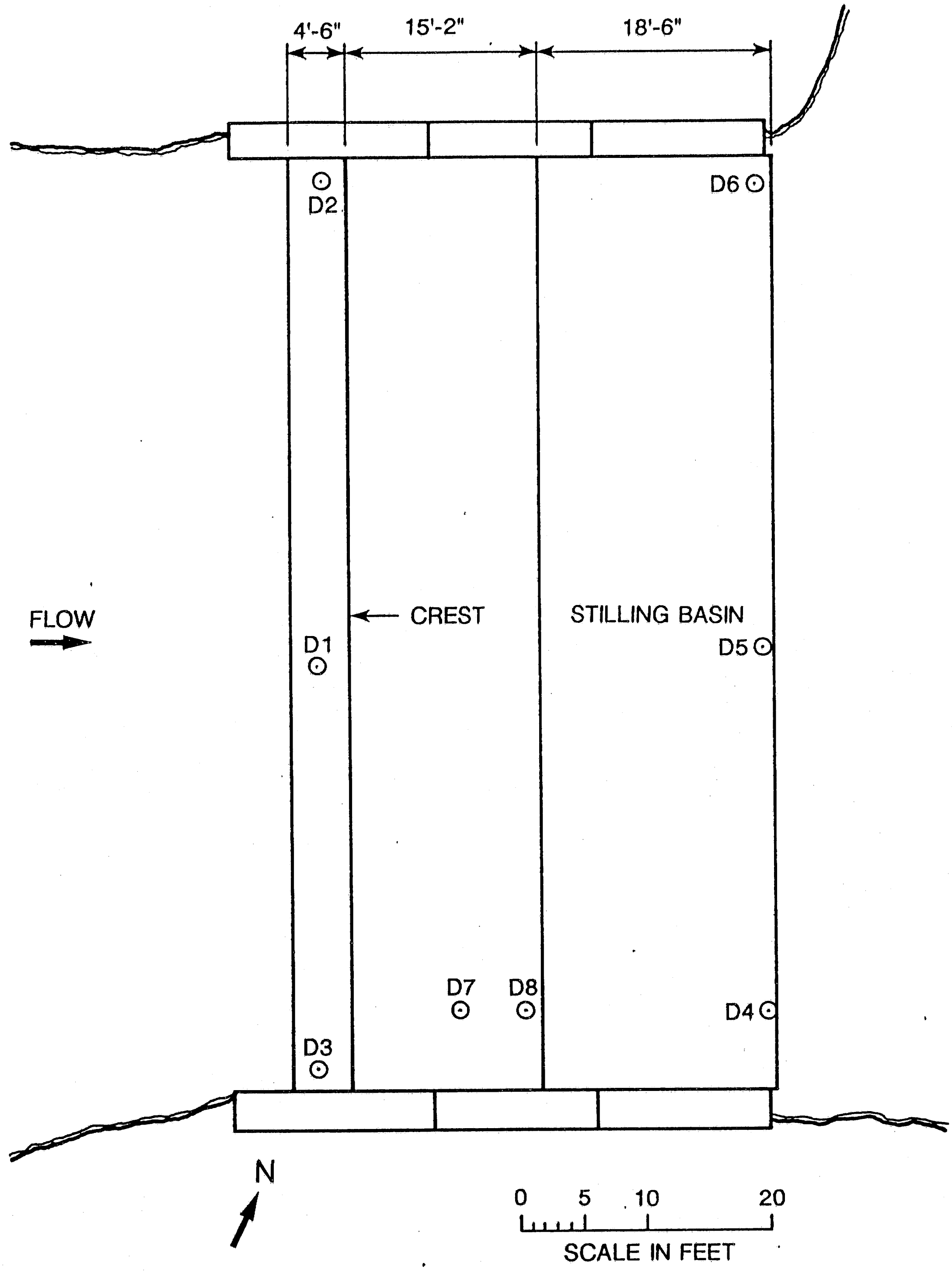


Fig. II–10. Plan view of January 13, 1986, sampling locations.

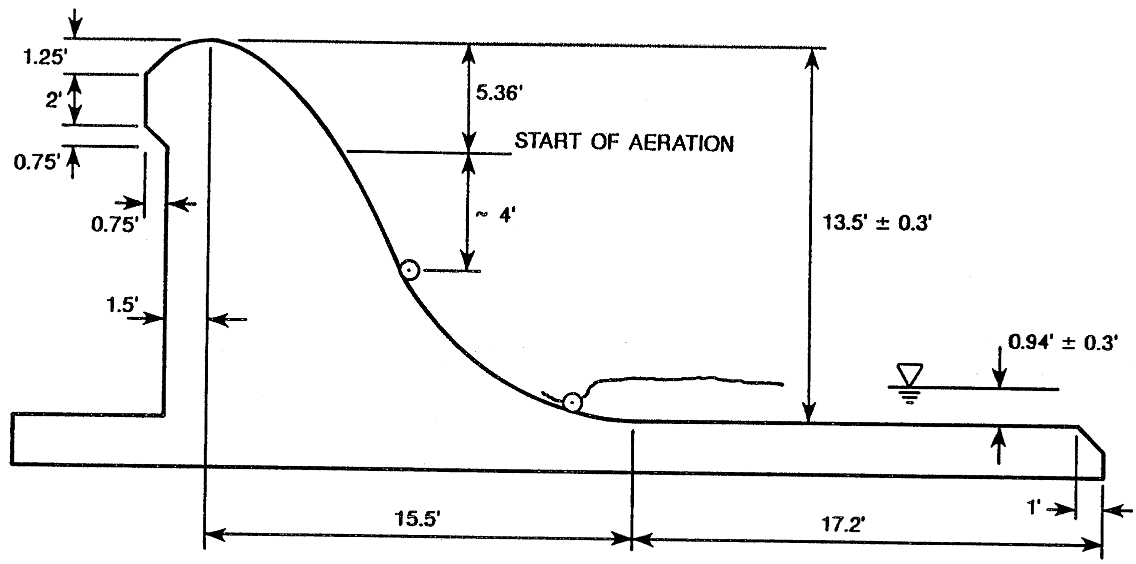


Fig. II–11. Section view of January 13, 1986, sampling locations.

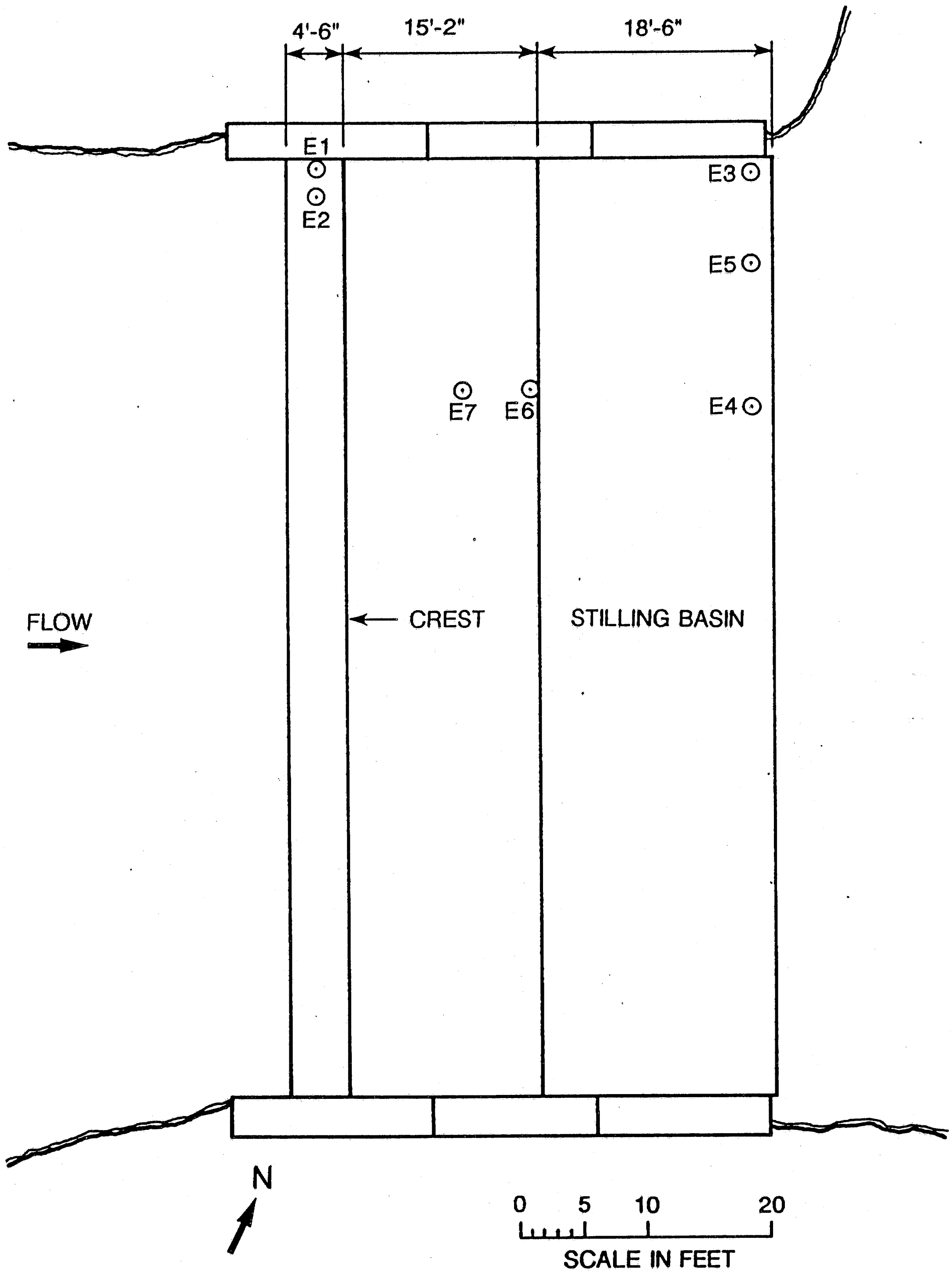


Fig. II–12. Plan view of February 21, 1986, sampling locations.

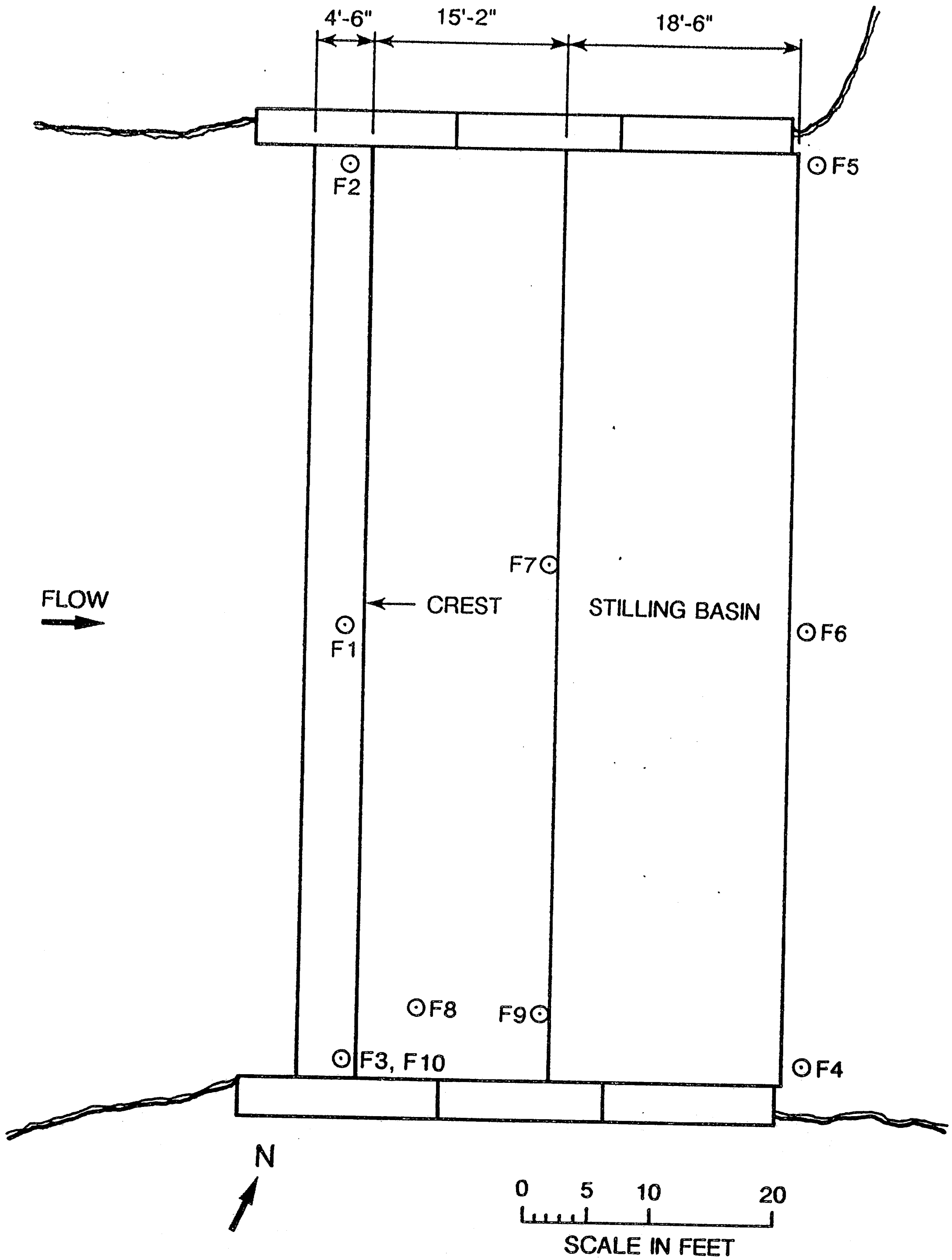


Fig. II–13. Plan view of March 10, 1986, sampling locations.

Photo II–1. Kost Dam, February 2, 1985, spillway face ice formation.

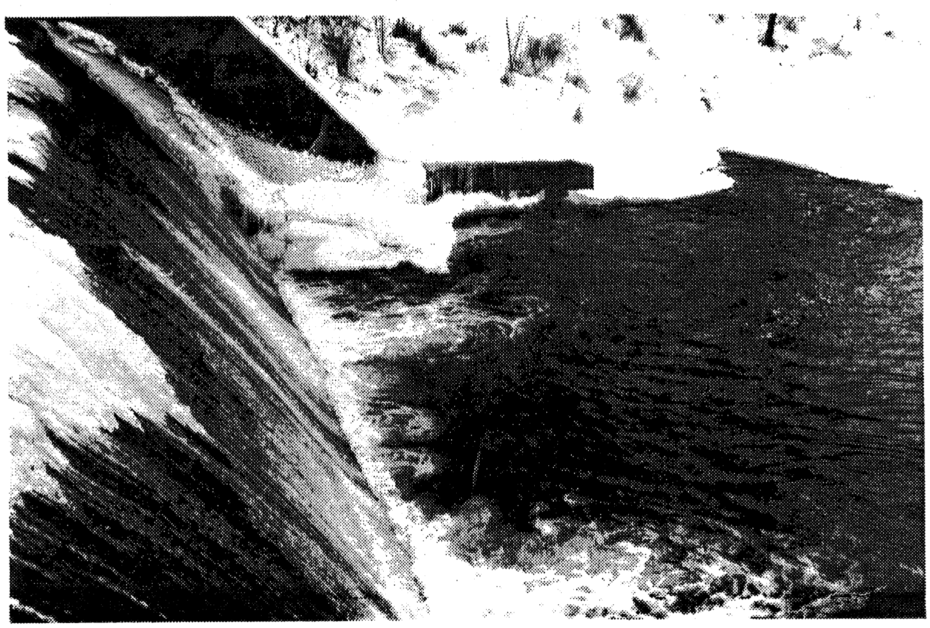


Photo II–2. Kost Dam, February 2, 1985, left bank hydraulic jump characteristics.

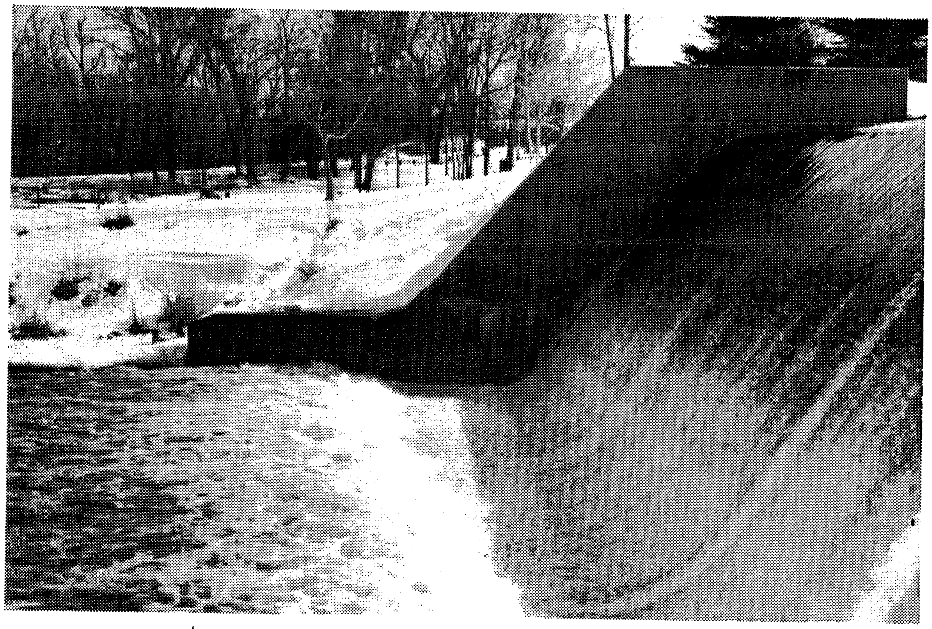


Photo II–3. Kost Dam, March 12, 1985, right bank hydraulic jump characteristics.

Photo II–4. Kost Dam, December 13, 1985, upstream ice formation after clearing with ice pick.

Photo II–5. Kost Dam, December 13, 1985, spillway aeration.

Photo II–6. Kost Dam, January 13, 1986, spillway aeration.

Photo II–7. Kost Dam, January 13, 1986, upstream water sample collection.

Photo II–8. Kost Dam, January 13, 1986, downstream water sample collection.

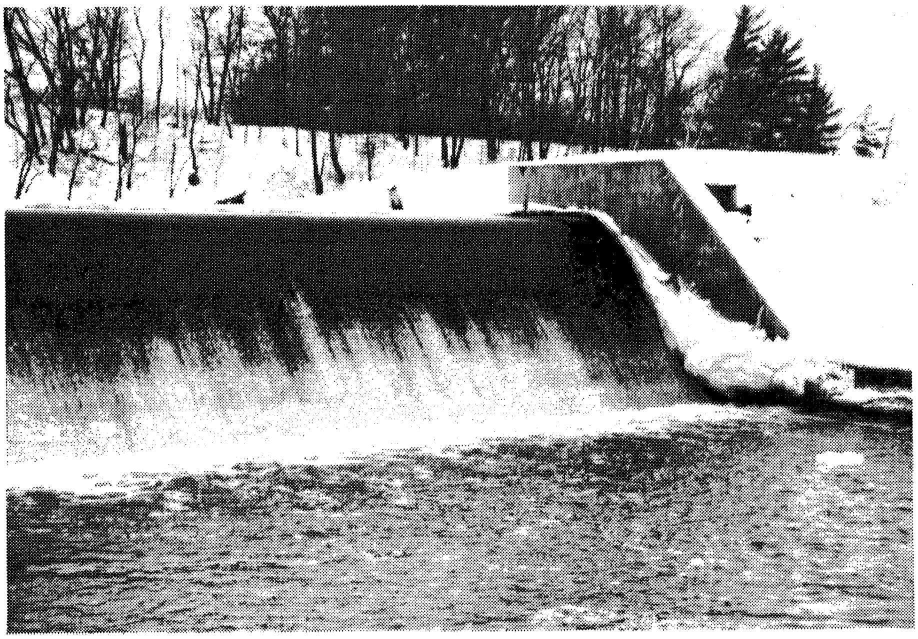


Photo II–9. Kost Dam, February 12, 1986, spillway aeration. Note: Location of biological growth as indicated by the increased aeration (white water)

Photo II–10. Kost Dam, March 10, 1986, spillway aeration.

III. ST. CLOUD DAM

A. PHYSICAL DESCRIPTION

The St. Cloud Dam consists of a concrete, fixed crest uncontrolled ogee spillway 19.5 ft high and 550 ft long centered on the Mississippi River. It is flanked on the right bank by an earth embankment approximately 420 ft long with a top width of 28 ft and an elevation 12.5 ft higher than the spillway crest. On the left bank a concrete wall and earth embankment extends from the spillway a distance of 200 ft to high ground. The top of the wall is 16 ft above the spillway crest. Training walls extend from the spillway crest to a point approximately 180 ft downstream, thus confining the width of flow to 550 ft immediately below the dam. The dam is located on the Mississippi River within the City of St. Cloud approximately 500 ft downstream below St. Cloud's 10th Street Bridge. A plan view of the spillway and a cross section through the spillway is shown in Figures III–1 and III–2, respectively.

Historically, the dam has been used for maintaining a reservoir for hydropower purposes but today the dam is used to maintain an impoundment for recreational purposes. The dam was retrofitted with a hydropower facility on the west bank in 1988.

B. DISCHARGE MEASUREMENTS

Discharge estimates were made using the headwater rating curve presented in Figure III–3 developed by Knowlton et al. (1982). The accuracy of the rating curve is not substantiated but estimated to be on the order of ± 5%. Stage measurements collected on January 17, 1986, indicated a possible source of error in using this discharge rating curve, attributable to the location of the measurement of upstream stage per each site survey. This location was not fixed, and the January 17, 1986, stage measurements revealed the water surface elevation fell .1 ft from the location of the gage to the spillway crest, causing an error on the order of ±.05 ft in the stage measurement dependent on discharge. However, it is unlikely that the magnitude of this error is greater than the error in determination of the discharge coefficient and was therefore ignored.

C. GAS TRANSFER MEASUREMENTS

Four dissolved oxygen surveys were performed at this site: March 2, 1985, March 14, 1985, December 19, 1985, and January 17, 1986. The results from these surveys are presented in Tables III–1 through III–4. Sampling location maps are presented in Figures III–4 through III–7. Photographs of the flow over the spillway and ice formation are given in Photos III–1 through III–4. Upstream sampling was accomplished immediately upstream of the spillway crest, through the ice as shown in Photo III–5.

During the March 2, 1985, and January 17, 1986, sampling an ice block was lodged on the crest of the spillway. This reduced the flow in the area of the ice block and caused a reduced jump downstream from this blockage in comparison to the jump below the undisturbed crest as shown in the photographs. It was not felt this influenced the downstream data since the area blocked was much less than the area of open flowing water. Ice did not distort the hydraulic jump for the other two sets of measurements.

An investigation of the amount of oxygen transferred downstream of the hydraulic jump was performed during the March 2, 1985 measurements.

The hydraulic jump at the St. Cloud Dam occurs in the stilling basin shown in Figure III–2. This jump has two regions where oxygen could be transferred: Region A, in the actual hydraulic jump and bubbly region downstream, or region B, in the swift flow downstream, where there are still some bubbles rising to the surface. The end of Region B is described by the point where all the bubbles appear to have risen out of the flow. At St. Cloud the end of Region B was approximately located on the end of the retaining wall shown on Fig. III–1, 130 ft from the lower end of the stilling basin. To investigate the oxygen transfer in this region, water samples were collected at approximately 60 ft, 102 ft, and 130 ft (lower end of the retaining wall) from the spillway toe. There is no statistically significant difference between these D.O. measurements, indicating that measurements taken where most, but not all, of the bubbles have risen out of the flow (Region A) are acceptable.

The winter 1986 measurements were collected on December 19, 1985, and January 17, 1986. Because the ice was very thick, it was impossible to break through the ice from the retaining walls along the left and right bank. Measurements were collected upstream of the spillway through the ice at the locations shown in Figures III–6 and III–7.

The January 17, 1986, measurements were also used to investigate any D.O. concentration variation with depth that could occur upstream from a dam in the winter months. Table III–4 indicates very little dissolved oxygen variation with depths. Any variation could easily be accountable by the measurements statistical error.

TABLE III–1. Results from St. Cloud Dam Site Survey, March 2, 1985

Atmospheric Pressure:	748 mm of Hg.
Water Temperature:	.7 °C ± .2°C
Saturation Concentration:	13.80 ± .28 mg $0_2/\ell$
Static Head:	1.72 ± .1 ft
Energy Loss:	17.44 ft
Upstream Water Surface Elevation:	980.72 ± .05 ft
Downstream Water Surface Elevation:	963.28 ± .05 ft
Discharge/Unit Crest Width:	7.27 cfs/ft.

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi– ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	9.30	4	.04	.06	11.67	5	.08	.13	.53	.05	0.8	
Left Bank	9.30	4	.05	.08	11.65	6	.03	.05	.53	.04	0.8	
	Mean for site								.53	.04	0.8	19

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table III–1 (Cont'd). Data from St. Cloud Dam Site Survey, March 2, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
9.25	10:00	A1	23 ft upstream from crest
9.30	10:00	A1	23 ft upstream from crest
9.30	10:15	A2	3.0 ft upstream from crest
9.35	10:15	A2	3.0 ft upstream from crest
11.75	10:25	A3	60 ft downstream from toe of spillway
11.75	10:30	A4	120 ft downstream from toe of spillway
11.65	10:30	A4	120 ft downstream from toe of spillway
11.60	10:35	A5	128.5 ft downstream from spillway toe
11.60	10:35	A5	128.5 ft downstream from spillway toe
9.25	12:10	A6	3.0 ft upstream from crest
9.30	12:10	A6	3.0 ft upstream from crest
9.35	12:20	A7	5.5 ft upstream from crest
11.70	12:30	A8	60 ft downstream from spillway toe
11.65	12:30	A8	60 ft downstream from spillway toe
11.65	12:35	A9	102 ft downstream from spillway toe
11.65	12:35	A9	102 ft downstream from spillway toe
11.65	12:40	A10	128.5 ft downstream from spillway toe
11.60	12:40	A10	128.5 ft downstream from spillway toe

TABLE III–2. Results from St. Cloud Dam Site Survey, March 14, 1985

Atmospheric Pressure:	744.4 mm of Hg.
Water Temperature:	1°C (Not measured ± .2°C).
Saturation Concentration:	13.61 ± .27 mg O_2/ℓ
Static Head:	1.96 ft.
Energy Loss:	17.55 ft.
Upstream Water Surface Elevation:	980.96 ft.
Downstream Water Surface Elevation:	963.41 ft.
Discharge/Unit Crest Width:	8.91 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	9.55	4	.038	.06	11.75	6	.16	.17	.54	.06	0.9	
Left Bank	9.36	4	.025	.05	11.74	6	.11	.12	.56	.05	0.9	
	Mean for site								.55	.04	0.9	19

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table III–2 (Cont'd). Data from St. Cloud Dam Site Survey, March 14, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
9.35	9:00	B1	Left bank, 5.5 ft upstream of crest ≃ 3 ft deep
9.40	9:00	B1	Left bank, 5.5 ft upstream of crest ≃ 3 ft deep
9.35	9:04	B2	Left bank, 3 ft upstream ofcrest ≃ 4 ft deep
9.35	9:04	B2	Left bank 3 ft upstream of crest ≃ 4 ft deep
11.70	9:12	B3	Left bank, 44 ft downstream of spillway toe ≃ 3 ft deep
11.85	9:12	B3	Left bank, 44 ft downstream of spillway toe ≃ 3 ft deep
11.90	9:17	B4	Left bank, 102 ft downstream of spillway toe ≃ 3 ft deep
11.70	9:17	B4	Left bank, 102 ft downstream of spillway toe ≃ 3 ft deep
11.60	9:50	B5	Left bank, 133 ft downstram of spillway toe ≃ 2 ft deep
11.70	9:50	B5	Left bank, 133 ft downstream of spillway toe ≃ 2 ft deep
11.45*	9:50	B6	Right bank, 138.5 ft downstream of spillway toe ≃ 1–1/2 ft deep
11.60	9:50	B6	Right bank, 138.5' downstream of spillway toe ≃ 1–1/2 ft deep
11.90	9:55	B7	Right bank, 133' downstream of spillway toe ≃ 2 ft deep
11.90	9:55	B7	Right bank, 133 ft downstream of spillway toe ≃ 2 ft deep
11.80	9:55	B8	Right bank, 102 ft downstream of spillway toe ≃ 2 ft deep
11.85	9:55	B8	Right bank, 102 ft downstream of spillway toe ≃ 2 ft deep
11.70	10:05	B9	Right bank, 59 ft downstream of spillway toe, ≃ .5 ft deep
11.80	10:05	B9	Right bank, 59 ft downstream of spillway toe ≃ 1.5 ft deep
9.55	10:14	B10	Right bank, 3 ft upstream of spillway crest
9.60	10:14	B10	Right bank, 3 ft upstream of spillway crest
9.55	10:20	B11	Right bank, 23 ft upstream of spillway crest ≃ 1.5 ft deep
9.50	10:20	B11	Right bank, 23 ft upstream of spillway crest ≃ 1.5 ft deep

*Obviously in error

TABLE III–3. Results from St. Cloud Dam Site Survey, December 19, 1985

Atmospheric Pressure:	747.3 mm of Hg.
Water Temperature:	14.03 ± .28 mg O_2/ℓ
Saturation Concentration:	.1°C ± .05°C
Static Head:	2.34 ft
Energy Loss:	16.34 ft
Upstream Water Surface Elevation:	981.34 ft
Downstream Water Surface Elevation:	965.00 ft
Discharge/Unit Crest Width:	11.82 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	10.83	6	.04	.05	12.27	6	.04	.05	.45	.05	0.8	10

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table III–3 (Cont'd). Data from St. Cloud Dam Site Survey, Dec. 19, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
10.90	1:20	C1	Right Bank ~ 50 ft upstream of crest, sample taken at 5 ft deep, note high velocity flow
10.80	1:20	C1	"
10.80	1:25	C1	"
10.80	1:25	C1	"
10.80	1:30	C1	"
10.85	1:30	C1	"
12.25	1:45	C2	Right Bank ~ 6 ft from bank, sample taken at 3 ft in depth
12.25	1:45	C2	"
12.20	1:50	C2	"
12.30	1:50	C2	"
12.30	1:55	C2	"
12.30	1:55	C2	"

TABLE III–4. Results from St. Cloud Dam Site Survey, January 17, 1986

Atmospheric Pressure:	28.99 mm of Hg.
Water Temperature:	13.78 ± .27 mg O_2/ℓ
Saturation Concentration:	.2°C ± .05°C
Static Head:	2.16 ft
Energy Loss:	17.16 ft ± .02 ft
Upstream Water Surface Elevation:	981.16 ± .02 ft
Downstream Water Surface Elevation:	964.01 ± .02 ft
Discharge/Unit Crest Width:	10.55 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	10.63	8	.059	.05	12.18	6	.068	.07	.99	.05	1.5	10
Left Bank	10.67	8	.026	.05	12.23	6	.027	.05	.50	.05	1.5	10
	Mean for site								.50	.05	1.5	10

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table III–4 (Cont'd). Data from St. Cloud Site Survey, January 17, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
10.65	10:10	D1	30 ft from crest, 40 ft from bank, 2 ft below water surface, Right Bank upstream
10.65	10:10	D1	"
10.65	10:14	D1	8 ft below water surface, Right Bank upstream
10.70	10:14	D1	8 ft below water surface, Right Bank upstream
10.60	10:19	D1	11 ft below water surface, Right Bank upstream
10.65	10:19	D1	11 ft below water surface, Right Bank upstream
10.50	10:35	D1	5 ft below water surface, Right Bank upstream
10.65	10.35	D1	5 ft below water surface, Right Bank upstream
12.20	10:50	D2	1–1/2 ft below water surface Right Bank upstream
12.20	10:50	D2	"
12.30	10:55	D2	"
12.10	10:55	D2	"
12.15	11:00	D2	"
12.15	11:00	D2	"
12.20	12:10	D3	1–1/2 ft below water surface, Left Bank downstream
12.20	12:10	D3	1–1/2 ft below water surface, Left Bank downstream
12.25	12:12	D3	3 ft below water surface, Left Bank downstream
12.20	12:12	D3	3 ft below water surface, Left Bank downstream
12.25	12:15	D3	3 ft below water surface, Left Bank downstream
12.25	12:15	D3	3 ft below water surface Left Bank downstream
10.65	12:35	D4	8' from Leftbank Wall & Leftbank Ret. Wall
10.65	12:35	D4	~ 2 ft below water surface, just below ice
10.65	12:38	D4	~ 5 ft below water surface, just below ice
10.65	12:38	D4	~ 5 ft below water surface, just below ice
10.70	12:40	D4	~ 12 ft below water surface
10.70	12:40	D4	~ 12 ft below water surface
10.70	12:45	D4	8 ft deep, Left Bank upstream
10.65	12:45	D4	8 ft deep, Left Bank upstream

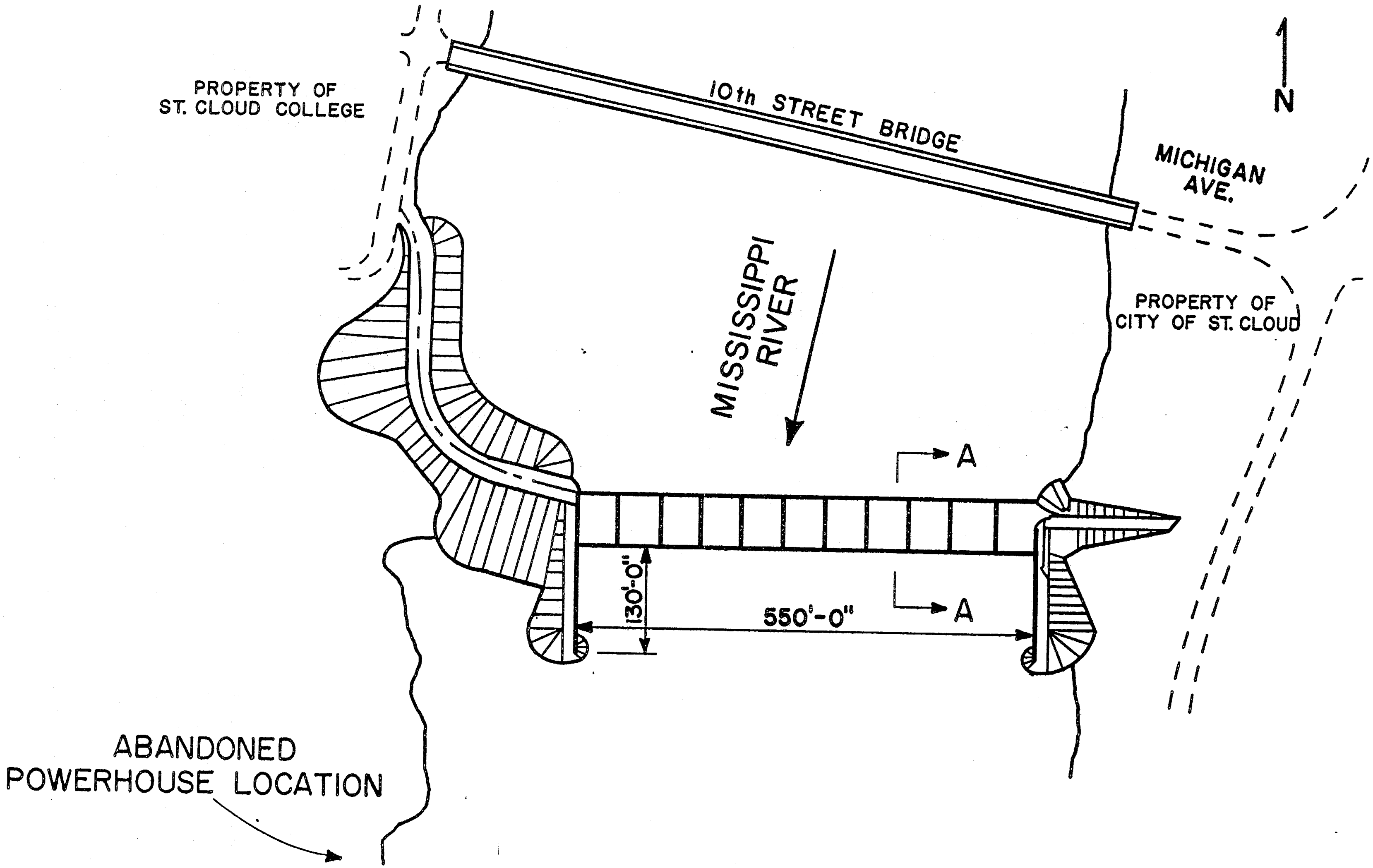


Fig. III–1. Plan of Mississippi River at St. Cloud Dam (taken from Knowlton et al., 1982).

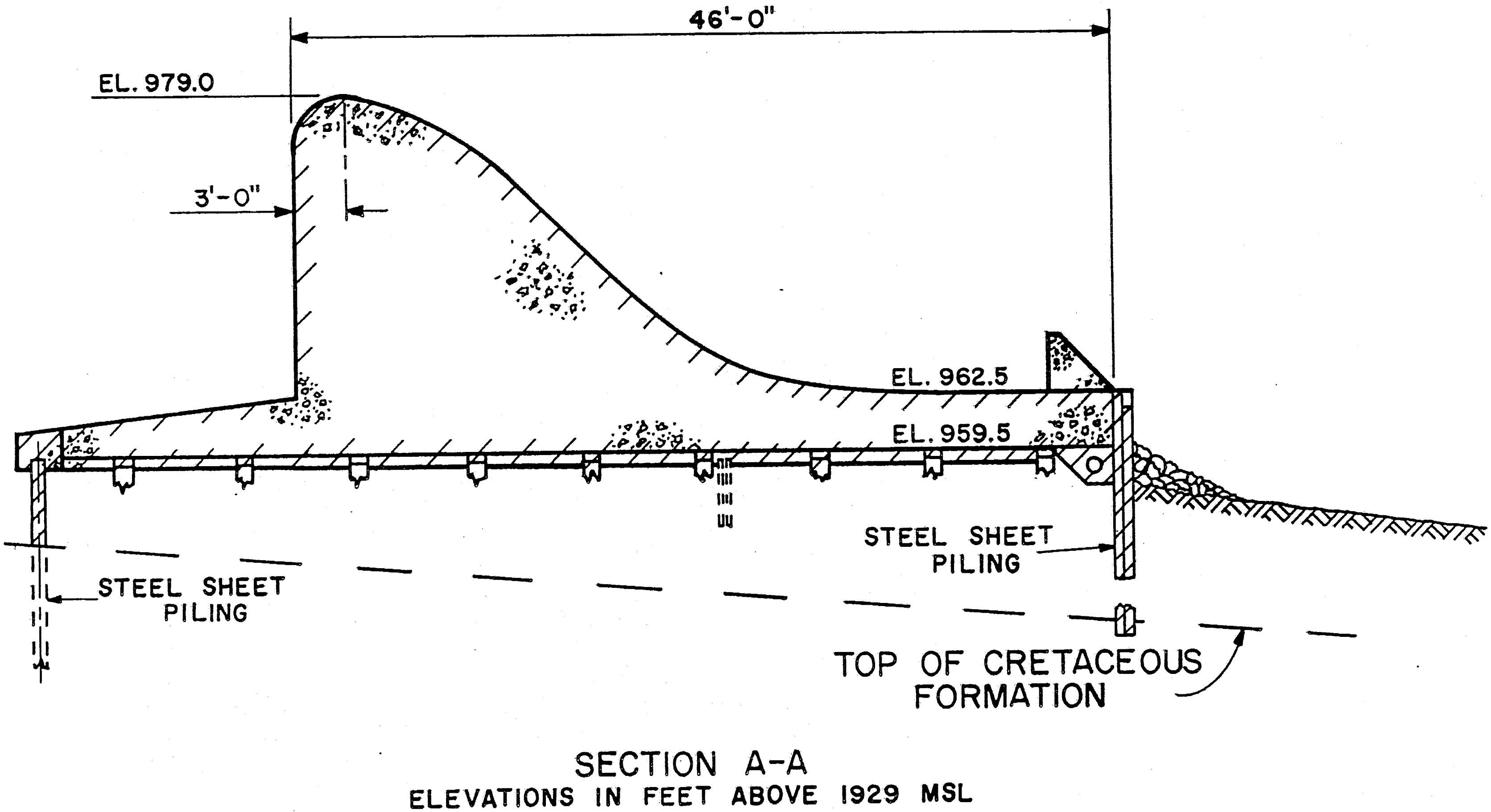


Fig. III-2. Section A–A through Ogee spillway crest (1). (taken from Knowlton et al., 1982).

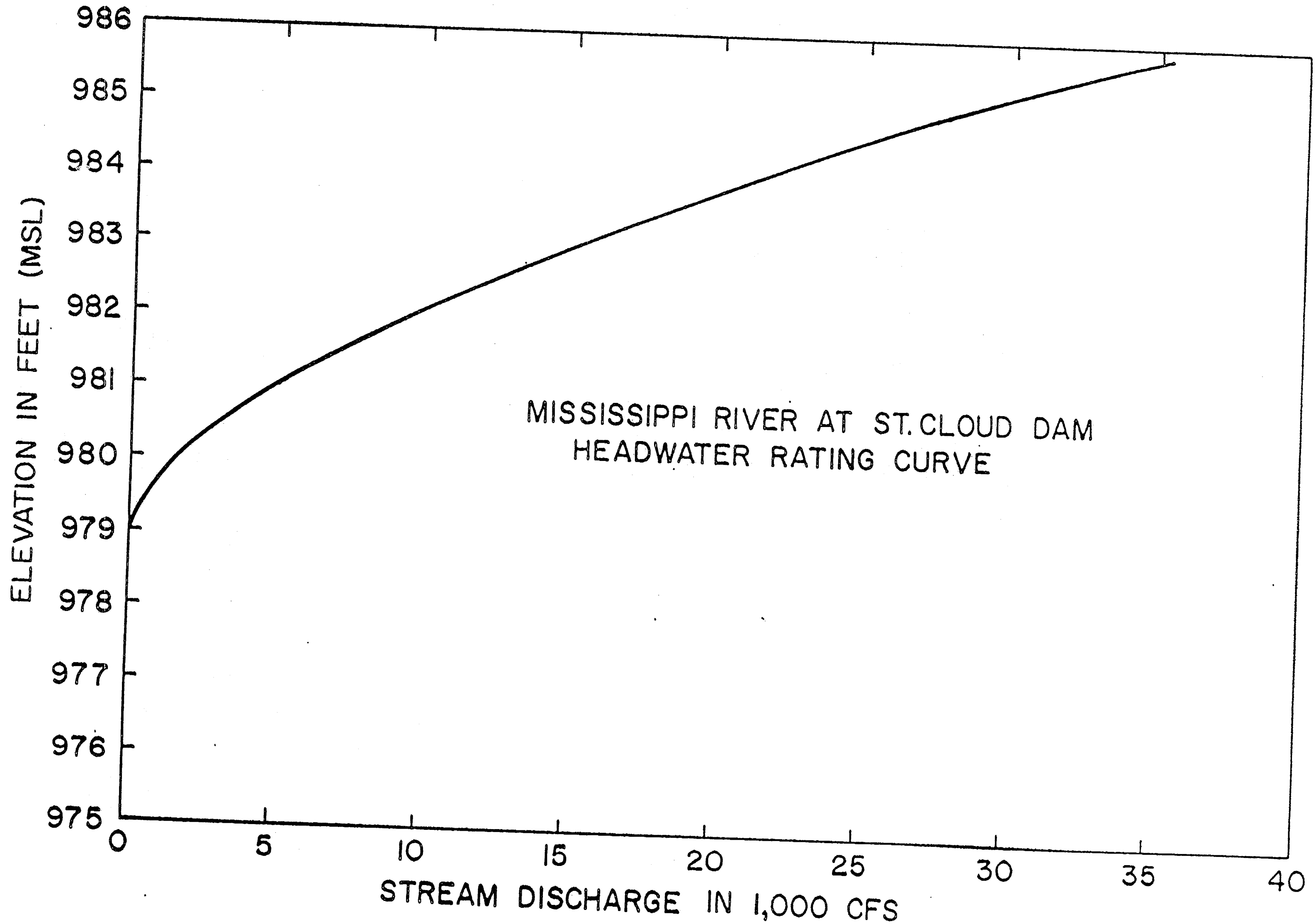


Fig. III–3. St. Cloud headwater rating curves taken from Knowlton et al. (1982).

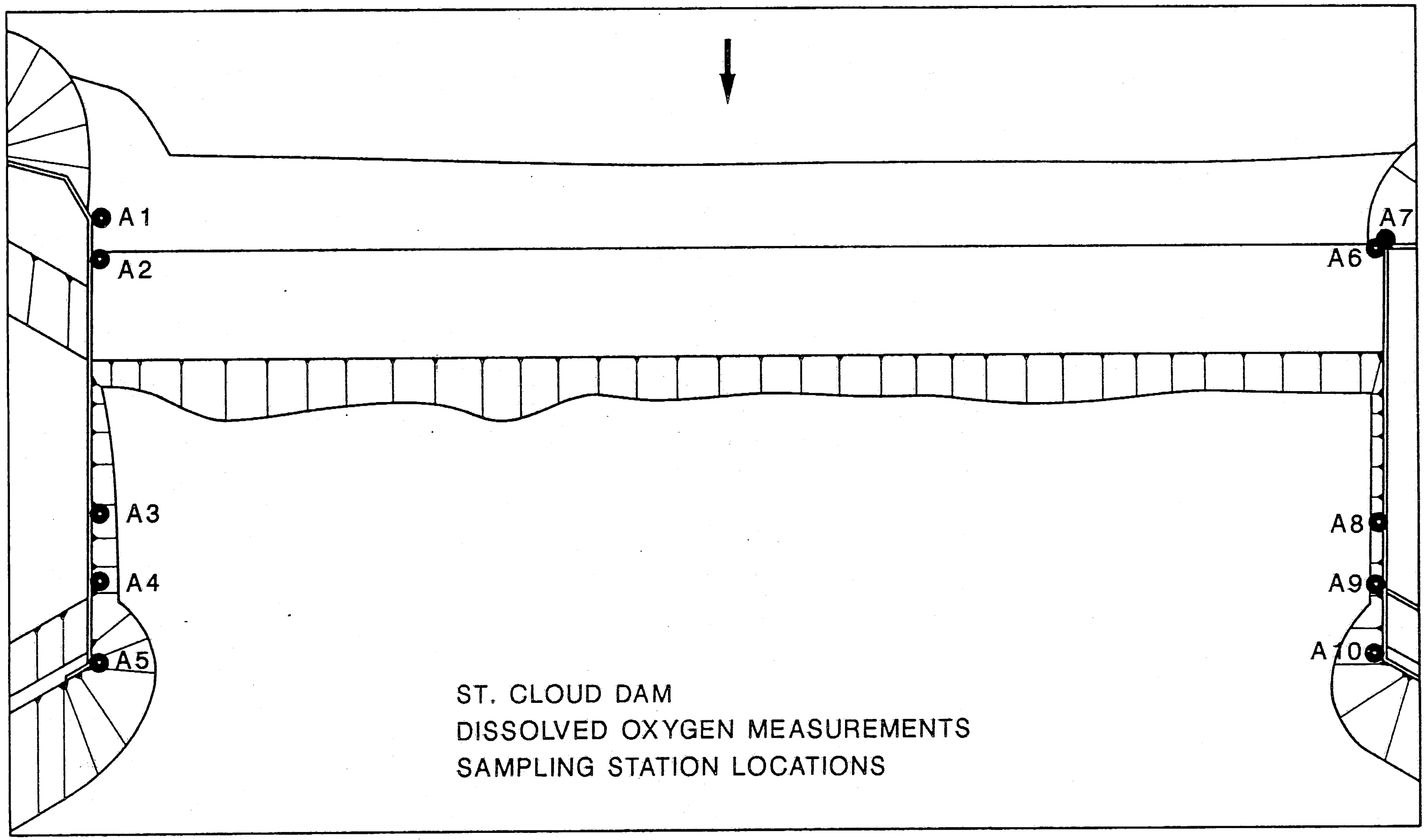


Fig. III–4. Sampling locations on March 2, 1985.

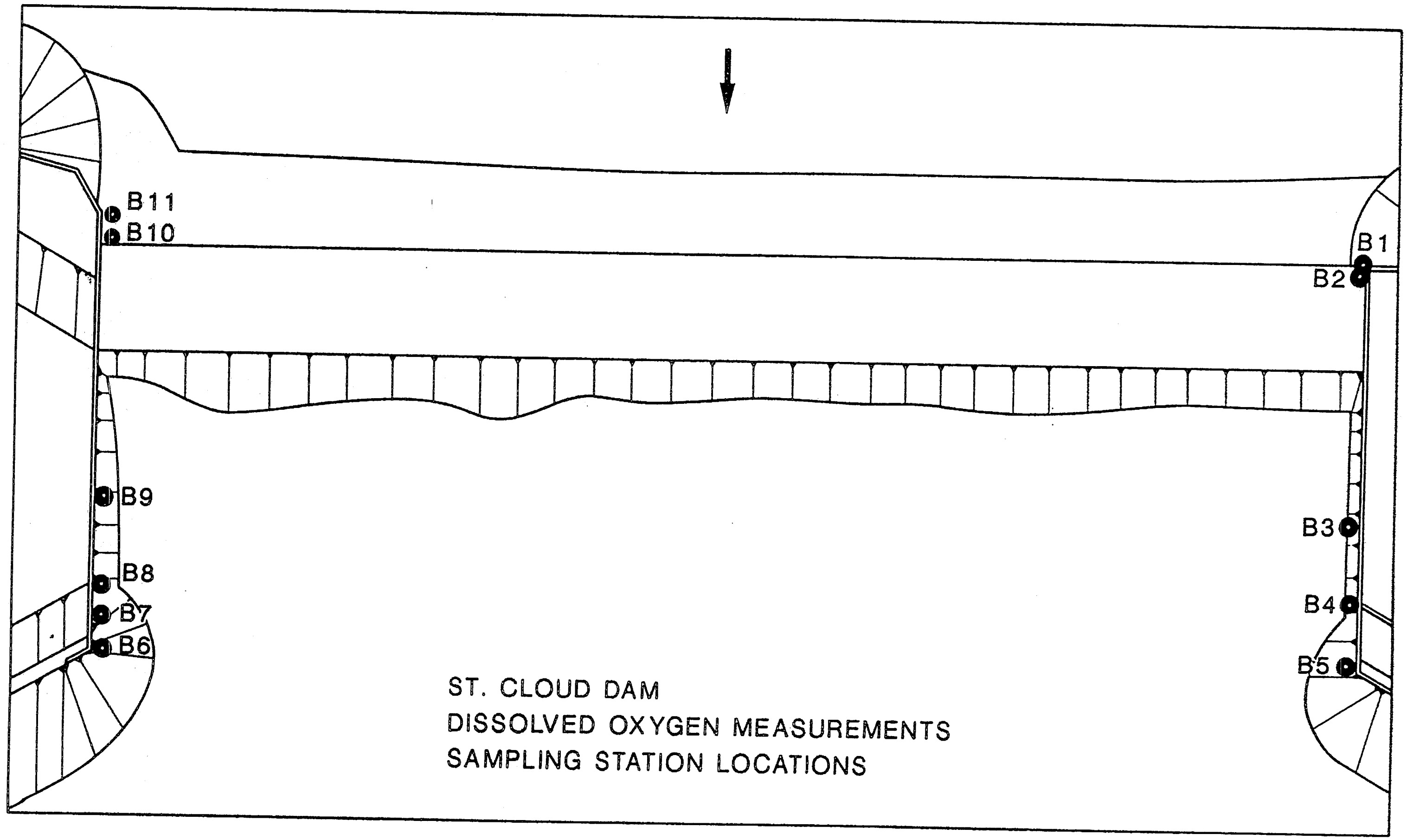


Fig. III–5. Sampling locations on March 14, 1985.

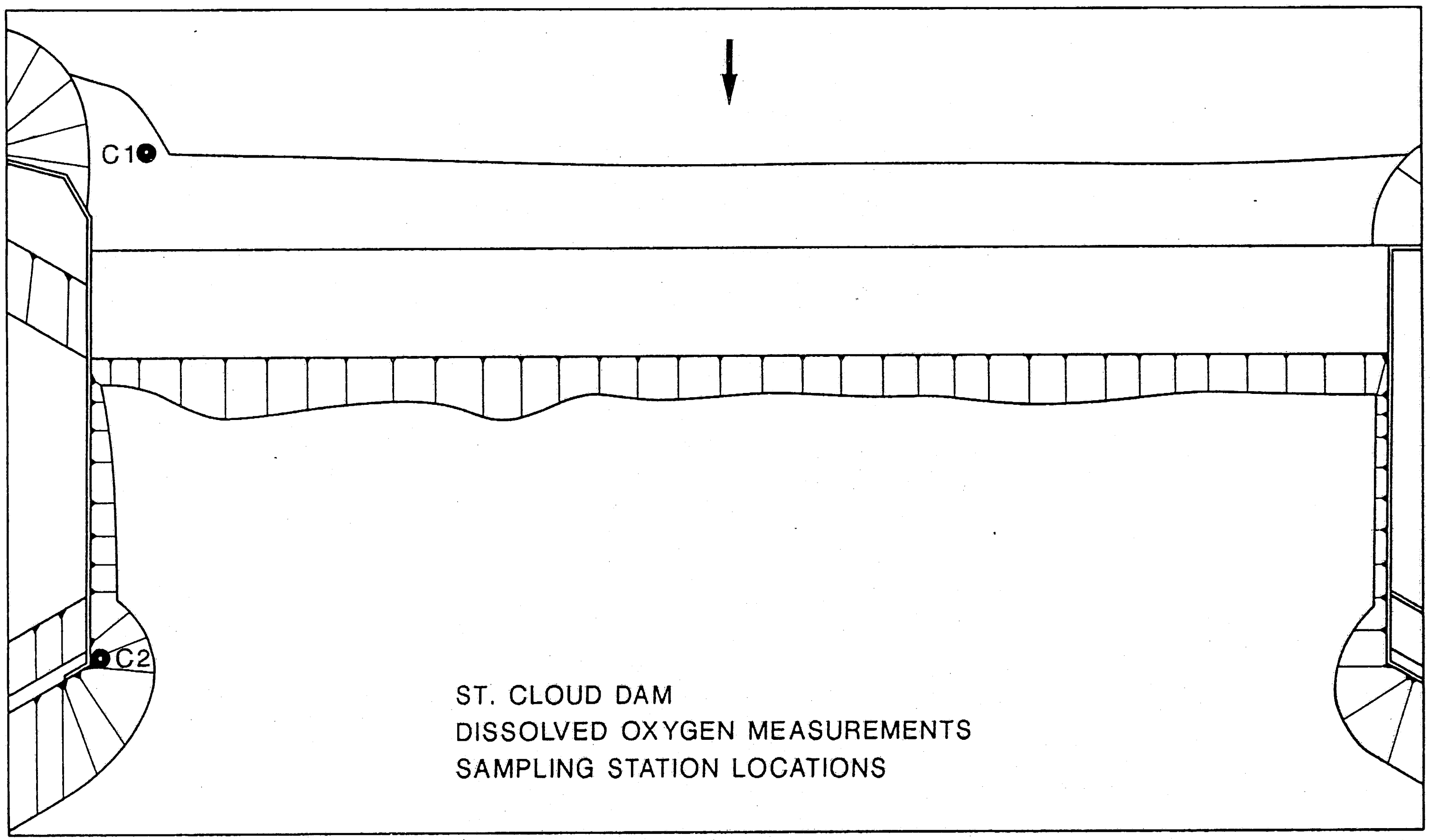


Fig. III–6. Sampling locations on December 14, 1985.

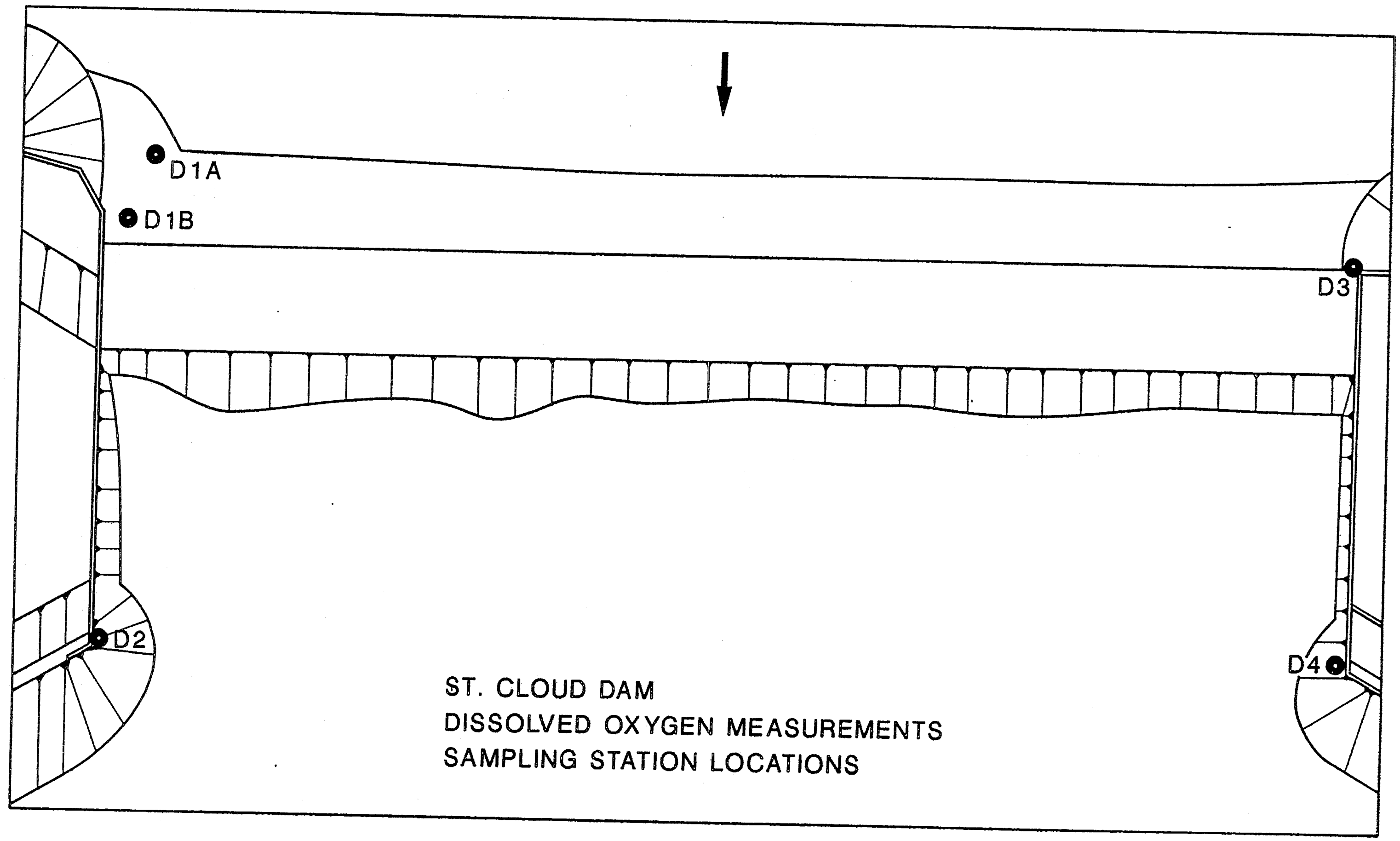


Fig. III–7. Sampling locations on January 17, 1986.

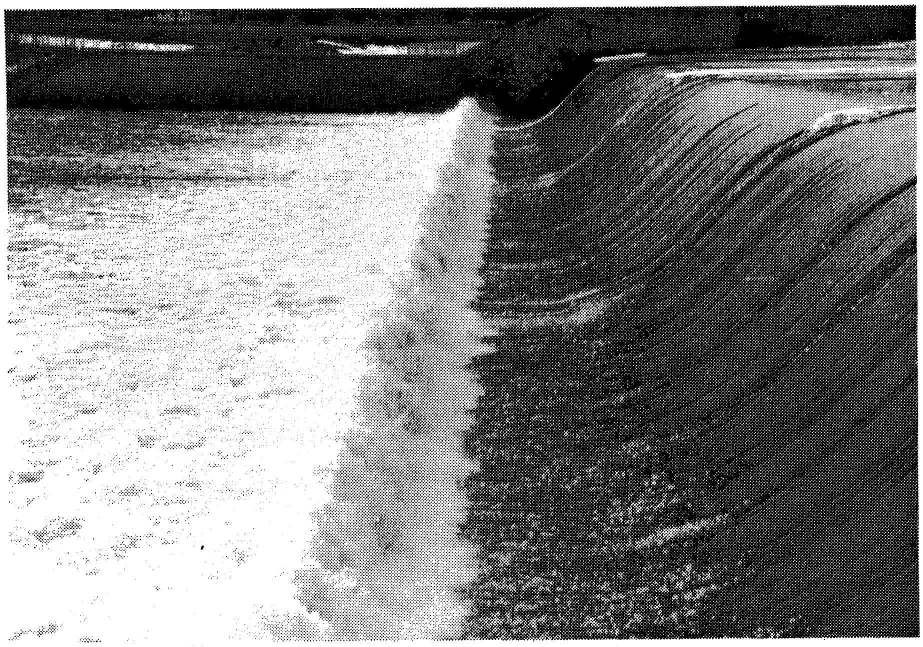


Photo III–1. St. Cloud Dam, March 2, 1985, spillway and hydraulic jump characteristics.

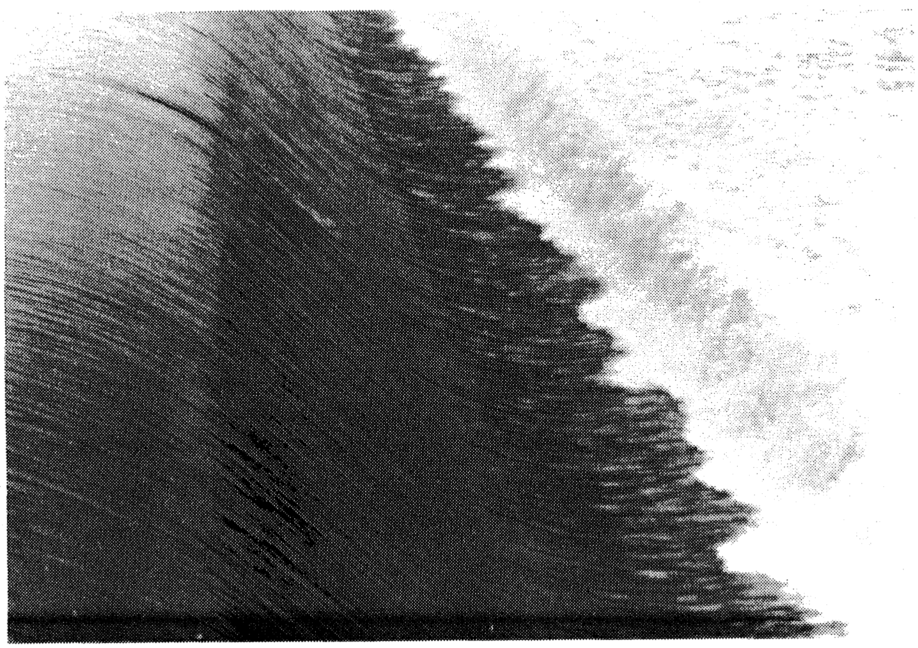


Photo III–2. St. Cloud Dam, March 14, 1985, spillway and hydraulic jump characteristics.

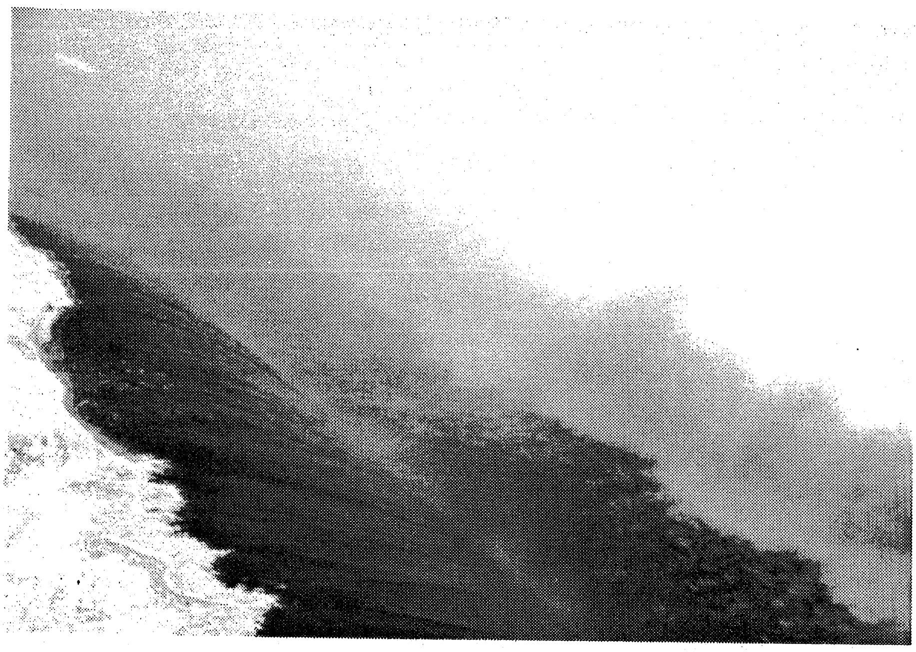


Photo III–3. St. Cloud Dam, December 19, 1985, spillway and hydraulic jump characteristics.

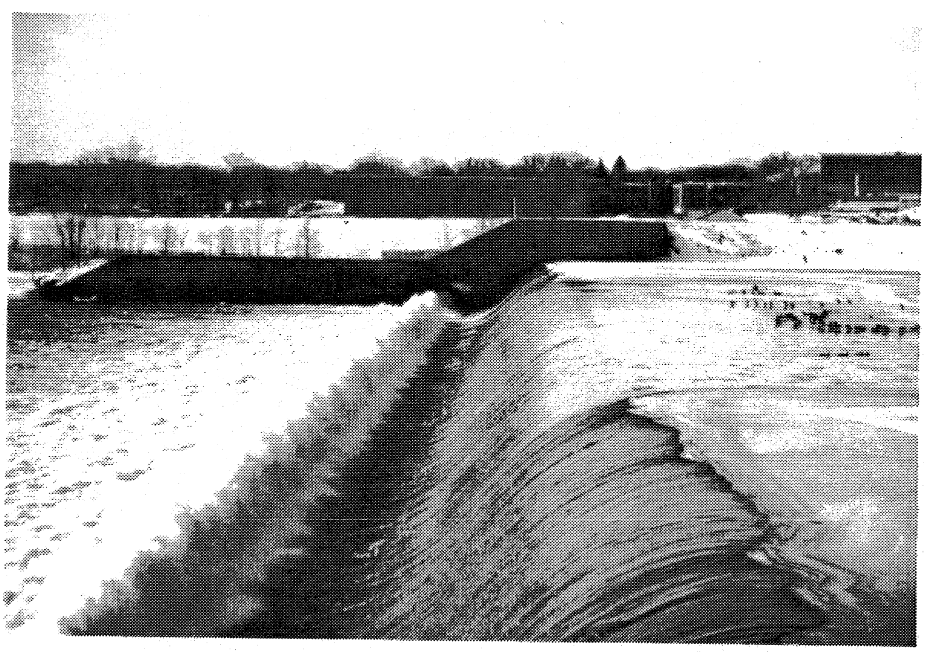


Photo III–4. St. Cloud Dam, January 17, 1986, spillway and hydraulic jump characteristics.

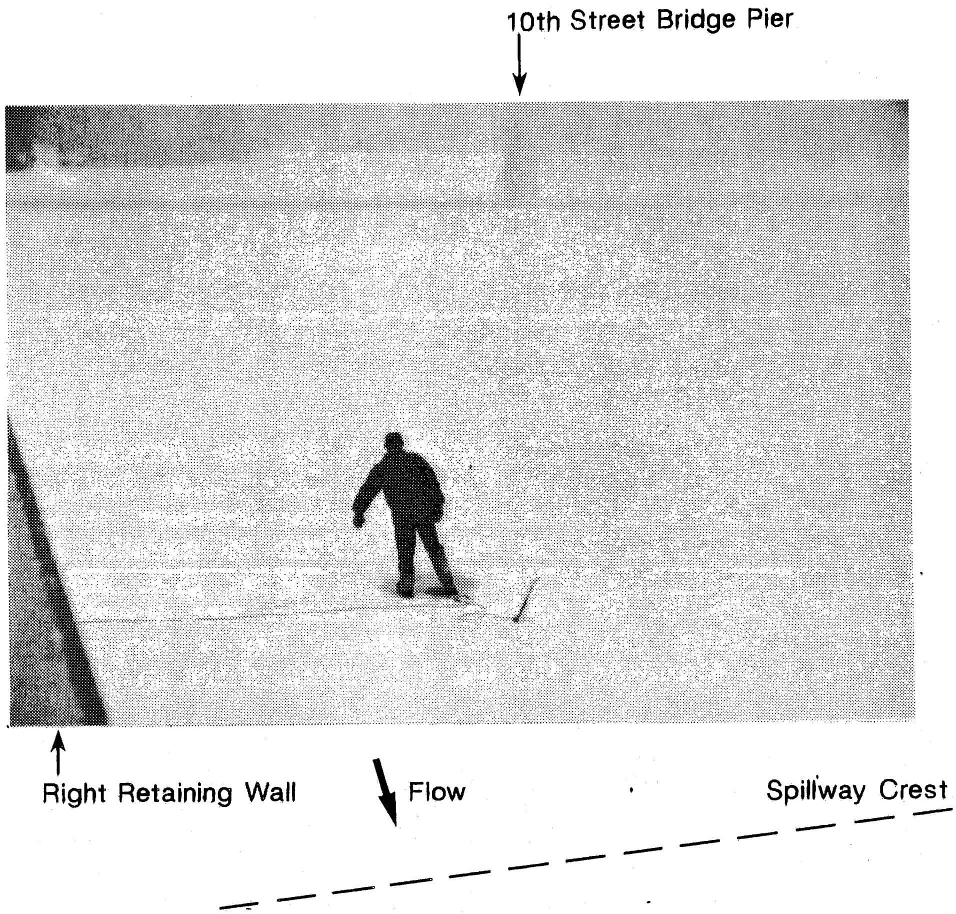


Photo III–5. St. Cloud Dam, December 19, 1985, upstream right bank sampling location.

IV. ANOKA RUM RIVER DAM

A. PHYSICAL DESCRIPTION

The Rum River Dam is located on the Rum River in the City of Anoka, approximately 500 ft upstream from the Main Street bridge. Shown in Figure IV–1, the dam consists of an Amburson type spillway 11.4 ft high and 236 ft long with a 20 ft wide tainter gate spillway located next to the left bank. This structure is shown in cross–section in Figure IV–2.

The tainter gate spillway utilizes a hydraulic jump run up against the spillway to dissipate the excess kinetic energy of the flow. A free overfall is used for the fixed crest spillway.

B. DISCHARGE MEASUREMENTS

The discharge for the tainter gate spillway was determined using the U. S. Army Corps of Engineers, Waterways Experiment Station, *Hydraulic Design Criteria*, Sheets 311–1 to 311–5. The accuracy of this method depends largely on a number of factors difficult to quantify, such as the condition of the rubber seal at the lip of the tainter gate, and the spillway roughness. Discharge for the spillway crest section was determined assuming the spillways discharge characteristics behaved like a broad crested weir, which is reasonable considering the flat 5 ft crown of the spillway crest.

C. GAS TRANSFER MEASUREMENTS

Data was collected at this site on February 2, 1984, January 24, 1986, and March 14, 1986. The results from these surveys are presented in Tables IV–1, through IV–3. Measurements were collected to indicate the gas transfer from both the tainter gate spillway and the Amberson spillway. However, because of the ability to manipulate the tainter gate openings, the measurements focused primarily on the tainter gate spillway. Sampling locations for the surveys are shown in Fig. IV–3, IV–4, and IV–5. Photographs taken during the surveys are represented in Photos IV–1 through IV–4.

The February 2, 1984, set of measurements were the first collected to investigate gas transfer during the winter at hydraulic structures. Dissolved oxygen measurements, collected using a Yellow Springs Instrument Model 54 dissolved oxygen meter, indicated the environment of below 32°F was not acceptable for the operation of this meter. Meter response was very slow and unstable. It was decided from these measurements that water samples would be collected and analyzed for dissolved oxygen instead of reliance on a meter.

At large tainter gate openings, it was not possible to measure the dissolved oxygen concentration downstream of the bubbly flow region. To eliminate this error, it was decided to investigate only smaller tainter gate openings.

Measurements were collected in 1986, at the gate openings listed in Tables IV–3 and IV–5. Photographs of the tainter gates and the flow leaving the tainter gates are shown in Photos IV–1 and IV–3. Tainter gate openings listed in these tables were determined from the physical geometry taken off the "As Built Plans" supplied by Barr Engineering, Inc. The tainter gate heater was inoperable so changing the gate opening was not possible during the February measurement. However, it was possible to change the gate settings for the March 14, 1986, measurement.

Also collected in 1986 were water samples from downstream of the Amburson spillway, or free overfall spillway, shown in Photos IV–2 and IV–4. Two locations were measured, spillway No. 1 downstream after the bubbles dissipated from the flow, and spillway No. 2 upstream from the energy dissipators of the spillway (location B4 and B5 in the January 29, 1986, sampling, respectively). These samples indicated that some gas transfer occurred in the slight 1 ft drop through the energy dissipators.

TABLE IV–1. Results from Anoka Rum River Dam Site Survey, February 2, 1984

Atmospheric Pressure: (mm of Hg)	736.8
Water Temperature (° C):	0.0° C
Saturation Concentration: (mg 02/ℓ)	14.15

Gate Opening feet	Discharge (cfs/ft)	Transfer Efficiency E	U
.44	8.2	.63	.03
.61	11.3	.65	.03
1.08	18.8	.68	.03
1.54	26.0	.54	.02
1.98	32.8	.44	.02
2.39	35.6	.40	.02
.51	9.8	.68	.03

Table IV–1 (Cont.). Data from Anoka Rum River Dam Site Survey, February 2, 1984.

Upstream Water Surface Elevation ft	Downstream Water Surface Elevation ft	Upstream Dissolved Oxygen Conc. mg 02/ℓ	Downstream Dissolved Oxygen Conc. mg 02/ℓ	Tailwater Depts (ft)
844.93	831.83	6.0	11.1	11.8
844.92	831.92	5.8	11.2	11.9
844.77	832.15	6.2	11.6	12.2
844.66	832.40	5.8	10.3	12.4
844.44	832.20	6.0	9.6	12.2
844.20	832.30	6.2	9.4	12.3
844.77	831.30	6.8	11.8	11.3

Note:

– All downstream measurements were taken approx. 30 ft downstream at Location A2.

– This data was collected using a Yellow Springs Instruments Model 54 Meter which lost its calibration with time. The data presented above are the values read from the meter adjusted using the dissolved oxygen concentration of collected samples analyzed using the Winkler method. To account for this inaccuracy, an upstream and downstream D.O. uncertainty of .1 mg/ℓ was used in the total E uncertainty.

TABLE IV–2. Results from Anoka Rum River Dam Site Survey, January 24, 1986

Atmospheric Pressure: (mm of Hg) 28.96 in of Hg
Water Temperature (°C): .2°C ± .05°C
Saturation Concentration: 13.77 mg 02/

		Location		
		Tainter Gate	Spillway 2	Spillway 1
Upstream Concentration mg 02/ℓ	$\bar{C}$	6.25	6.32	6.32
	n	6	6	6
	σ	.055	.026	.026
	Wu	.06	.05	.05
Downstream Concentration mg 02/ℓ	$\bar{C}$	10.89	10.60	10.69
	n	6	6	6
	σ	.074	.063	.020
	W	.08	.07	.05
Transfer Efficiency	E	.62	.57	.59
	U	.03	.03	.03
Upstream Water Surface Elev. ft		842.11	842.11	842.11
Downstream Water Surface Elev. ft		831.77	831.77	831.77
Discharge cfs/ft		4.5	2.03	2.03
Tainter Gate Opening (ft)		.31	N.A.	N.A.
Tailwater Depth ft		11.8	N.A.	N.A.

TABLE IV–2 (Cont'd). Data from Anoka Rum River Dam Site Survey, January 24, 1986

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
6.35	10:30	B1	10 ft Upstream from the Tainter Gate ~ 9 ft deep
6.25	10:30	B1	10 ft Upstream from the Tainter Gate ~ 9 ft deep
6.25	10:31	B1	10 ft Upstream from the Tainter Gate ~ 6 ft deep
6.25	10:31	B1	10 ft Upstream from the Tainter Gate ~ 6 ft deep
6.20	10:32	B1	10 ft Upstream from the Tainter Gate ~ 2 ft deep
6.20	10:32	B1	10 ft Upstream from the Tainter Gate ~ 2 ft deep
10.80	10:35	B2	Downstream from the Tainter Gate
10.80	10:35	B2	Bubbles out of the flow
10.95	10:36	B2	Bubbles out of the flow
10.95	10:36	B2	Bubbles out of the flow
10.90	10:38	B2	Bubbles out of the flow
10.95	10:38	B2	Bubbles out of the flow
6.35	10:48	B3	Upstream on the crest ~ 2' deep
6.30	10:48	B3	Upstream on the crest ~ 2' deep
6.30	10:49	B3	Upstream on the crest ~ 2' deep
6.30	10:49	B3	Upstream on the crest ~ 2' deep
6.35	10:50	B3	Upstream on the crest ~ 2' deep
6.30	10:50	B3	Upstream on the crest ~ 2' deep
10.60	11:10	B4	Downstream, upstream of 2nd small spillway
10.70	11:10	B4	Downstream, upstream of 2nd small spillway
10.55	11:11	B4	Downstream, upstream of 2nd small spillway
10.65	11:11	B4	Downstream, upstream of 2nd small spillway
10.55	11:12	B4	Downstream, upstream of 2nd small spillway
10.55	11:12	B4	Downstream, upstream of 2nd small spillway
10.70	11:32	B5	Downstream from Second Spillway
10.70	11:32	B5	Downstream from Second Spillway
10.70	11:33	B5	Downstream from Second Spillway
10.70	11:33	B5	Downstream from Second Spillway
10.65	11:35	B5	Downstream from Second Spillway
10.70	11:35	B5	Downstream from Second Spillway

TABLE IV–3. Results from Anoka Rum River Dam Site Survey, March 14, 1986

Atmospheric Pressure: (mm of Hg) 733.90
Water Temperature (°C): .2 ± .05
Saturation Concentration: (mg 02/ℓ) 13.77

		Location			
		Tainter Gate	Tainter Gate	Spillway 1	Spillway 2
Upstream Concentration mg 02/ℓ	$\bar{C}$	8.99	9.00	9.18	9.18
	n	8	3	4	4
	σ	.04	.05	.03	.03
	W	.05	.05	.05	.05
Downstream Concentration mg 02/ℓ	$\bar{C}$	12.23	11.81	11.77	11.71
	n	6	8	3	4
	σ	.07	.10	.06	.03
	W	.06	.10	.05	.05
Deficit Ratio	E	.68	.59	.57	.55
	U	.05	.04	.04	.04
Upstream Water Surface Elev. ft		842.15	842.14	842.14	842.14
Downstream Water Surface Elev. ft		831.77	831.87	831.87	831.87
Discharge cfs/ft		4.1	6.8	2.16	2.16
Tainter Gate Opening (ft)		.21	.41	N.A.	N.A.
Tailwater Depth (ft)		11.8	11.9	N.A.	N.A.

Table IV–3 (Cont'd). Data from Anoka Rum River Dam Site Survey, March 14, 1986

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
9.00	10:35	C1	Upstream right bank 9' deep, just off bottom
9.00	10:35	C1	Upstream right bank 9' deep, just off bottom
9.00	10:40	C2	Upstream left bank,9' deep, just off bottom
8.90	10:40	C2	Upstream right bank 9' deep, just off bottom
9.00	10:40	C1	Upstream right bank ~ 7 ft down
9.00	10:43	C1	Upstream right bank ~ 7 ft down
9.00	10:50	C2	Upstream left bank ~ 7 ft down
9.00	10:50	C2	Upstream left bank ~ 7 ft down
12.25	11:00	C3	Downstream right bank, 36' from edge of bridge
12.25	11:00	C3	Bubbles in flow (approx 1/4 – 3/8 in. in diameter)
12.25	11:05	C4	Downstream right bank, 51 ft from D.S. bridge
12.30	11:05	C4	Downstream right bank, 51 ft from D.S. bridge
12.25	11:10	C5	Downstream right bank ~ 40 ft from D.S. bridge
12.10	11:10	C5	Downstream right bank ~ 40 ft from D.S. bridge
9.00	11:50	C1	Upstream right bank ~ 7 ft down
9.10	11:55	C2	Upstream right bank ~ 7 ft down
8.90	11:55	C2	Upstream right bank ~ 7 ft down
11.90	12:05	C5	Downstream right bank
11.90	12:05	C5	Downstream right bank
11.80	12:09	C5	Downstream right bank
11.80	12:09	C5	Downstream right bank
11.80	12:15	C5	Downstream right bank
11.60	12:15	C5	Downstream right bank
11.90	12:13	C5	Downstream right bank
11.80	12:13	C5	Downstream right bank
11.80	12:40	C5	Downstream right bank
11.70	12:40	C5	Downstream right bank
11.80	12:45	C6	Left bank (Amburson Spillway)
11.80	12:50	C6	Left bank (Amburson Spillway)
11.70	12:50	C6	Left bank (Amburson Spillway)
11.70	12:56	C7	Downstream left bank (Amburson Spillway upstream of 2nd spillway
11.70	12:56	C7	Downstream left bank (Amburson Spillway upstream of 2nd spillway
11.75	12:58	C7	Downstream left bank (Amburson Spillway upstream of 2nd spillway

Table IV–3 (Cont'd). Data from Anoka Rum River
Dam Site Survey, March 14, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
11.70	12:58	C7	Downstream left bank (Amburson Spillway) upstream of 2nd spillway.
9.15	1:00	C8	Upstream on crest of Amburson Spillway
9.20	1:00	C8	Upstream on crest of Amburson Spillway
9.20	1:05	C8	Upstream on crest of Amburson Spillway
9.15	1:05	C8	Upstream on crest of Amburson Spillway

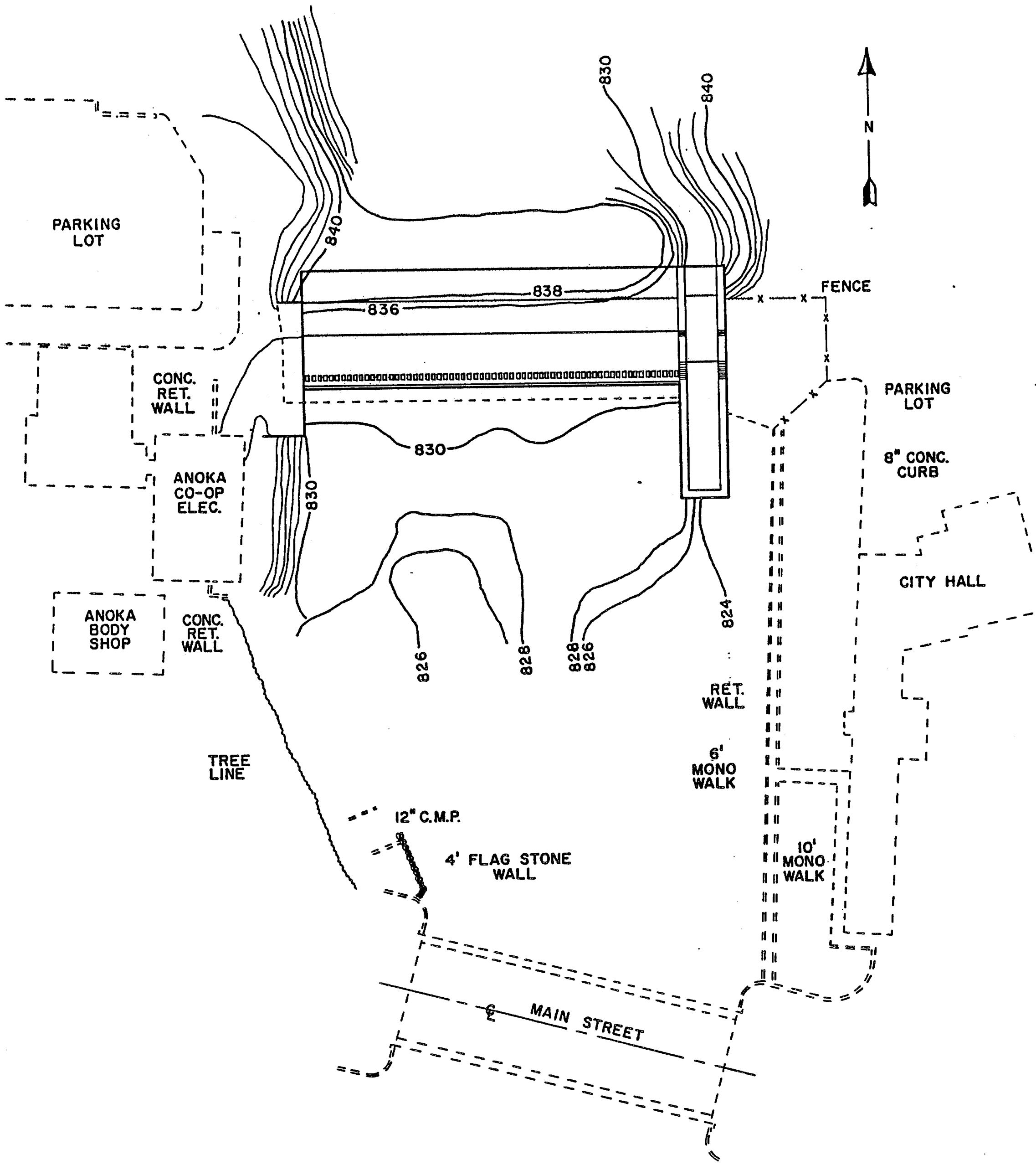


Fig. IV–1. Plan view of the Rum River Dam at Anoka.

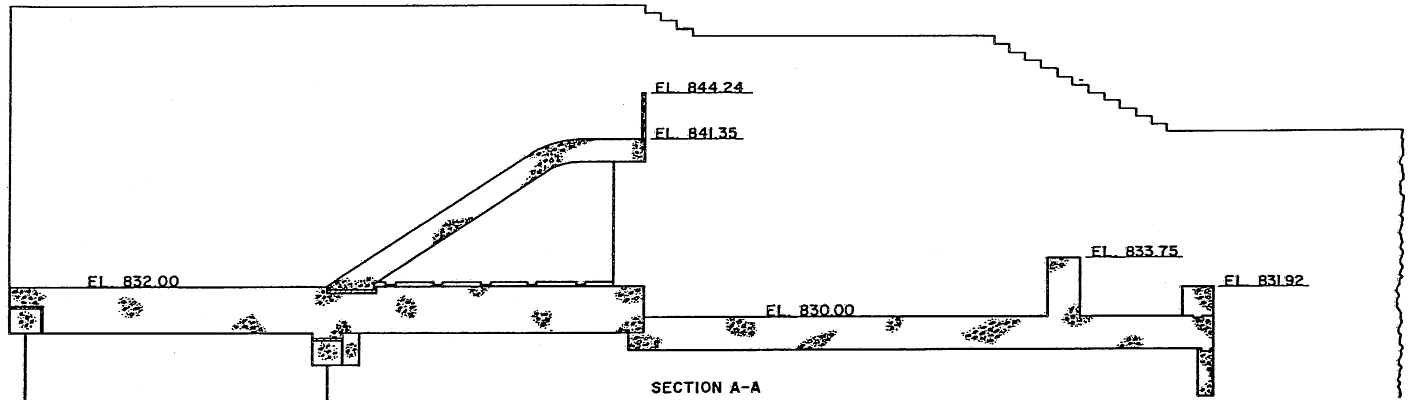


Fig. 3. Section A-A through fixed crest spillway.

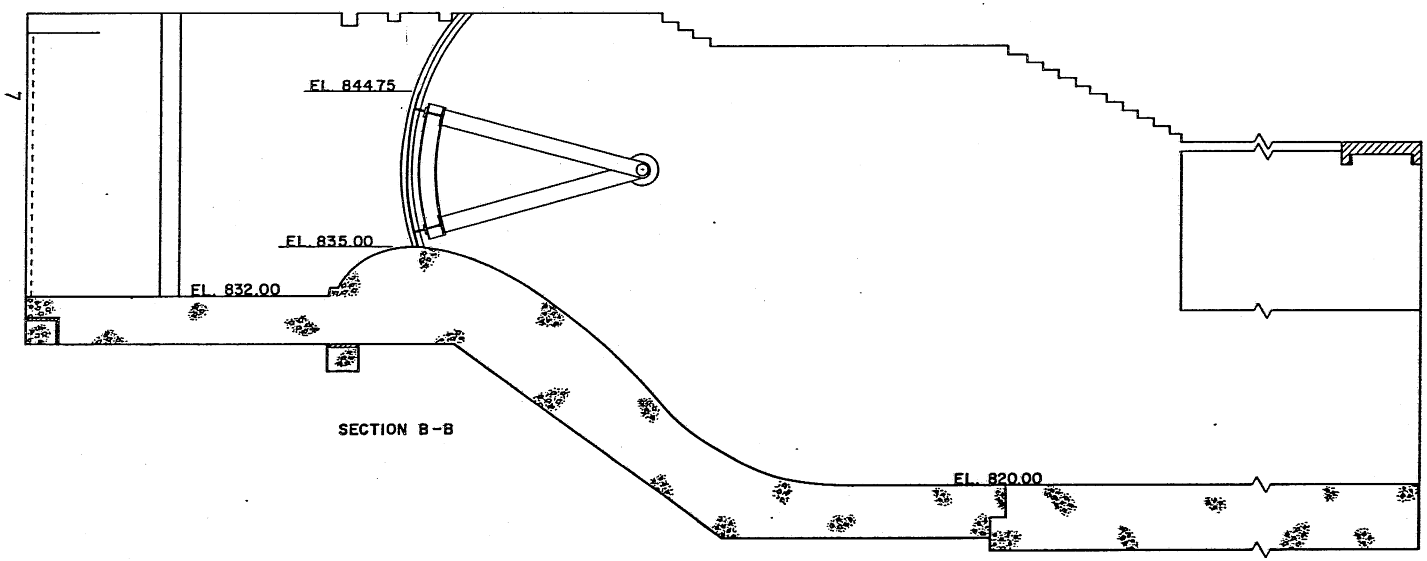


Fig. IV–2. Section B–B through tainter gate spillway.

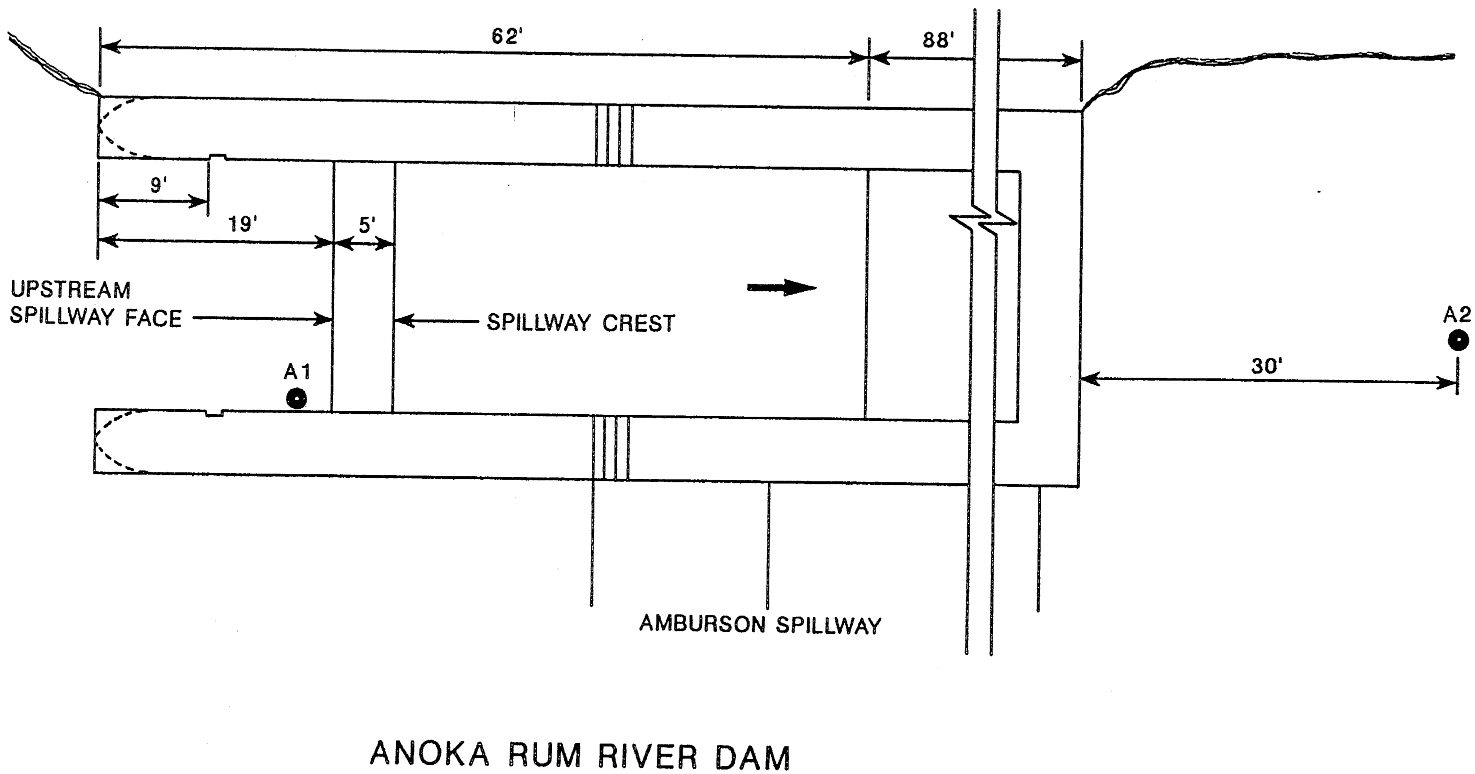
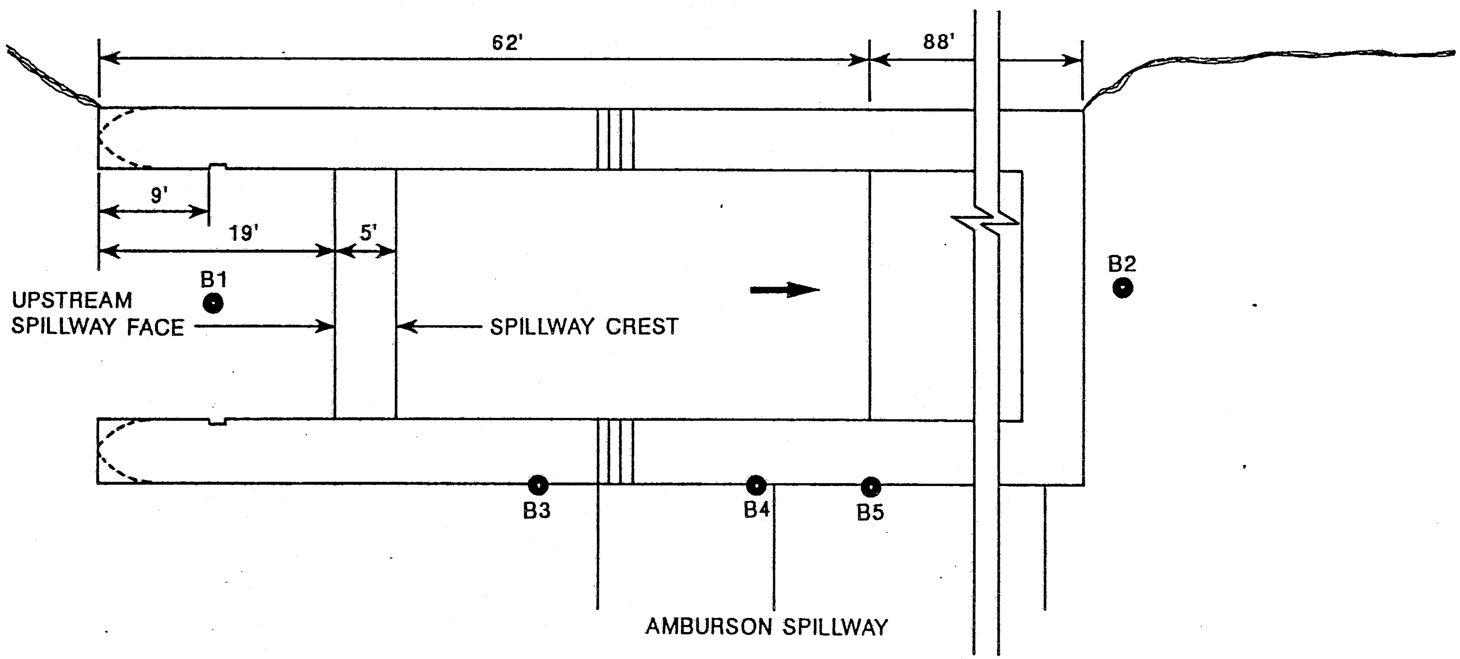
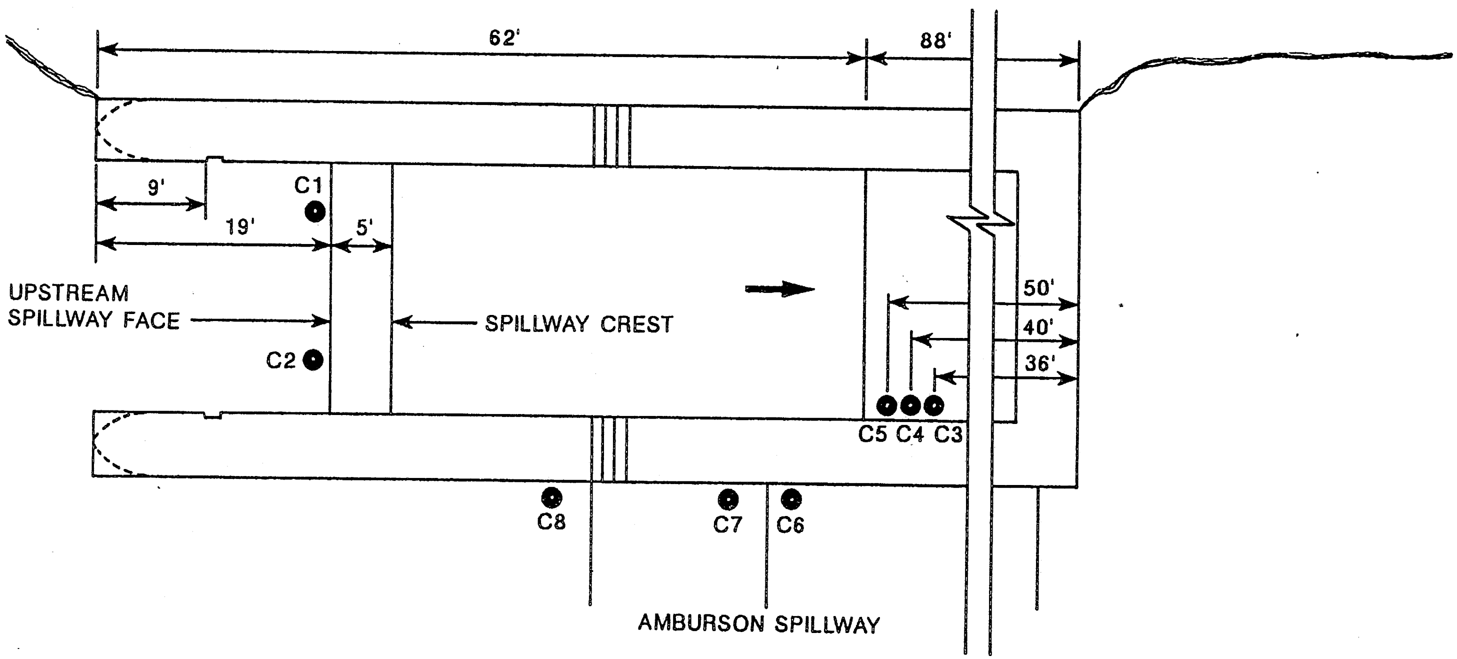


Fig. IV–3. Sampling locations on February 2, 1984.



ANOKA RUM RIVER DAM

Fig. IV–4. Sampling locations on January 24, 1986.



ANOKA RUM RIVER DAM

Fig. IV–5. Sampling locations on March 14, 1986.

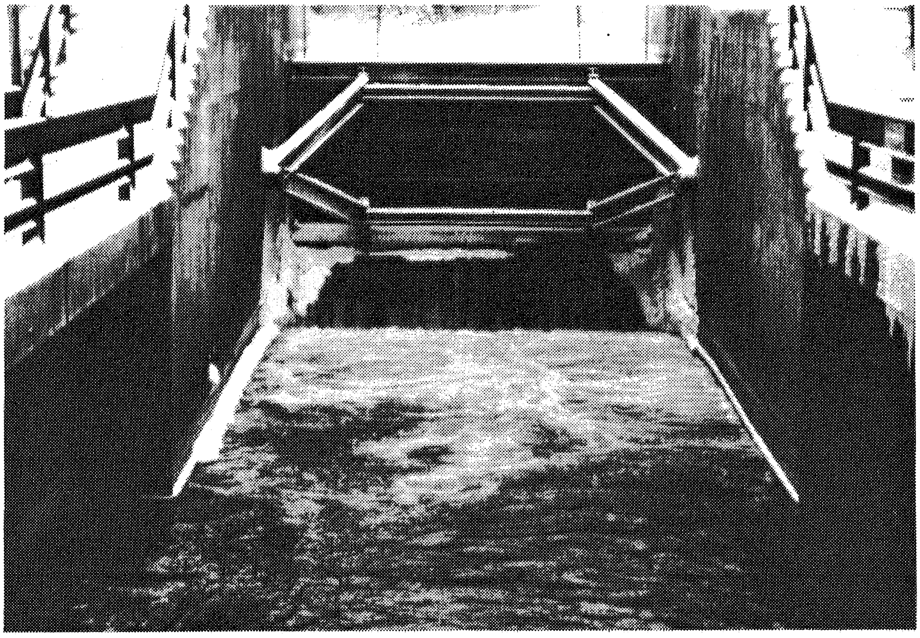


Photo IV–1. Anoka Rum River Dam, January 24, 1986, tainter gate discharge characteristics.

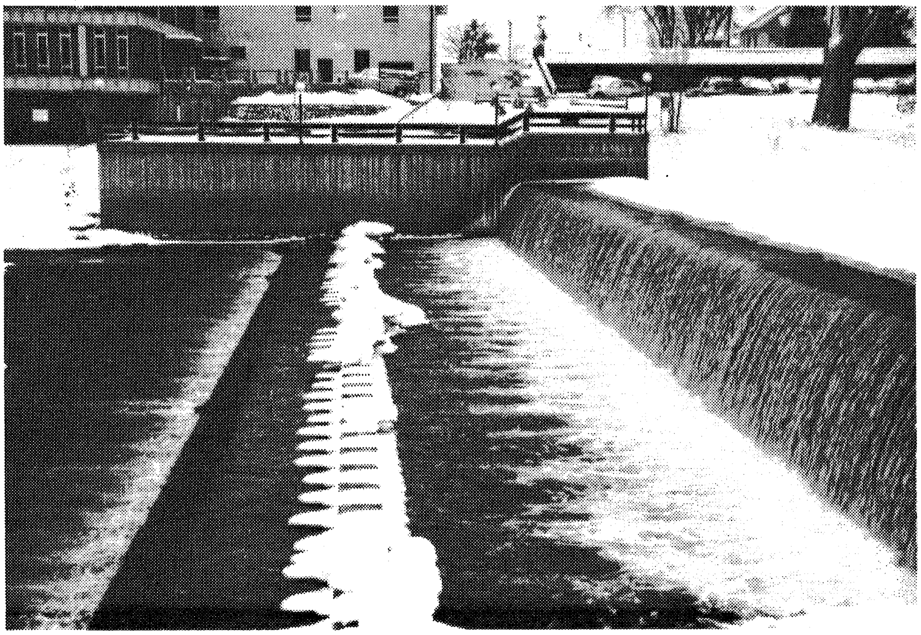


Photo IV–2. Anoka Rum River Dam, January 24, 1986, weir and stilling basin characteristics.

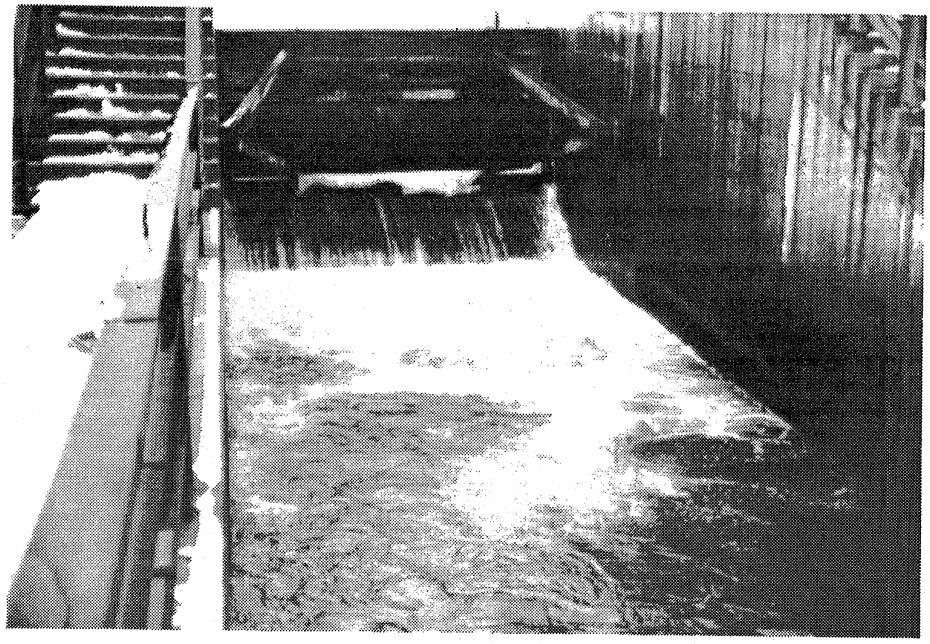


Photo IV–3. Anoka Rum River Dam, March 14, 1986, tainter gate discharge characteristics.

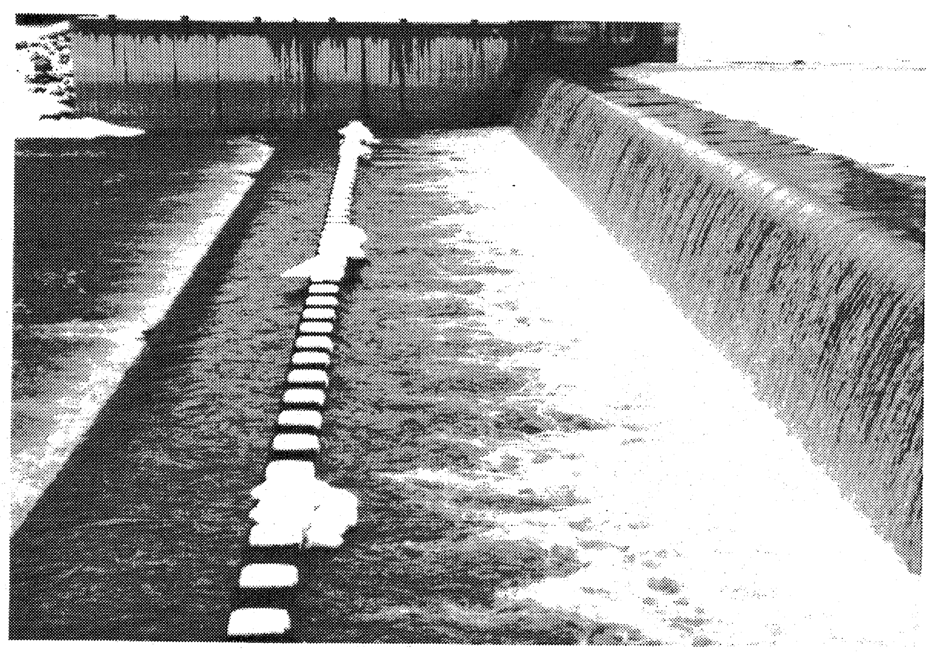


Photo IV–4. Anoka Rum River Dam, March 14, 1986, weir and stilling basin characteristics.

V. ELK RIVER DAM

A. PHYSICAL DESCRIPTION

The Elk River Dam is located on the Elk River approximately 20 ft upstream from the Main Street bridge on the Southwestern edge of Elk River, Minnesota. The dam maintains a small reservoir for a source of cooling water for the Elk River municipal electric power plant and for recreational purposes. It was completely reconstructed in 1981 after being determined unsafe during the National Inspection Program of non–federal dams.

The dam consists of two fixed crest modified ogee spillways separated by three tainter gate bays shown in Photo V–1 and illustrated by plan in Fig. V–1, and cross–section in Fig. V–2. Gas transfer was investigated at the main 116 ft long northern spillway, and the 20 ft long south weir. The tainter gate spillway was also of interest; however, during the winter months the tainter gates were inoperable due to ice.

The main spillway cross section shown in Fig V–2 is not a true ogee spillway. Instead, the Elk River Dam Spillway can be described as a broad crested weir with a rounded downstream portion which transcends into a straight section leading into a U.S. BUREC, Type VII, stilling basin. This latter stilling basin was required because of the low tailwater conditions found at this structure.

B. DISCHARGE MEASUREMENTS

The spillway crest was approximated by two flat sections instead of a smooth radii. Discharge estimates were not made according to a Bureau of Reclamation Design but that due to a broadcrested weir. As shown in Photo V–1 the backwater profile is typical for a broadcrested weir, with the depth near critical across the structure. U.S.G.S. Circ. 397, *Discharge Characteristics of Broad Crested Weirs*, was used to determine the discharge as a function of head at this structure. Two rating curves are presented in Fig V–3, one for a weir with a sloping front face, and one for a vertical front face. The Elk River spillway crest consists of a composite of these shapes, a small sloping front face, and then a vertical face cutting back slightly to a smooth vertical face. The two curves are presented to obtain an estimate of the effect this shape has on the discharge characteristics. The rating curve used was an average of these two rating curves. The error associated with this estimate for the discharge characteristics is the difference between the average curve and the other two discharge characteristic curves shown.

C. GAS TRANSFER MEASUREMENTS

Seven dissolved oxygen surveys were performed at this site: January 16, 1985, January 20, 1985, January 24, 1985, February 26, 1985, December 6, 1985, January 10, 1986, and January 31, 1986. The results from these surveys are presented in Tables V–1 through V–7. Sampling location maps are shown on Figures V–4 through V–10. Photographs of the flow over the spillway and ice formation are shown on Photographs V–1 through V–4.

The first two sampling dates listed, January 16 and 20, were initial investigations and not as detailed as latter testing. All of the latter sampling involved a larger number of samples to improve the accuracy of the results. Again as at the previous sites, the January and February 1985 sampling involved measurements from the ice upstream on either bank. The December 1985 – January 1986 measurements involved clearing the ice from the upstream crest of the spillway. This clearing, in general, improved the flow profile over the crest of the spillway, with fewer surface disturbances in the flow. In addition clearing enabled sampling the flow just before it passed over the spillway, as shown in Photo V–4.

An interesting anomaly was discovered in the January 31, 1986, measurements. Samples were collected at a number of different locations in the rapids area just downstream from the hydraulic jump. The difference between G4 and G7 was a slight rapids downstream from the hydraulic jump at G7. which was not at G4. In addition it was noted that G4 was upstream of a large rock in the flow and G5 was just downstream from this stone. A slight increase in D.O. was observed attributed to the flow over the stone.

TABLE V–1. Results of Elk River Site Survey, January 16, 1985

Atmospheric Pressure:	740.6 ± 0.1 mm of Hg
Water Temperature	0.5 ± 0.3 °C
Saturation Concentration	13.76 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	871.97 ± 0.03 ft
Downstream Water Surface Elevation	858.29 ± 0.05 ft
Headloss:	13.68 ± 0.05 ft
Head on Crest:	0.67 ± 0.03 ft
Discharge Crest Width:	1.51 ± 0.15 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi– ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Left Bank	5.89	4	.0075	.12	11.15	4	.100	.16	0.67	.03	5.5	~13

*Taken from the lowest point of the flip bucket, which was fully submerged.

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table V–I (Cont'd). Data from Elk River Site Survey, January 16, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
5.95	1:50	A1	Upstream Left Bank at Crest
5.95	1:50	A1	Upstream Left Bank at Crest
5.80	1:50	A1	Upstream Left Bank at Crest
5.85	2:00	A1	Upstream Left Bank at Crest
11.20	3:05	A2	Downstream Left Bank 5 ft from Old Powerhouse
11.20	3:05	A2	Downstream Left Bank 5 ft from Bank, 12 ft from Old Powerhouse
11.00	3:00	A2	Downstream Left Bank 5 ft from ;Bank, 13 ft from Old Powerhouse
11.20	3:00	A2	Downstream Left Bank 5 ft from Bank, 13 ft from Old Powerhouse

TABLE V–2. Results of Elk River Site Survey, January 20, 1985

Atmospheric Pressure:	742 ± 0.1 mm of Hg
Water Temperature:	0.2 ± 0.3 °C
Saturation Concentration;	13.87 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation	871.97 ± 0.03 ft
Downstream Water Surface Elevation	858.29 ± 0.05 ft
Static Head:	13.68 ± 0.05 ft
Head on Crest:	0.67 ± 0.03 ft
Discharge/ft. Crest width:	1.55 ± 0.1 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Left Bank	6.20	3	0.13	.35	11.1	4	.095	.15	.64	.04	5.5	~13

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table V–2 (Cont'd). Data from Elk River Dam Site Survey, January 20, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
6.05	12:00	B1	Left Bank Upstream of Crest, 1 ft from Observation Deck
6.25	12:00	B1	Left Bank Upstream of Crest, 1 ft from Observation Deck
6.30	12:20	B1	Left Bank Upstream of Crest, 2 ft from Observation Deck
11.05	12:45	B2	Left Bank Downstream Approximately 3 ft Deep
11.05	12:45	B2	Left Bank Downstream Approximately 3 ft Deep
11.25	14:00	B2	Left Bank Downstream Approximately 3 ft Deep
11.10	14:00	B2	Left Bank Downstream Approximately 3 ft Deep

TABLE V–3. Results of Elk River Site Survey, January 24, 1985

Atmospheric Pressure mm of Hg:	731.1 ± .1 mm of Hg
Water Temperature :	0.5 ± 0.3 °C
Saturation Concentration:	13.58 ± 0.28 mg $O^{\lambda}/1$
Upstream Water Surface Elevation :	871.94 ± 0.03 ft
Downstream Water Surface Elevation:	857.8 ± 0.05 ft
Headloss :	14.18 ± 0.05 ft
Head on Crest ft:	0.64 ± 0.03 ft
Discharge/ft. Crest width :	1.41 ± 0.1 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi– ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Overall	5.62	10	.279	.20	10.25	12	.229	.15	0.58	.03	5.0	13

LEGEND:
$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table V–3 (Cont'd). Data from Elk River Dam Site Survey, January 24, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
10.35	10:00	C1	Downstream Left Bank 3 ft deep 15 ft form Bank
10.50	10:00	C1'	Downstream Left Bank 3 ft deep 15 ft from Bank
10.25	10:10	C2	Downstream Left Bank 3 ft deep 50 ft from Bank
10.05	10:10	C2	Downstream Left Bank 3 ft deep 50 ft from Bank
10.70	10:20	C3	Downstream Left bank 3 ft deep, 33 ft from Bank
10.40	10:20	C3	Downstream Left Bank 3 ft deep, 33 ft from Bank
10.15	10:30	C4	Downstream Left Bank 3 ft deep, 24 ft from Bank
9.80	10:30	C4	Downstream Left Bank 3 ft deep, 24 ft from Bank
10.30	10:40	C5	Downstream Left Bank 1.5 ft deep, 14 ft from Bank
10.15	10:40	C5	Downstream Left Bank 1.5 ft deep, 14 ft from Bank
10.20	10:50	C6	Downstream Left Bank 1 ft deep, 5 ft from Bank
10.15	10:50	C6	Downstream Left Bank 1 ft deep, 5 ft from Bank
5.70	11:00	C7	Upstream Left Bank at Stage Gauge
5.65	11:00	C7	Upstream Left Bank at Stage Gauge
5.25	11:20	C8	Upstream Left Bank, 6 ft from Crest
5.35	11:20	C8	Upstream Left Bank, 6 ft from Crest
5.40	11:30	C9	Upstream Left Bank at Spillway Crest
5.40	11:30	C9	Upstream Left Bank at Spillway Crest
5.80	11:35	C10	Upstream Right Bank at Spillway Crest
6.20	11:35	C10	Upstream Right Bank at Spillway Crest
5.75	11:50	C10	Upstream Right Bank at Spillway Crest
5.65	11:50	C10	Upstream Right Bank at Spillway Crest

TABLE V–4. Results of Elk River Site Survey, February 26, 1985

Atmospheric Pressure:	743.75 ± 0.1 mm of Hg
Water Temperature:	1.5 ± 0.3 °C
Saturation Concentration:	13.43 ± 0.27 mgO_2/ℓ
Upstream Water Surface Elevation:	872.09 ± 0.03 ft
Downstream Water Surface Elevation:	860.00 ± 0.05 ft
Headloss:	12.090 ± 0.05 ft
Head on Crest :	0.79 ± 0.03 ft
Discharge/ft. Crest width :	1.95 ± 0.1 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	8.21	4	.048	.08	11.23	6	.071	.07	.58	.04	7.2	
Left Bank	7.44	4	.128	.20	11.0	4	.096	.15	.59	.04	7.2	
Right Spillway	8.25	2		.05	11.26	4	.025	.05	.58	.04	7.2	
	Mean for Site								0.58		0.03	7.2

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table V-4 (Cont'd). Data from Elk River Dam Site Survey, February 26, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
7.30	9:30	D1	Left Bank Upstream of Crest 1 ft in Depth
7.30	9:30	D1	Left Bank upstream of Crest 1 ft in Depth
7.60	9:45	D1	Left Bank Upstream of Crest 1 ft in Depth
7.40	9:45	D1	Left Bank Upsteam of Crest 1 ft in Depth
7.50	14:55	D1	Left Bank Upstream of Crest
7.55	14:55	D1	Left Bank Upstream of Crest
8.25	13:30	D3	Right Bank Mainspillway, Upstream of Crest
8.25	13:30	D3	Right Bank Mainspillway Upstream of Crest
8.20	13:40	D3	Right Bank Mainspillway, Upstream of Crest
8.15	13:40	D3	Right Bank Mainspillway Upstream of Crest
8.25	13:46	D4	Centerline Right Spillway Upstream
8.25	13:46	D4	Centerline Right Spillway Upsteam
11.25	14:02	D5	Right Spillway, Downstream in Jet 2 ft Down
11.25	14:02	D5	Right Spillway, Downstream in Jet 2 ft Down
11.30	14:27	D5	Right Spillway Downstream in Jet 3 ft Down
11.25	14:27	D5	Right Spillway, Downstream in Jet 3 ft Down
11.25	14:30	D6	Main Spillway, 10 ft from Right Bank
11.35	14:30	D6	Main Spillway 10 ft from Right Bank
11.20	14:45	D7	Just to the Right of First Bridge Pier, Left of Main Spillway
11.15	14:45	D7	Just to the Right of First Bridge Pier, Left of Main Spillway
11.10	14:50	D8	Spillway Center
11.20	14:50	D8	Spillway Center
11.00	10:00	D2	Left Bank Downstream 15 ft from the Shore
11.00	10:00	D2	Left Bank Downstream 15 ft from the Shore

TABLE V–5. Results of Elk River Site Survey, December 6, 1985

Atmospheric Pressure:	746.8 ± .1 mm of Hg
Water Temperature:	0.3 ± 0.3 °C
Saturation Concentration:	13.82 ± .28 mg O_2/ℓ
Upstream Water Surface Elevation:	872.16 ± .03 ft
Downstream Water Surface Elevation:	857.50 ± .05 ft
Headloss :	14.66 ± .05 ft
Head on Crest:	.86 ± .03 ft
Discharge/Unit Crest Width:	2.25 ± .1 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Overall	6.48	8	.119	.10	10.59	6	.067	.07	0.56	.03	4.7	~13

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table V–5 (Cont'd). Data from Elk River Dam Site Survey, December 6, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
6.55	10:00	E1	Upstream Left Bank 1 ft deep
6.55	10:00	E1	Upstream Left Bank 1 ft deep
6.55	10:10	E1	Upstream Left Bank 1 ft deep
6.50	10:20	E1	Upstream Left Bank 1 ft deep
6.30	10:20	E1	Upstream Left Bank 1 ft deep
6.40	10:30	E1	Upstream Left Bank 3 ft deep
6.35	10:35	E1	Upstream Left Bank 3 ft deep
6.65	10:40	E1	Upstream Left Bank 3 ft deep
10.50	11:30	E2	Downstream Center off of Bridge
10.65	11:30	E2	Downstream Center off of Bridge
10.55	11:45	E2	Downstream Center off of Bridge
10.65	11:45	E2	Downstream Center off of Bridge
10.65	11:50	E2	Downstream Center off of Bridge
10.55	11:50	E2	Downstream Center off of Bridge

Misc. Comments: The start of the aeration zone is approx. at elevation 862.7 ft

TABLE V–6. Results of Elk River Site Survey, January 10, 1986

Atmospheric Pressure:	729.4 ± .1 (mm of Hg)
Water Temperature:	0.5 ± 0.3 °C
Saturation Concentration:	13.54 ± 0.26 mg $O2/\ell$
Upstream Water Surface Elevation:	871.98 ± 0.03 ft
Downstream Water Surface Elevation:	856.98 ± 0.05 ft
Headloss:	15 ± 0.05 ft
Head on Crest:	0.68 ± 0.03 ft
Discharge/Unit Crest Width:	1.6 ± 0.10 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	4.16	4	.026	.05	9.90	4	.091	.14	0.61	.02	4.2	~13
Left Bank	4.01	4	.063	.10	9.55	4	.071	.11	0.58	0.2	4.2	
Center	4.20	4	.041	.07	9.61	4	.095	.15	0.58	.02	4.2	
	Mean for site								0.59	.02	4.2	~13

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table V–6 (Cont'd). Data from Elk River Dam Site Survey, January 10, 1986

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
4.00	13:11	F1	Left Bank on Crest .5 ft deep
3.95	13:11	F1	Left Bank on Crest .5 ft deep
4.00	13:15	F1	Left Bank on Crest .5 ft deep
4.10	13:15	F1	Left Bank on Crest .5 ft deep
4.25	13:20	F2	Center on Crest, .5 ft deep
4.20	13:20	F2	Center on Crest, .5 ft deep
4.20	13:25	F2	Center on Crest, .5 ft deep
4.15	13:25	F2	Center on Crest, .5 ft deep
4.20	13:32	F3	Right Bank on Crest, .5 ft deep
4.15	13:32	F3	Right Bank on Crest, .5 ft deep
4.15	13:35	F3	Right Bank on Crest, .5 ft deep
4.15	13:35	F3	Right Bank on Crest, .5 ft deep
9.50	13:48	F4	Approx. 3 ft from L.B. Pier on Right Side of Pier 1 – 2 ft deep.
9.65	13:48	F4	Approx. 3 ft from L.B. Pier on Right Side of Pier 1 – 2 ft deep.
9.50	13:50	F4	Approx. 3 ft from L.B. Pier on Right Side of Pier 1 – 2 ft deep
9.55	13:50	F4	Approx. 3 ft from L.B. Pier on Right Side of Pier 1 – 2 ft deep.
9.60	13:55	F5	Spillway Center, 1 – 2 ft deep
9.55	13:55	F5	Spillway Center, 1 – 2 ft deep
9.75	14:00	F5	Spillway Center, 1 – 2 ft deep
9.55	14:00	F5	Spillway Center, 1 – 2 ft deep
9.80	14:10	F6	Approx. 10 ft of Right Side of Spillway
9.85	14:10	F6	Approx. 10 ft of Right Side of Spillway
10.00	14:15	F6	Approx. 10 ft of Right Side of Spillway
9.95	14:15	F6	Approx. 10 ft of Right Side of Spillway

Misc. Comments: The start of the aeration zone is approx. at elev. 863.7 on the spillway, measured on Jan. 24, 1986.

TABLE V–7. Results of Elk River Site Survey, January 31, 1986

Atmospheric Pressure:	29.4 ± .1 mm of Hg
Water Temperature:	0.1 ± 0.3 °C
Saturation Concentration:	13.97 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	872.08 ± 0.03 ft
Downstream Water Surface Elevation:	857.25 ± 0.05 ft
Headloss:	14.83 ±.05 ft
Head on Crest:	0.78 ± 0.03 ft
Discharge/Unit Crest Width:	1.90 ± 0.15 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Efficiency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	5.00	4	.041	.07	10.16	6	.073	.08	0.58	.02	4.5	~13
Left Bank	4.95	4	.00	.05	9.1	4	0	.05	.54	.02	4.5	
Center	4.95	4	.00	.05	9.8	6	.061	.06	.55	.02	4.5	~13
	Mean for Site								.56	.02	4.5	~13

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table V–7. (Cont'd). Data from Elk River Dam Site Survey, January 31, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
4.95	11:05	G1	Left Bank on Crest, approx. 1 ft down
4.95	11:05	G1	Left Bank on Crest, approx. 1 ft down
4.95	11:10	G1	Left Bank on Crest, approx. 1 ft down
4.95	11:10	G1	Left Bank on Crest, approx. 1 ft down
5.00	11:15	G2	10 ft from Right Bank on Crest, 3.5 ft deep
5.05	11:15	G2	10 ft form Right Bank on Crest, 3.5 ft deep
4.95	11:20	G2	10 ft from Right Bank on Crest, 3.5 ft deep
5.00	11:20	G2	10 ft from Right Bank on Crest, 3.5 ft deep
4.95	11:23	G3	Center on the Crest, approx. 1.5 ft deep
4.95	11:23	G3	Center on the Crest, approx. 1.5 ft deep
4.95	11:27	G3	Center on the Crest, approx. 1.5 ft deep
4.95	11:27	G3	Center on the Crest, approx. 1.5 ft deep
10.15	11:50	G4	Right Bank Downstream in Rapids (see map)
10.10	11:50	G4	Right Bank Downstream in Rapids (see map)
10.10	11:55	G4	Right Bank Downstream in Rapids (see map)
10.10	11:55	G4	Right Bank Downstream in Rapids (see map)
10.25	12:00	G5	Right Bank Downstream in Rapids (see map)
10.25	12:00	G5	Right Bank Downstream in Rapids (see map)
9.95	12:05	G6	Downstream Right of Center (see map)
9.90	12:05	G6	Downstream Right of Center (see map)
9.90	12:07	G6	Downstream Right of Center (see map)
9.90	12:07	G6	Downstream Right of Center (see map)
9.80	12:20	G8	Downstream Right of Center (see map)
9.80	12:20	G8	Downstream Right of Center (see map)
9.80	12:10	G7	Downstream Left Bank (see map)
9.80	12:10	G7	Downstream Left Bank (see map)
9.80	12:15	G7	Downstream Left Bank (see map)
9.80	12:15	G7	Downstream Left Bank (see map)

Misc. Comments: The start of the aeration zone is at elevation 864.37 on the spillway.

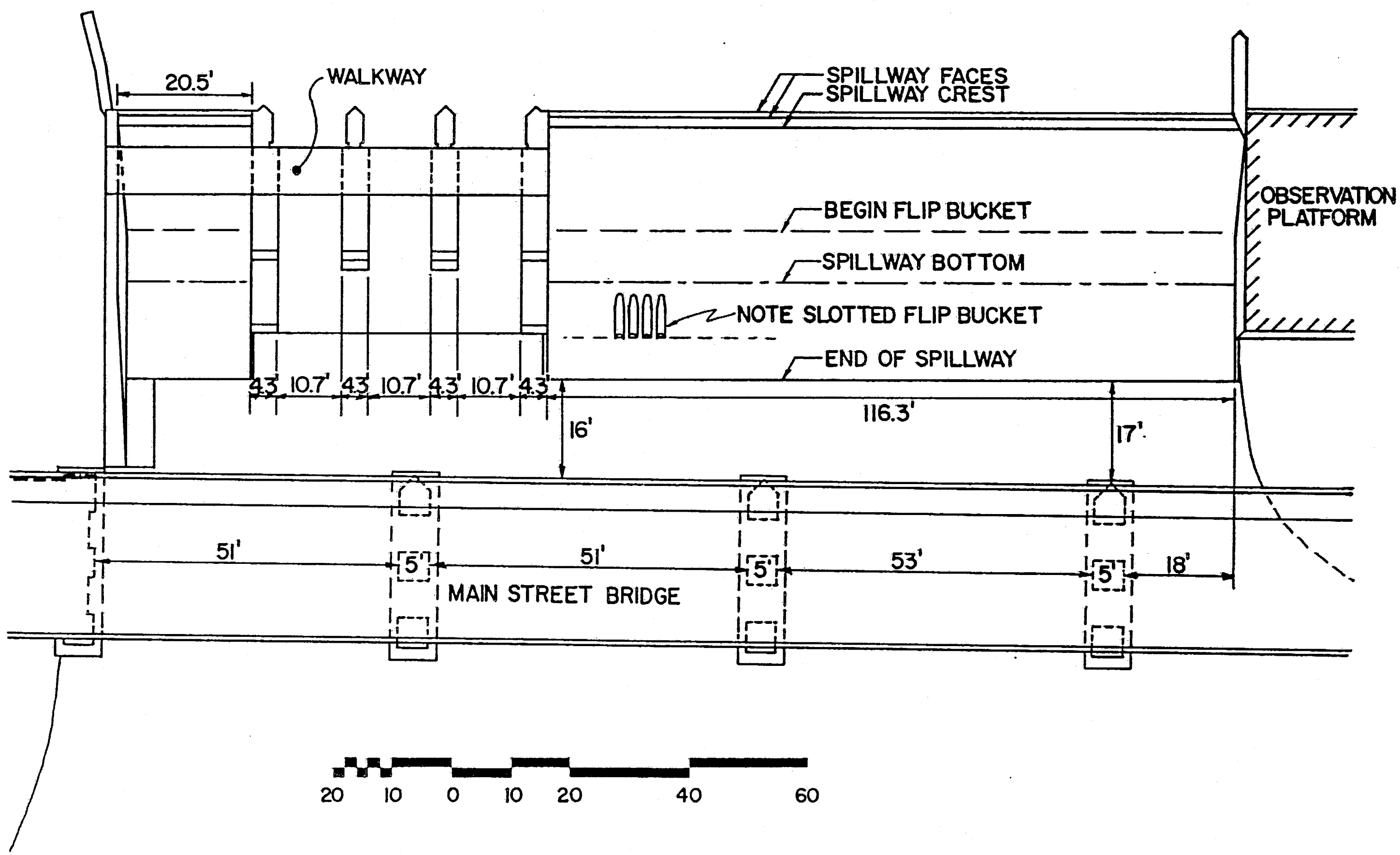


Fig. V–1. Plan of Elk River Dam.

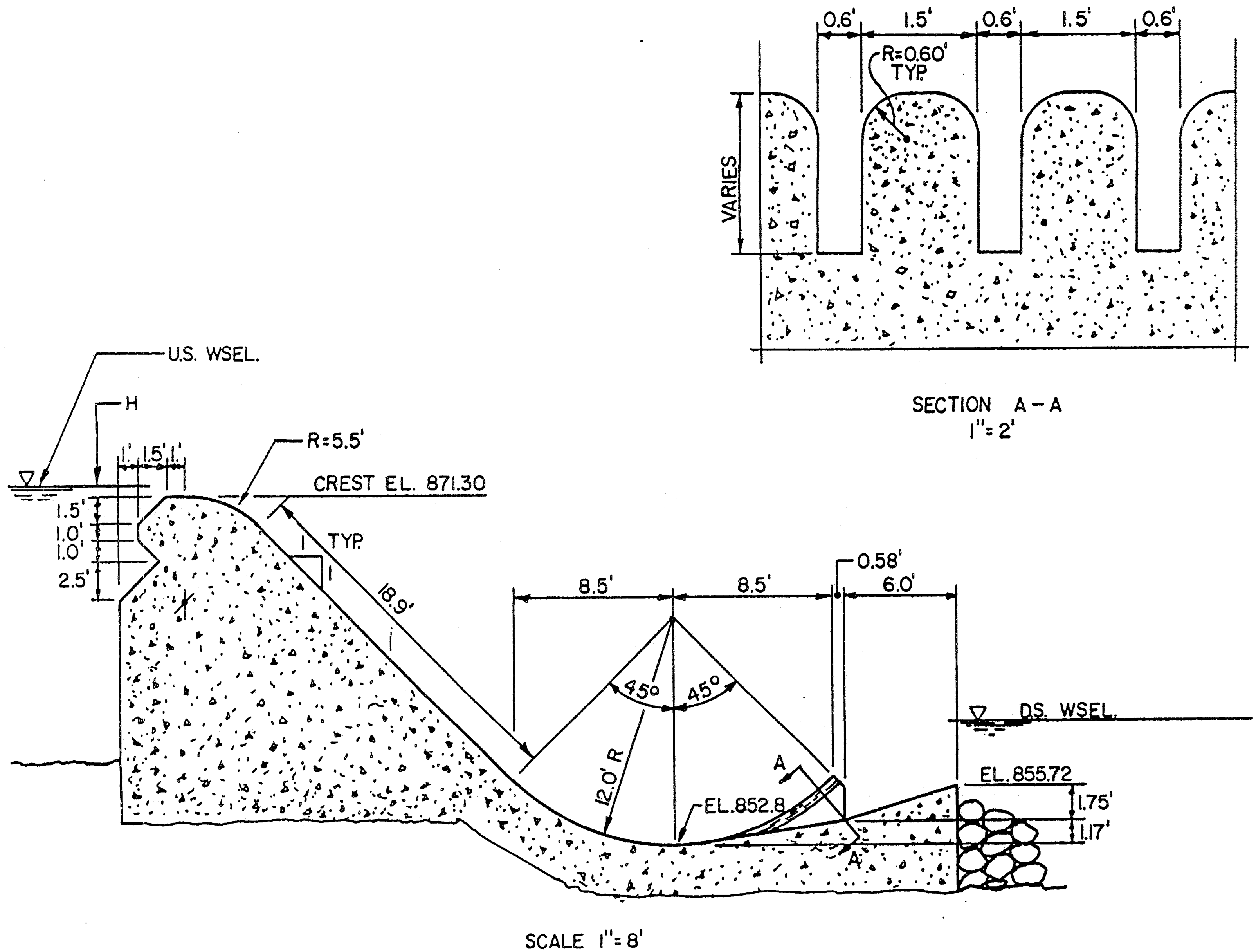


Fig. V–2. Elk River Main Spillway cross section.

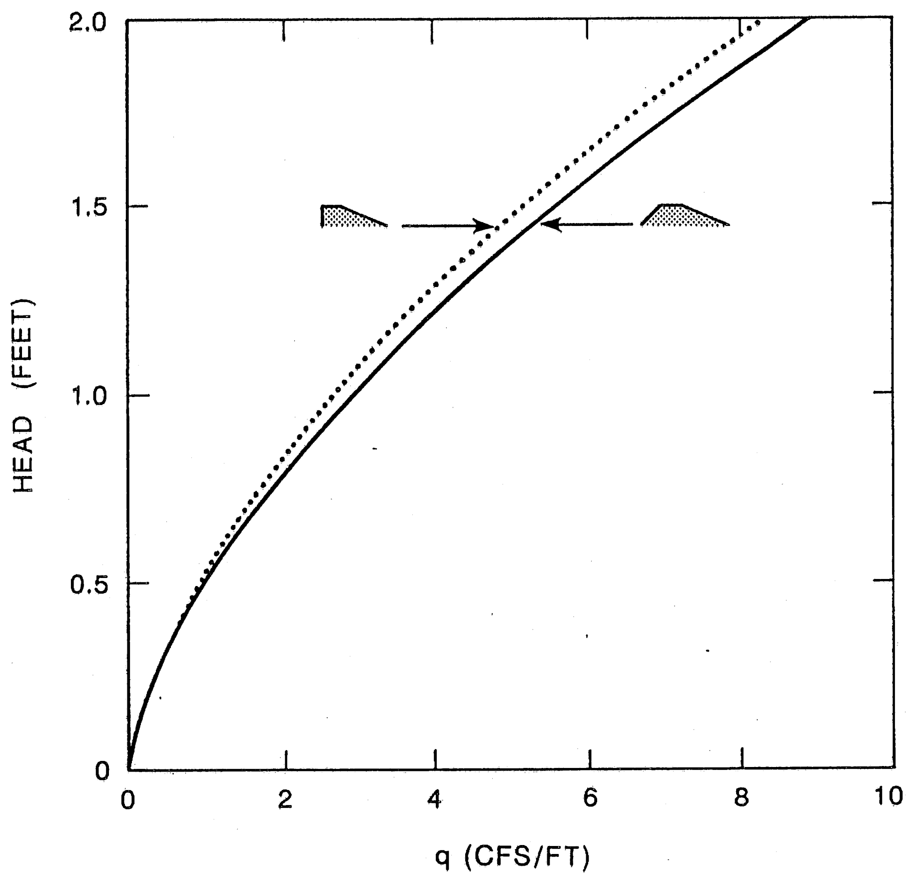


Fig. V–3. Discharge rating curves for broad crested weirs demonstrating discharge variation with upstream face.

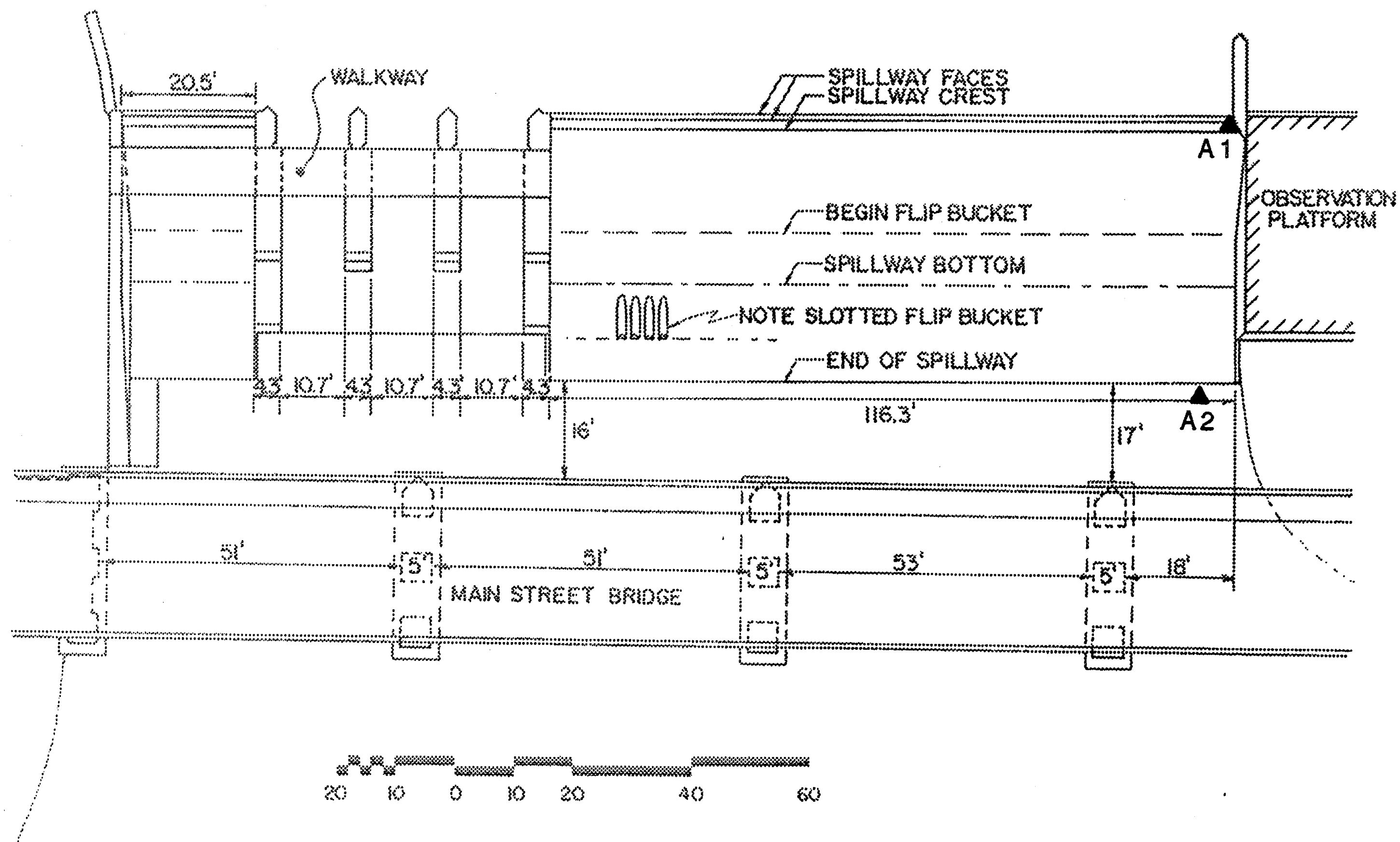


Fig. V–4. Plan view, January 16, 1985, sampling locations.

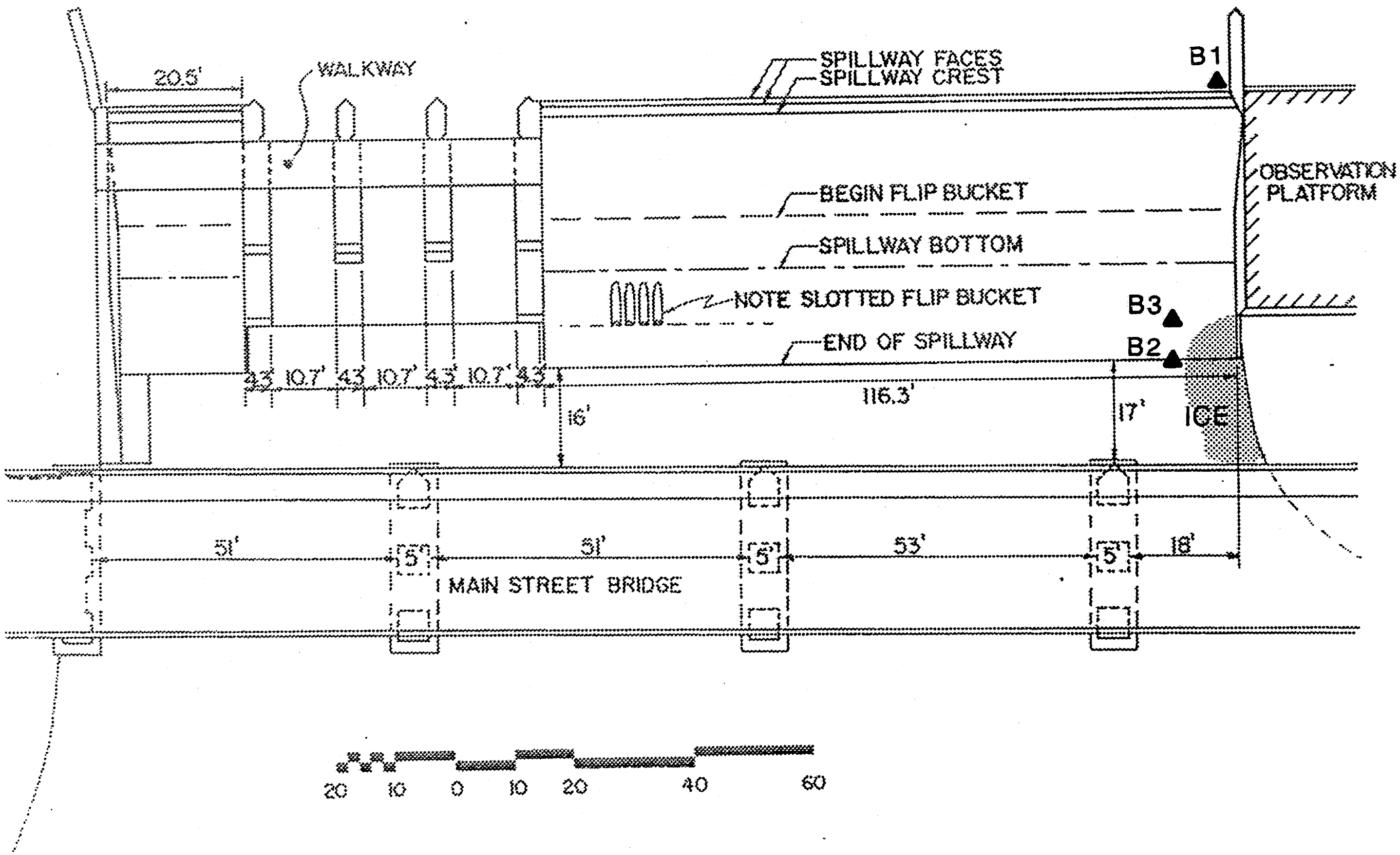


Fig. V–5. Plan view, January 20, 1985, sampling locations.

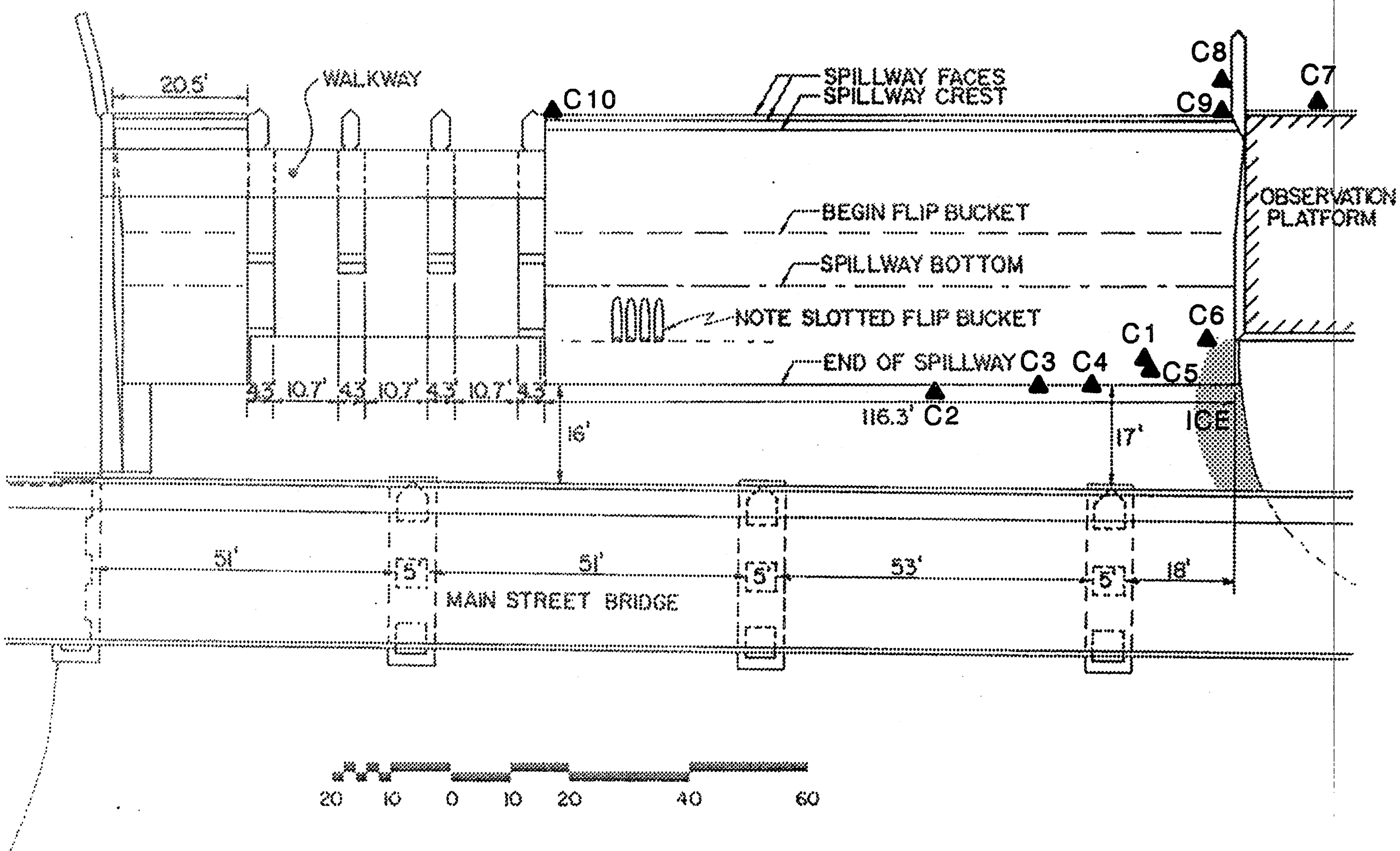


Fig. V–6. Plan view, January 24, 1985, sampling locations.

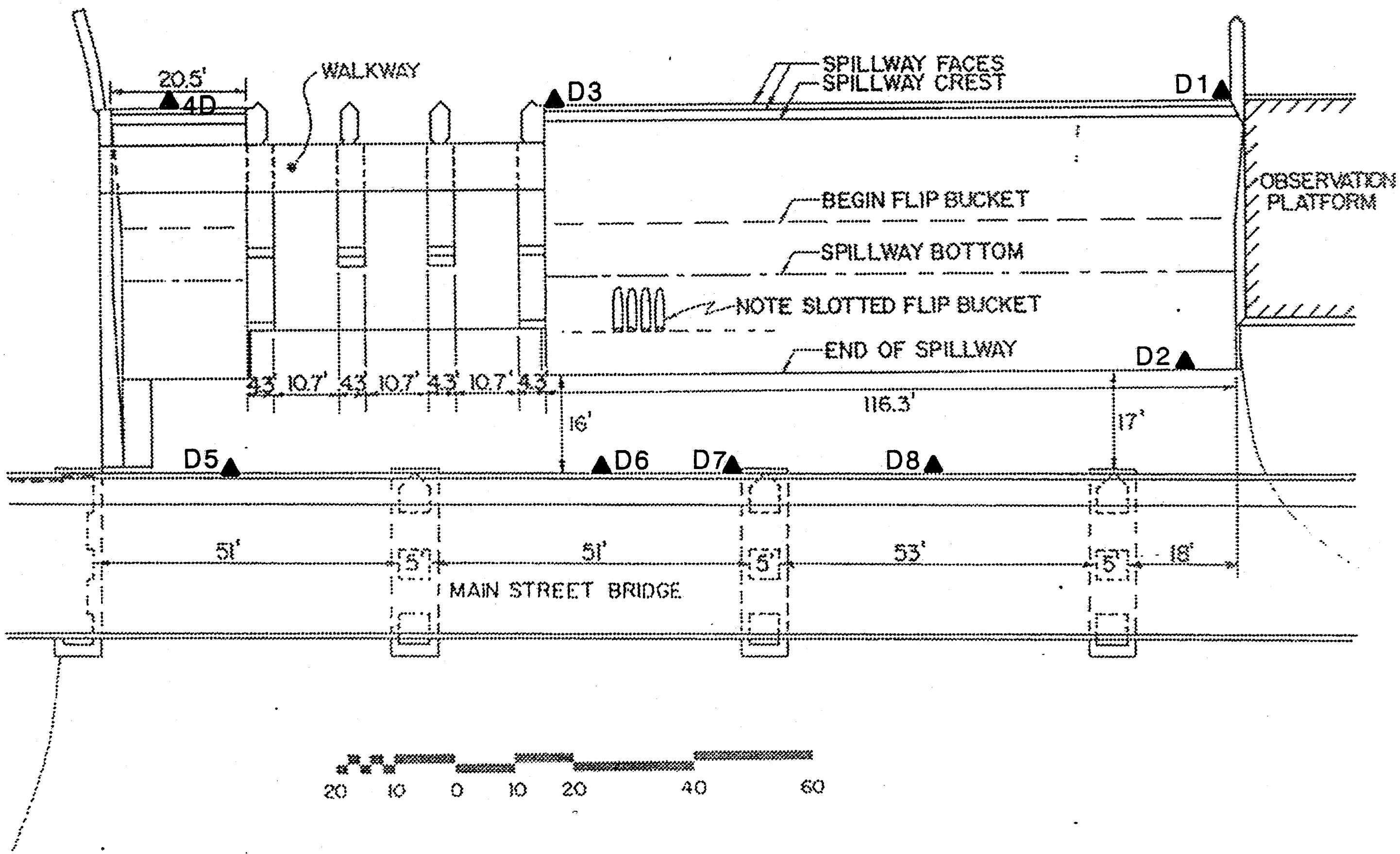


Fig. V–7. Plan view, February 26, 1985, sampling locations.

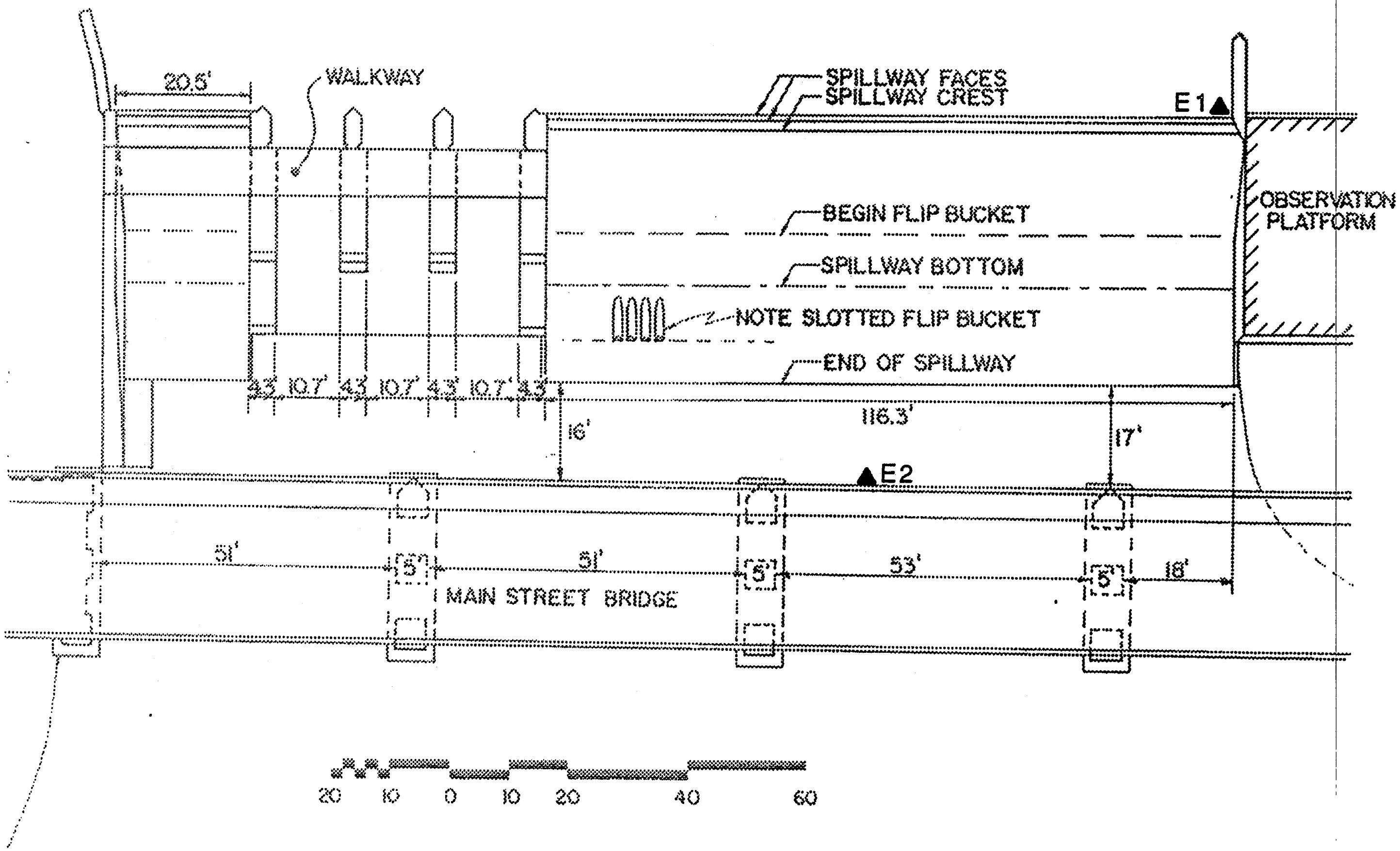


Fig. V–8. Plan view, December 6, 1985, sampling locations.

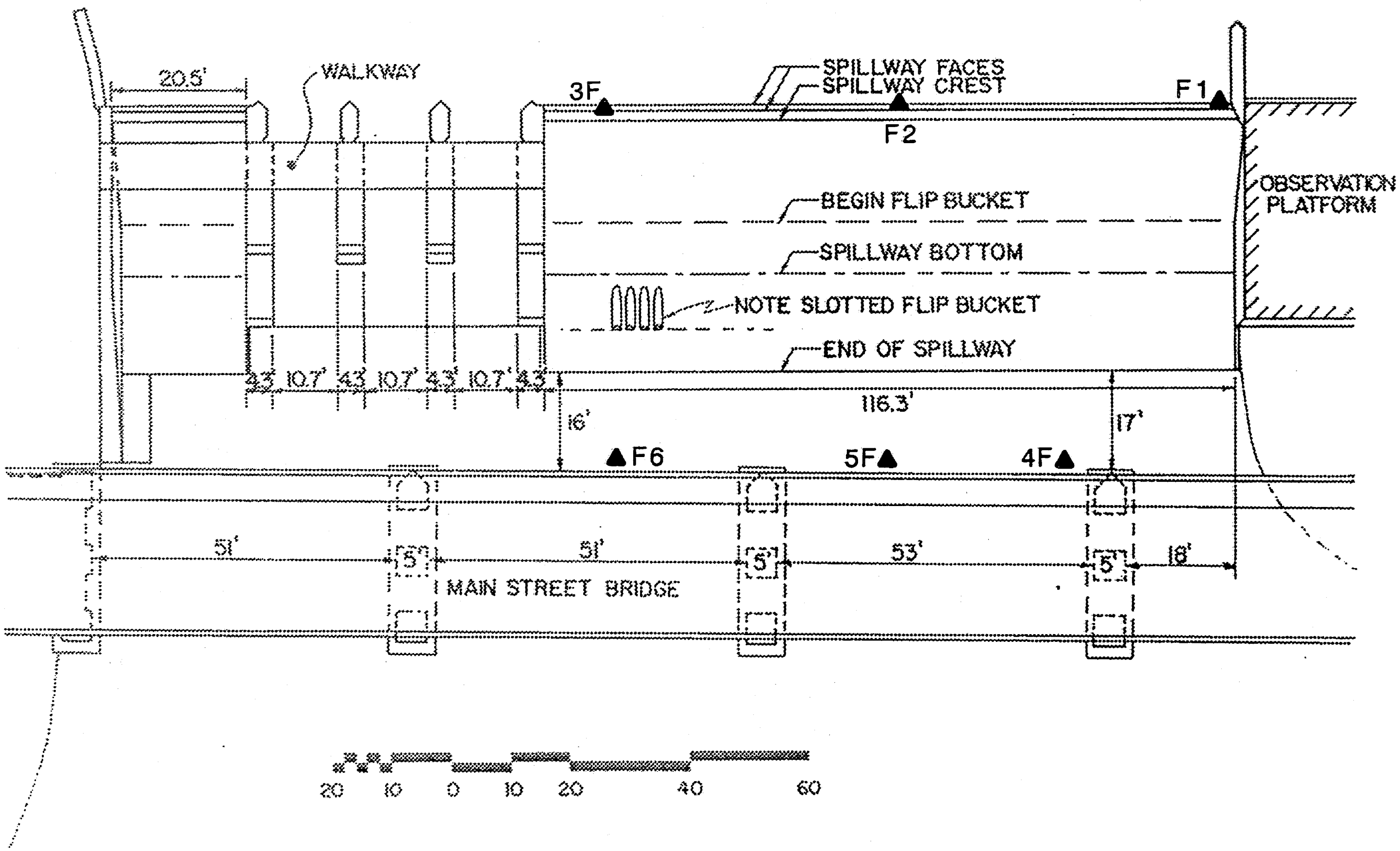


Fig. V–9. Plan view, January 10, 1986, sampling locations.

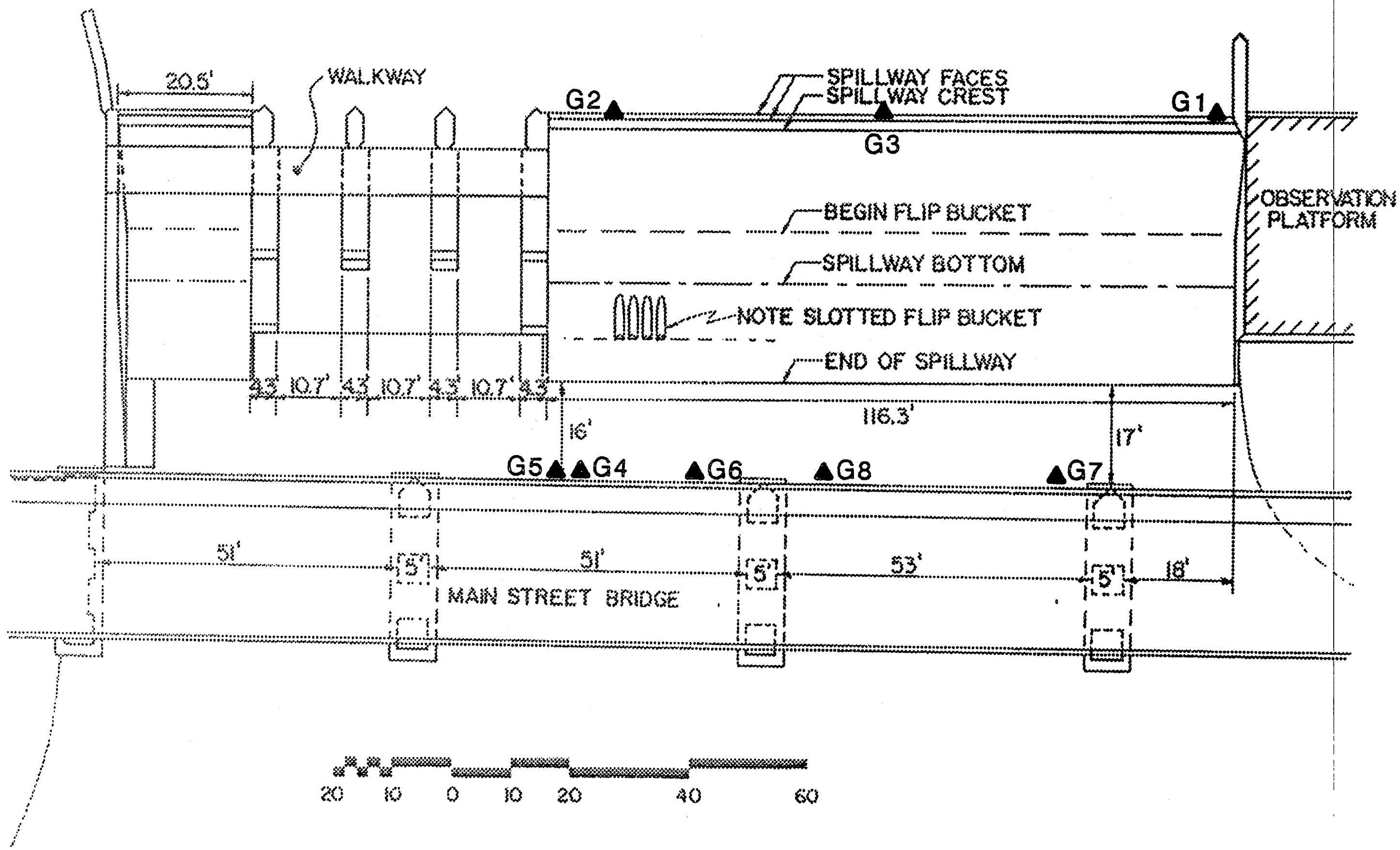


Fig. V–10. Plan view, January 31, 1986, sampling locations.

Photo V–1. Elk River Dam, January 10, 1986, right bank upstream sampling location.

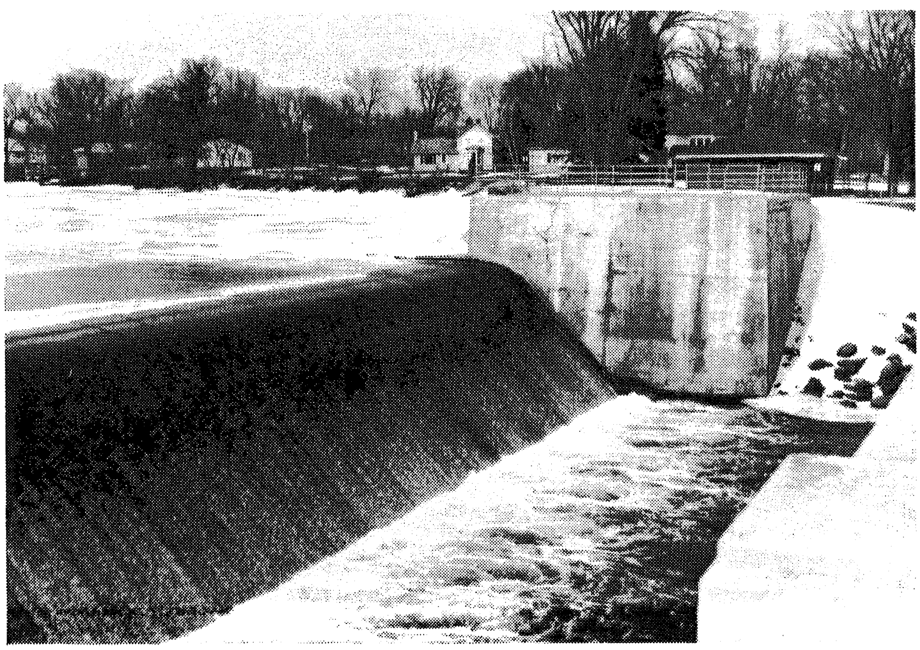


Photo V–2. Elk River Dam, February 26, 1985, left bank upstream and downstream sampling location.

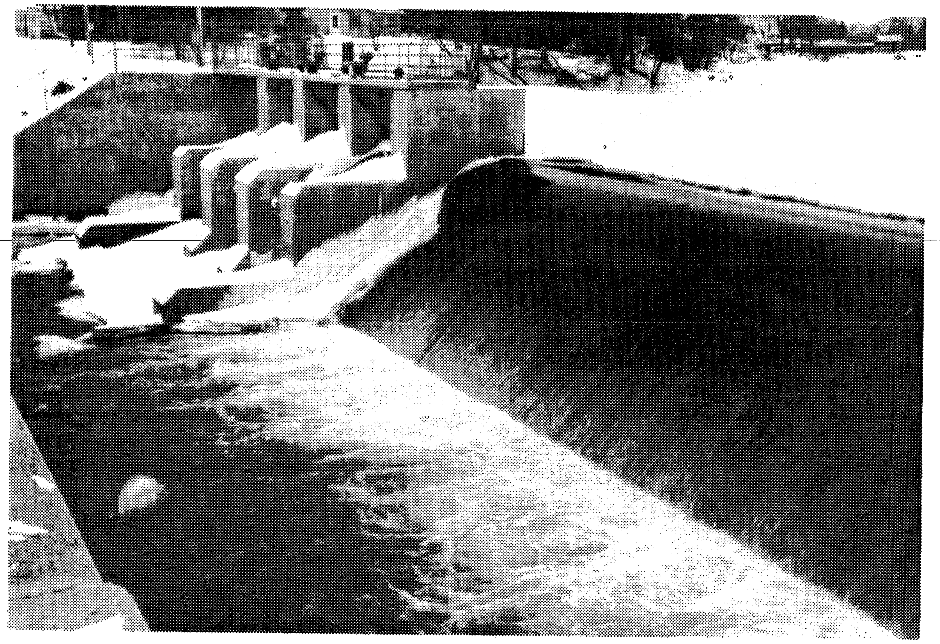


Photo V–3. Elk River Dam, January 31, 1986, right bank sampling location.

Photo V–4. Elk River Dam, January 10, 1986, location F2 upstream sampling. Note: The jagged ice edge the result of ice clearing from spillway crest.

VI. FARIBAULT WOOLEN MILL DAM

A. PHYSICAL DESCRIPTION

The Faribault Woolen Mill Dam is an earthen dam flanked by a north gated control structure, and a south fixed crest gravity spillway. The dam is located on the Cannon River just upstream of Second Avenue bridge over the Cannon River in the City of Faribault, Minnesota. At one time this dam supplied water power to the Faribault Woolen Mill, adjacent to the fixed gravity spillway, but today the dams purpose is to serve as a source of cooling water for the adjacent Woolen Mill and maintain a small reservoir for recreational purposes.

The structure of interest for this study was the south fixed crest gravity spillway. The south spillway illustrated in plan in Fig VI–1 and shown in section view in Fig VI–2 consists of a broadcrested weir, sloped spillway and flip bucket stilling basin. The crest elevation was assumed to be 100.0 ft and found to have a measured variability of ±.05 ft. The site was surveyed with all elevations related to spillway crest. The concrete surfaces are in good shape with the water flowing smoothly over the crest. As normally found on concrete surfaces with flowing water considerable biological growth was found fixed to the surface of the spillway crest. This growth was measured to be approximately .05 feet thick but did not extend down the face of the spillway.

B. DISCHARGE MEASUREMENTS

Since the crest of the dam is flat, the flow over the crest of the spillway behaves like flow over a broad crested weir. This flow is predominantly at critical depth across the spillway, and the specific discharge can be estimated by

$$q = \frac{2}{3} H \sqrt{\frac{2}{3} gh}$$

which can also be written as

$$q = 3.088H^{3/2}$$

where H is the height of the reservoir water surface above the spillway crest. This equation is valid for a frictionless weir, however, for a weir with frictional loss there is a definite boundry layer growth. Considering the variation due to biological growth and other physical ambiguities, such as variation in crest elevation, crest roughness, etc. the above equation should yield an acceptable estimate of the discharge characteristics of the structure.

C. Gas Transfer Measurements

Four dissolved oxygen surveys were performed at this site: January 26, 1985, March 7, 1985, December 17, 1985 and February 28, 1986. The results from these surveys are presented in Tables VI–1, through VI–4. The locations of the sampling stations is given in Fig. VI–3 through Fig. VI–8. Spillway aeration is shown in Photos VI–2 and VI–3. Both overall spillway and actual spillway gas transfer were investigated at this structure. The structure, because of the limited discharge and low head, allowed positioning to obtain measurements just downstream on the face of the dam, as shown in Photo VI–3.

To better define the cross section of the dam, the face of the dam was surveyed on Dec. 17, 1985. This survey indicated the face of the dam was located on an angle from vertical of approximately 21 degrees.

Spillway measurements were collected according to the procedures described in Section I. Photograph VI–3 shows the spillway sampler in use, immediately before sample collection.

TABLE VI–1. Results Faribault Woolen Mill Site Survey January 26, 1985

Atmospheric Pressure:	738.65 ± 0.01 mm of Hg
Water Temperature:	0.8 ± 0.30 °C
Saturation Concentration:	13.99 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	100.45 ± 0.03 ft
Downstream Water Surface Elevation:	91.38 ± 0.05 ft
Headloss:	9.07 ± 0.05
Head on Crest:	.45 ± .03
Discharge/Unit Crest Width:	.93 ± .10 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Hydr. Jump	10.48	4	.065	.10	12.08	6	.035	.05	0.42	.04		
Left Bank	10.48	4	.065	.10	11.55	6	.089	.09	0.28	.04	1.0	~6

*Tailwater Depth taken to bottom of flip bucket, EL 90.37.

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table VI–1 (Cont'd). Data from Faribault Woolen Mill Dam, January 26, 1985

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
~~10.30~~	~~12:00~~	~~A1~~	~~Upstream Weir Face 40 ft from Right Bank~~
10.30	12:00	A1	Upstream Weir Face 40 ft from Right Bank
10.40	NR	A2	Upstream Weir Face 6 ft from Right Bank
10.40	NR	A2	Upstream Weir Face 6 ft from Right Bank
10.55	NR	A3	Upstream Weir Face 40 ft from Left Bank
10.40	NR	A3	Upstream Weir Face 40 ft from Left Bank
10.50	NR	A4	Upstream Weir Face 6 ft from Left Bank
10.45	NR	A4	Upstream Weir Face 6 ft from Left Bank
11.55	NR	A5	Downstream 7 ft from Dam, 40 ft from Left Bank
11.50	NR	A5	Downstream 7 ft from Dam, 40 ft from Left Bank
11.70	NR	A6	Downstream 7 ft from Dam, 20 ft from Left Bank
11.60	NR	A6	Downstream 7 ft from Dam, 20 ft from Left Bank
11.50	NR	A7	Downstream 6 ft from Dam, 10 ft from Left Bank
11.45	NR	A7	Downstream 6 ft from Dam, 10 ft from Left Bank
12.10	1:30	A8	In Hydraulic Jump, 10 ft from Left Bank
12.05	1:30	A8	In Hydraulic Jump, 10 ft form Left Bank

NR = Not recorded

TABLE VI–2. Results Faribault Woolen Mill Site Survey, March 7, 1985

Atmospheric Pressure:	737.75 ± 0.01 mm of Hg
Water Temperature:	1.7 ± 0.30 °C
Saturation Concentration:	13.25 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	100.59 ± 0.03 ft
Downstream Water Surface Elevation:	91.99 ± 0.05 ft
Headloss:	8.6 ± 0.05 ft
Head on Crest:	0.58 ± 0.03 ft
Discharge/ft Gate Width:	1.36 ± 0.10 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Overall	11.19	4	.069	.11	11.88	6	.054	.06	.33	.07	1.6	~6

*Taken to bottom of flip bucket, EL 90.37

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table VI–2 (Cont'd). Data from Faribault Woolen Mill Dam, March 7, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
11.20	9:25	B1	Left Bank Upstream Face of Spillway, near Water Surface
11.20	9:25	B1	Left Bank Upstream Face of Spillway, near Water Surface
11.10	9:30	B2	Center, Upstream Face of Spillway, near Water Surface
11.20	9:30	B2	Center, Upstream Face of Spillway, near Water Surface
11.20	9:35	B3	Right Bank Upstream Face of Spillway, near Water Surface
11.30	9:40	B2	Center Upstream Face of Spillway Approx. 3 ft Deep
11.10	9:40	B2	Center Upstream Face of Spillway Approx. 3 ft Deep
11.80	9:45	B4	Recirculation Zone Near Spillway
12.00	9:45	B4	Recirculation Zone Near Spillway
11.75	10:00	B5	15 ft from Spillway, 15 ft from Left Bank
11.85	10:00	B5	15 ft from Spillway, 15 ft from Left Bank
11.90	10:05	B6	10 ft from Spillway, Center of Spillway
11.90	10:05	B6	10 ft from Spillway, Center of Spillway
11.90	10:10	B7	6 ft from Spillway, Center of Spillway
11.90	10:10	B7	6 ft from Spillway, Center of Spillway
11.90	10:15	B8	10 ft from Spillway, 15 ft from Right Bank
11.85	10:15	B8	10 ft from Spillway, 15 ft from Right Bank
11.85	10:25	B9	3–4 ft from Spillway, 20 ft from Left Bank
11.95	10:25	B9	3–4 ft from Spillway, 20 ft from Left Bank
11.40	10:35	B10	1.5 ft from Water Surface on the Spillway Face
11.50	10:35	B10	1.5 ft from Water Surface on the Spillway Face
11.40	10:35	B10	1.5 ft from Water Surface on the Spillway Face
11.30	10:45	B11	10:45 3 ft from Water Surface on the Spillway Face
11.30	10:45	B11	3 ft from Water Surface on the Spillway Face
11.90	10:50	B12	40 ft from Spillway, 30 ft from Left Bank
12.10	10:50	B12	10:50 40 ft from Spillway, 30 ft from Left Bank
11.90	11:00	B13	11:00 Off of Right Bank Retaining Wall approx. 100 ft Downstream
12.00	11:00	B13	Off of Right Bank Retaining Wall approx. 100 ft Downstream

TABLE VI–3. Results of Faribault Woolen Mill Site Survey, December 17, 1985

Atmospheric Pressure:	744.2 ± 0.01 mm of Hg
Water Temperature:	0.2 ± 0.30 °C
Saturation Concentration:	13.91 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	100.50 ± 0.03 ft
Downstream Water Surface Elevation:	91.55 ± 0.05 ft
Headloss:	8.95 ± 0.05 ft
Head on Crest:	0.5 ± 0.03 ft
Discharge/ft crest width:	1.09 ± 0.10 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Efficiency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Overall	10.0	12	0.05	.05	11.46	6	.055	.06	0.37	.03	1.2	6
Sp. F. El.	10.0	12	0.05	.05	10.20	5	.061	.08	0.05	.02	NA	0
Sp. F. El.	10.2	5	.045	.06	10.42	5	.045	.06	0.05	.02	NA	6

*Taken to bottom of flip bucket, EL 90.37

*LEGEND:
$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table VI–3 (Cont'd). Data from Faribault Woolen Mill Dam, Dec. 17, 1985

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
11.30	12:15	C1	Left Bank Downstream, 7 ft from Left Bank
11.20	12:15	C1	Left Bank Downstream, 7 ft from Left Bank
11.10	12:20	C1	Left Bank Downstream, 7 ft from Left Bank
11.10	12:20	C1	Left Bank Downstream, 7 ft from Left Bank
11.10	12:25	C1	Left Bank Downstream, 7 ft from Left Bank
11.10	12:25	C1	Left Bank Downstream, 7 ft from Left Bank
11.40	12:30	C2	Downstream 1/3 of Distance Across the Spillway
11.45	12:32	C2	Downstream 1/3 of Distance Across the Spillway
11.45	12:32	C2	Downstream 1/3 of Distance Across the Spillway
11.55	12:35	C2	Downstream 1/3 of Distance Across the Spillway
11.45	12:35	C2	Downstream 1/3 of Distance Across the Spillway
10.00	13:00	C3	Upstream Left Bank, 7 ft from the Left Bank
9.95	13:00	C3	Upstream Left Bank, 7 ft from the Left Bank
10.05	13:05	C3	Upstream Left Bank, 7 ft from the Left Bank
10.00	13:05	C3	Upstream Left Bank, 7 ft from the Left Bank
10.00	13:10	C3	Upstream Left Bank, 7 ft from the Left Bank
10.00	13:10	C3	Upstream Left Bank, 7 ft from the Left Bank
9.95	13:10	C4	Upstream 1/3 of Distance Across the Spillway
9.90	13:10	C4	Upstream 1/3 of Distance Across the Spillway
10.10	13:13	C4	Upstream 1/3 of Distance Across the Spillway
10.00	13:13	C4	Upstream 1/3 of Distance Across the Spillway
10.00	13:20	C4	Upstream 1/3 of Distance Across the Spillway
10.00	13:20	C4	Upstream 1/3 of Distance Across the Spillway

Table VI–3 (Cont'd). Data from Faribault Woolen Mill Dam, Dec. 17, 1985

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
11.15	14:30	C5	Downstream Left Bank in Hydraulic Jump
11.20	14:30	C5	Downstream Left Bank in Hydraulic Jump
10.25	14:50	C6	Spillway Sample at Elev. 95.95
10.10	14:50	C6	Spillway Sample at Elev. 95.95
10.25	14:50	C6	Spillway Sample at Elev. 95.95
10.20	14:50	C6	Spillway Sample at Elev. 95.95
10.20	14:50	C6	Spillway Sample at Elev. 95.95
10.40	15:10	C7	Spillway Sample 3 in. above D.S. Stage.
10.40	15:10	C7	Spillway Sample 3 in. above D.S. Stage.
10.40	15:10	C7	Spillway Sample 3 in. above D.S. Stage.
10.40	15:10	C7	Spillway Sample 3 in. above D.S. Stage.
10.50	15:10	C7	Spillway Sample 3 in. above D.S. Stage.

TABLE VI–4. Results from Faribault Woolen Mill Site Survey, February 28, 1986

Atmospheric Pressure:	744.3 ± .01 mm of Hg
Water Temperature:	0.2 ± 0.30 °C
Saturation Concentration:	13.95 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	100.43 ± 0.03 ft
Downstream Water Surface Elevation:	91.40 ± 0.05 ft
Headloss:	9.03 ± 0.05 ft
Head on Crest:	0.43 ± 0.03 ft
Discharge/ft. Crest width:	0.87 ± 0.10 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	8.64	8	.088	.07	10.94	8	.088	.07	0.43	.03	1.0	6
Left Bank	8.91	17	.064	.05	8 91	17	.064	.05	0.05	.02	N/A	0
Sp.F. El.92.3	8.91	17	.064	.05	9.33	6	.041	.05	0.08	.02	N/A	6

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Sp. F. El. = Spillway Face Sampling Location Elevation (ft)

Table VI–4 (Cont'd). Data from Faribault Woolen Mill Dam, Feb. 28, 1986

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
10.90	11:45	D1	Downstream 20 ft from Left Bank
10.80	11:45	D1	Downstream 20 ft from Left Bank
10.90	11:50	D2	Downstream 23 ft from Left Bank
11.10	11:50	D2	Downstream 23 ft from Left Bank
10.95	11:55	D2	Downstream 23 ft from Left Bank
11.00	12:00	D2	Downstream 23 ft from Left Bank
8.95	12:10	D3	Spillway Face at Elevation 97.47
8.90	12:10	D3	Spillway Face at Elevation 97.47
8.95	12:13	D3	Spillway Face at Elevation 97.47
8.95	12:13	D3	Spillway Face at Elevation 97.47
8.90	12:15	D3	Spillway Face at Elevation 97.47
8.80	12:18	D4	Spillway Face at Elevation 95.67 ft
8.80	12:18	D4	Spillway Face at Elevation 95.67 ft
8.90	12:20	D4	Spillway Face at Elevation 95.67 ft
8.85	12:20	D4	Spillway Face at Elevation 95.67 ft
8.90	12:21	D4	Spillway Face at Elevation 95.67 ft
8.80	12:21	D4	Spillway Face at Elevation 95.67 ft
8.95	12:35	D5	Spillway Face at Elevation 91.27 ft
8.95	12:35	D5	Spillway Face at Elevation 91.27 ft
9.00	12:35	D5	Spillway Face at Elevation 91.27 ft
8.95	12:35	D5	Spillway Face at Elevation 91.27 ft
9.00	12:35	D5	Spillway Face at Elevation 91.27 ft
8.90	12:35	D5	Spillway Face at Elevation 91.27 ft
10.90	12:40	D6	Downstream of Spillway ≃ 10 ft from Left Banks.
10.95	12:40	D6	Downstream of Spillway ≃ 10 ft from Left Banks.
8.75	12:50	D7	Upstream From D.S. Sampling Location Dam Center
8.75	12:50	D7	Upstream From D.S. Sampling Location Dam Center
8.65	12:55	D8	Upstream From Left Bank Samplin Location
8.60	12:55	D8	Upstream From Left Bank Samplin Location
8.65	14:00	D9	Upstream at 2/3 dist. to Center Location
8.65	14:00	D9	Upstream at 2/3 dist. to Center Location
8.55	12:55	D10	Upstream at 1/3 dist. to Center Location
8.50	12:55	D10	Upstream at 1/3 dist. to Center Location
8.90	13:20	D5	Spillway Face at Elevation 91.27 ft, just off Left Bank
8.95	:	D5	Spillway Face at Elevation 91.27 ft, just off Left Bank
8.80	:	D5	Spillway Face at Elevation 91.27 ft, just off Left Bank

Table VI–4 (Cont'd). Data from Faribault Woolen Mill Dam, Feb. 28, 1986

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
8.95	:	D5	Spillway Face at Elevation 91.27 ft, just off Left Bank
8.80	:	D5	Spillway Face at Elevation 91.27 ft, just off Left Bank
8.90	13:20	D3	Spillway Face at Elevation 91.27 ft, just off Left Bank
9.40	13:55	D11	Spillway Face at Elevation 91.27 10 ft from Left Bank (see note)
9.30	:	D11	Spillway Face at Elevation 91.27 ft, 10 ft from Left Bank (see note)
9.30	:	D11	Spillway Face at Elevation 91.27 ft, 10 ft from Left Bank (see note)
9.35	:	D11	Spillway Face at Elevation 91.27 ft, 10 ft from Left Bank (see note)
9.30	:	D11	Spillway Face at Elevation 91.27 ft, 10 ft from Left Bank (see note)
9.35	14:05	D11	Spillway Face at Elevation 91.27 ft 10 ft from Left Bank (see note)

Misc. Comments: D11 was taken in an area of greater aerated flow.

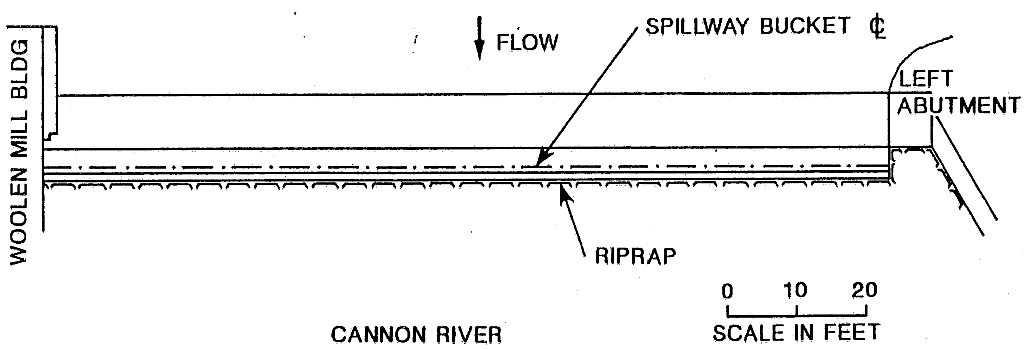


Fig. VI–1. Plan of Faribault Woolen Mill south fixed crest gravity spillway.

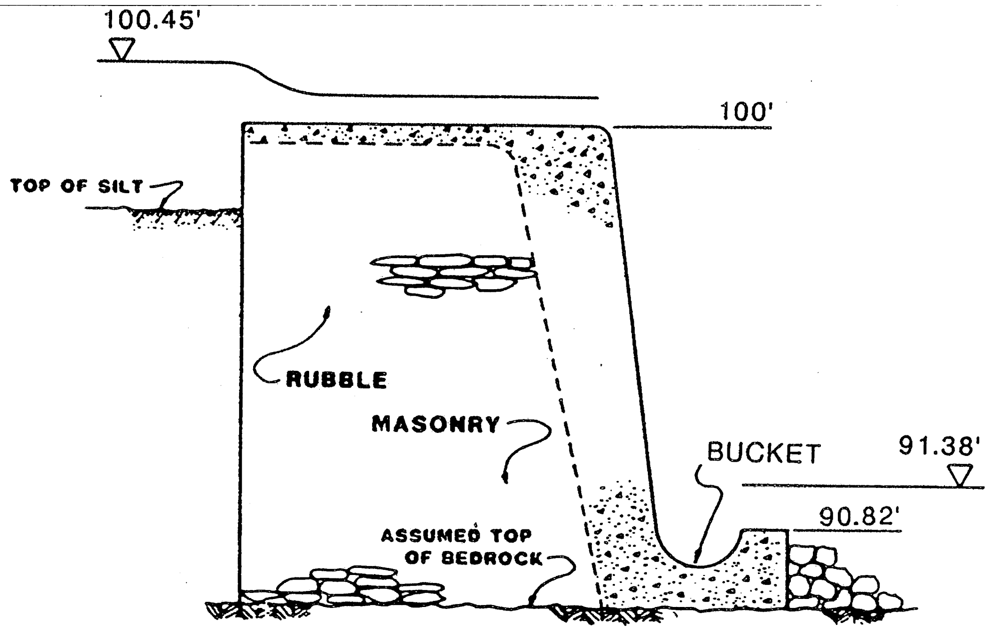


Fig. VI–2. Faribault Woolen Mill Dam spillway cross section with January 26, 1985, water levels.

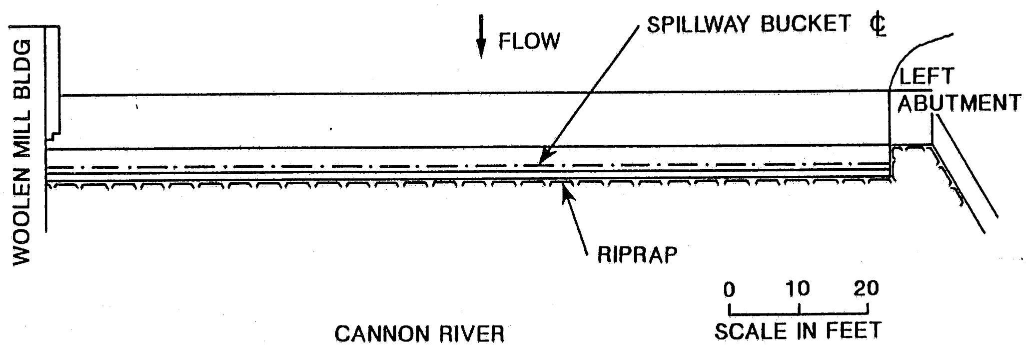


Fig. VI–3. Plan view, January 26, 1985, sampling locations.

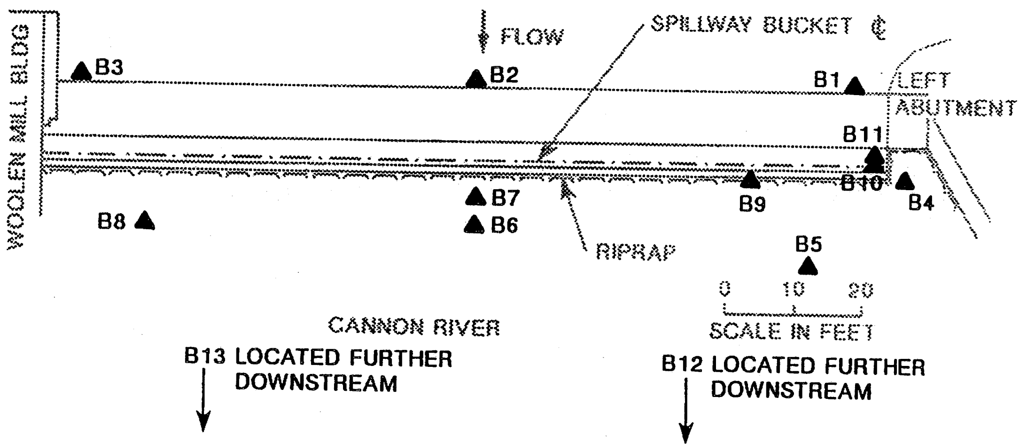


Fig. VI–4. Plan view, January 24, 1986, sampling locations.

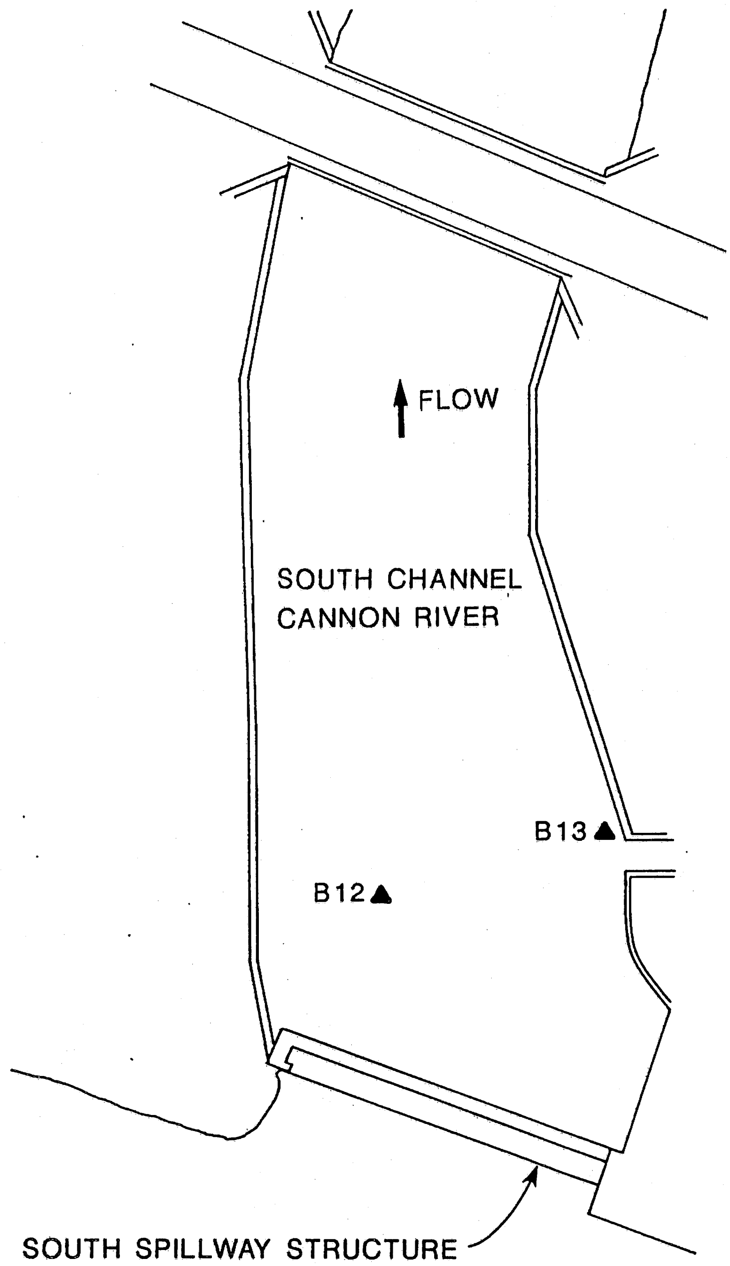


Fig. VI–5. Plan view of March 7, 1985, additional downstream sampling locations.

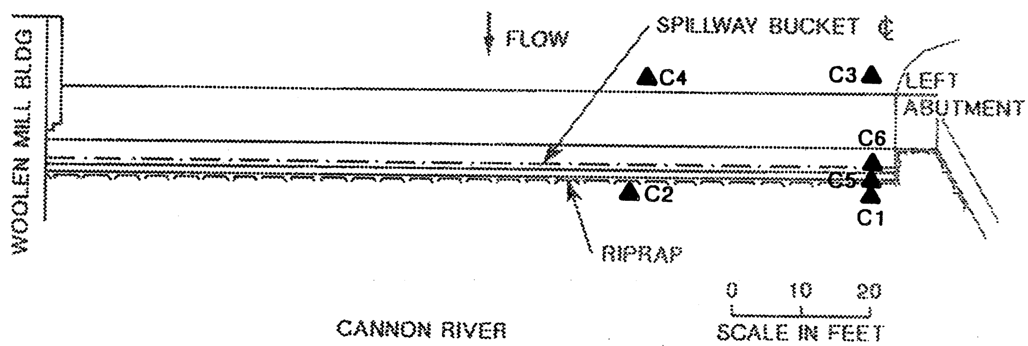


Fig. VI–6. Plan view of December 17, 1985, sampling locations.

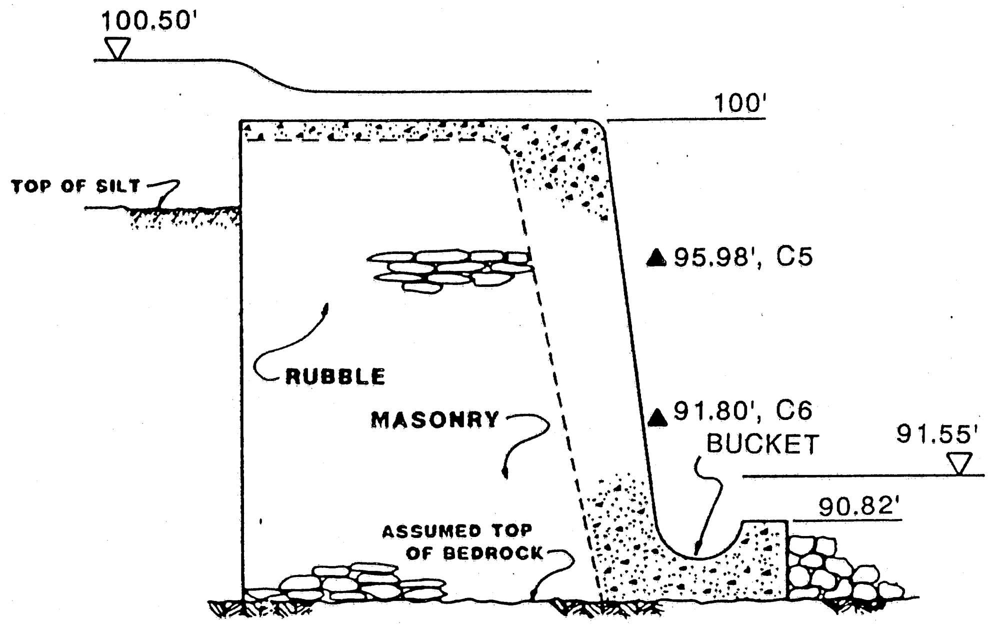


Fig. VI–7. Spillway cross section showing December 17, 1985, spillway sampling locations.

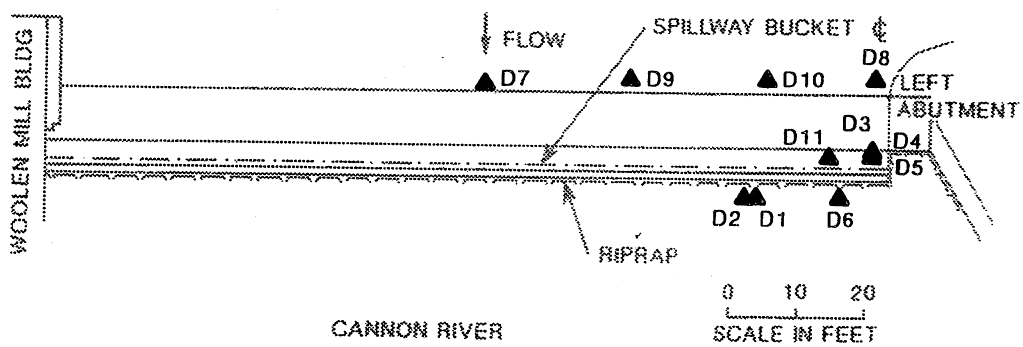


Fig. VI–8. Plan view of February 28, 1986, sampling locations.

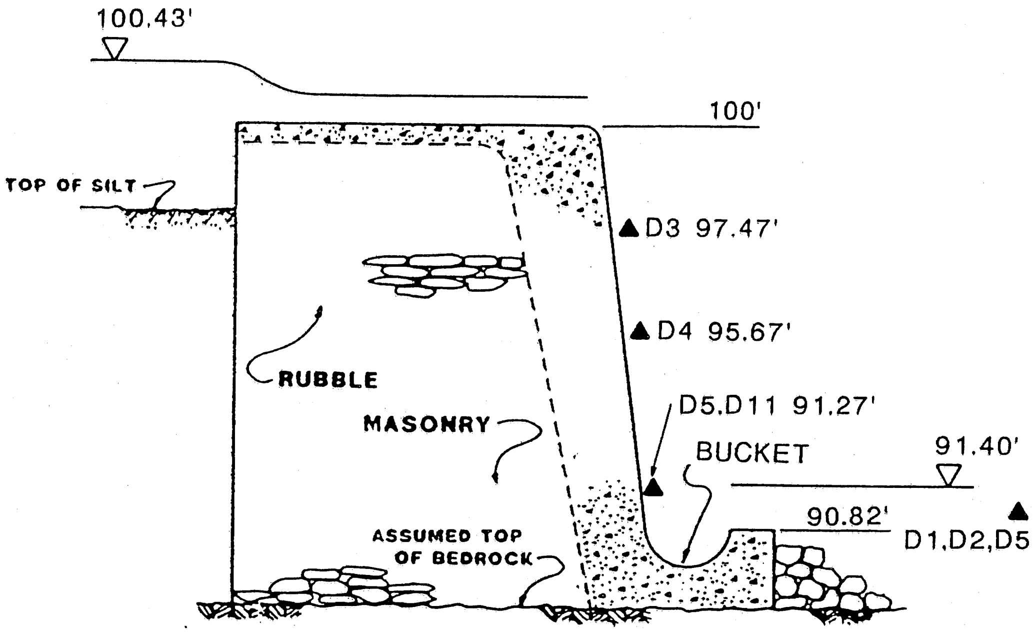


Fig. VI–9. Spillway cross–section showing Woolen Mill Dam, February 28, 1986, spillway sampling locations.

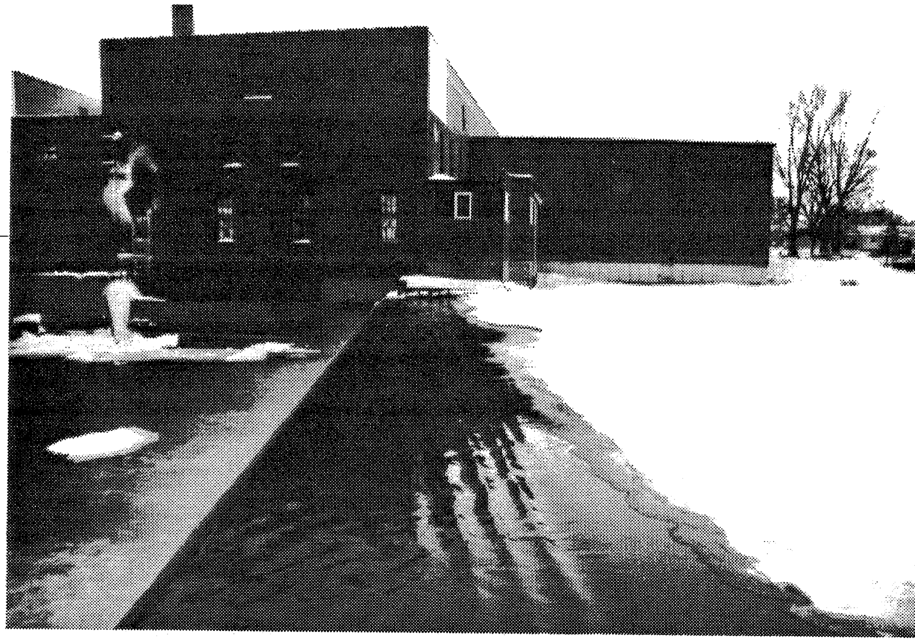


Photo VI–1. Faribault Woolen Mill Dam, December 17, 1985, upstream flow characteristics.

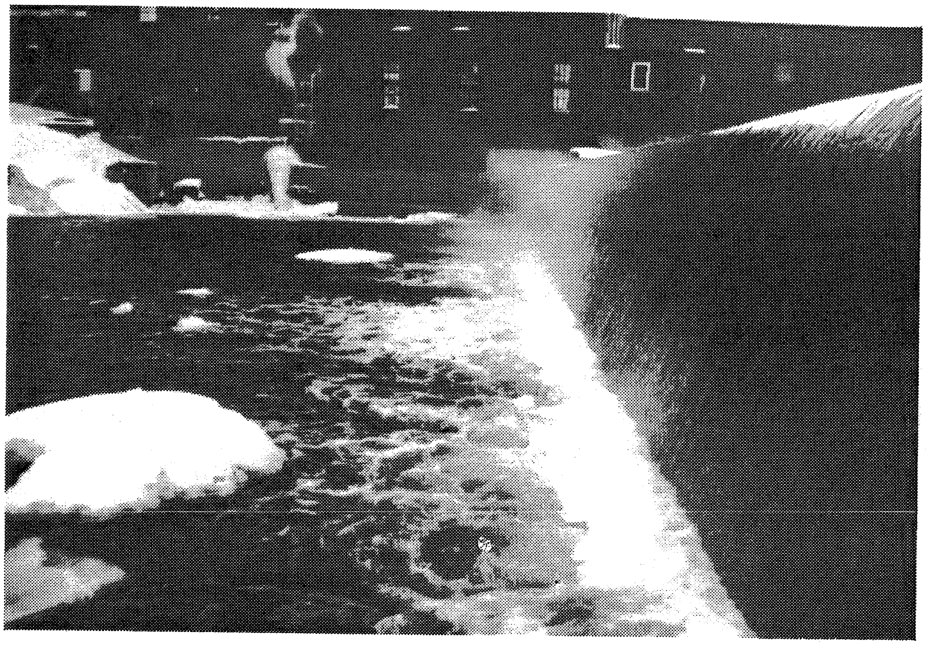


Photo VI–2. Faribault Woolen Mill Dam, December 17, 1985, spillway aeration and downstream jump characteristics.

Photo VI–3. Faribault Woolen Mill Dam February 28, 1986, spillway aeration. Note: Spillway sampler in foregrounds.

VII. AMERY DAM

A. PHYSICAL DESCRIPTION

The Amery Dam is located on the Apple River in the City of Amery, Wisconsin. The dam consists of three sections: an earthen dam, fixed crest gravity section, tainter gate chute spillway, and two stoplog control structures. The structure focused on herein for gas transfer measurements was the 10 ft, 1 inch, wide tainter gate control structure shown in plan and section in Figs. VII–1 and VII–2, respectively. Detailed plans do not exist for this structure. The drawings shown in Figs. VII–1 and VII–2 were taken from a file at the Army Corps of Engineers dam safety section and give very little detail.

The tainter gate control structure consists of a 10 ft, 1 inch wide, 16 ft. long, wooden tainter gate, with an approximately 25 ft long downstream chute spillway as shown in Photo VII–1. The downstream chute is sloped causing the flow to appear to remain at a fairly constant depth along its entire length. The flow in the chute spillway due to its high velocity upon exiting the gate and short sloped spillway appears to consist of aerated two–phase spillway flow along its entire length. At the end of the chute the water leaves the base of the chute and falls approximately 1 foot into the lower pool as shown in Photo VII–1. Energy dissipation at this structure occurs due to friction along the chute spillway and in the disintegration of the jet leaving the spillway floor in the lower plunge pool.

B. DISCHARGE

The discharge at this structure was estimated using water surface elevations collected at various locations downstream of the gate. A critical measurement which was not collected was the elevation of the floor at the vena contracta. This elevation used for this measurement was the elevation of the floor at the end of the chute spillway. Further gas transfer data collection at this site should consider better defining the geometry of the tainter gate (i.e. determine the elevation of the tainter gate lip, and floor elevation at which the tainter gate lip intersects). The discharge at this site was estimated using the following gate equation taken from Henderson (1970).

$$q = y_1 y_2 \sqrt{\frac{2g}{y_1 + y_2}}$$

where y_1 = difference from Upstream water surface elevation and chute spillway floor

y_2 = depth of water at vena contracta

This estimate was based on the assumption that the chute spillway was flat, which is not the case according to Figure VII–2, and the measurement of chute water surface elevation was at the vena contracta. The actual discharge may be slightly lower due to the floor of the spillway sloping downward, or smaller vena contracta. However, these aspects cannot be incorporated due to the crudeness of the plans.

C. GAS TRANSFER MEASUREMENTS

There was only one dissolved oxygen survey performed at this site: February 16, 1985. The results from this survey are given in Table VII–1. These measurements were performed to establish the gas transfer of the tainter gate control structure, and the gas transfer in the aerated chute flow. The locations of these measurements are shown in Figure VII–1 and correspond to sample collection to the immediate left and right of the jet issuing from the chute spillway, and samples collected in the return flow to the jet. To establish the aeration occurring in the aerated chute flow, additional water samples were collected by hand from the jet falling into the lower pool.

As shown in Photo VII–1, water was also being discharged from the stoplog control structure to the left (looking downstream) of the tainter gate chute spillway. Gas transfer was not established at this structure due to the severe leakage between the stoplogs. This leakage caused a number of small jets to issue out between the stoplogs. It would be very difficult to differentiate between aeration from the free wier flow, and aeration from the thin jets.

In addition the downstream measurements were clouded by the amount of dissolved oxygen added to the water by the recirculatory nature of the plunge pool basin. The processes of reaeration was significantly different than from a hydraulic jump downstream from a ogee spillway which can be modeled by two dimensional theory. In the case of a free jet falling into a plunge pool the flow is predominantly three dimensional. Gas transfer of specific processes are clouded by the recirculation which exists in such a flow. This recirculation causes an increased residence time of the flow downstream from the tainter gate control structure, and may lead to increased exposure to bubbles resulting in greater gas transfer than to a flow without recirculation.

TABLE VII–1. Results from Amery Dam Survey, February 16, 1985

Atmospheric Pressure:	743.3 ± .1 mm of Hg
Water Temperature:	0.70 ± 0.3 °C
Saturation Concentration:	13.54 ± 0.27 mg $0_2/\ell$
Upstream Water Surface Elevation:	109.78 ± 0.03 ft
Downstream Water Surface Elevation:	98.91 ϕ 0.05 ft
Headloss:	10.87 ± 0.05 ft
Head on Crest:	N/A N/A
Discharge/ft Crest Width:	22.70 ± 0.3 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Overall	7.45	10	0.094	0.07	9.81	11	0.161	0.11	0.39	0.03	7	25
Spillway	7.45	10	0.094	0.07	8.90	2	0.283	2.54	0.24	0.42	NA	25

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table VII–1 (Cont'd). Data from Amery Dam, February 16, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
7.00	13:45	A1	Upstream Right Pier, 3 ft in depth
6.95	13:45	A1	Upstream Right Pier, 3 ft in depth
6.95	13:50	A2	Upstream Right Pier, Surface
6.90	13:50	A2	Upstream Right Pier, Surface
7.10	13:55	A3	Upstream Left Pier, Bottom
7.05	13:55	A3	Upstream Left Pier, Bottom
7.15	14:00	A4	Upstream Right Pier, Surface
7.20	14:00	A4	Upstream Right Pier, Surface
7.05	14:05	A5	Upstream Tainter Gate Center, Surface
7.05	14:05	A6	Upstream Tainter Gate Center, Surface
9.35	14:25	A6	Upstream Tainter Gate Center, 3 ft in Depth
9.60	14:25	A6	Upstream Tainter Gate Center, 3 ft in Depth
9.70	14:32	A7	Downstream Right Bank, Just to the right of the Jet
9.70	14:32	A7	Downstream Right Bank, Just to the right of the Jet.
9.80	14:40	A8	Downstream Right Bank, 15 ft Downstream
9.80	14:40	A8	Downstream Right Bank, 15 ft Downstream
8.70	14:45	A9	Hand Sample in Jet Leaving the Spillway
9.10	14:45	A10	Hand Sample in Jet Leaving the Spillway.
9.85	15:15	A11	Downstream Left Pier
9.80	15:24	A12	Downstream, 10 ft in the Jump
9.85	15:24	A12	Downstream, 10 ft in the Jump
9.90	15:33	A13	Downstream Right Bank, approx. 50 ft Downstream
9.90	15:33	A13	Downstream Right Bank, approx. 50 ft Downstream.

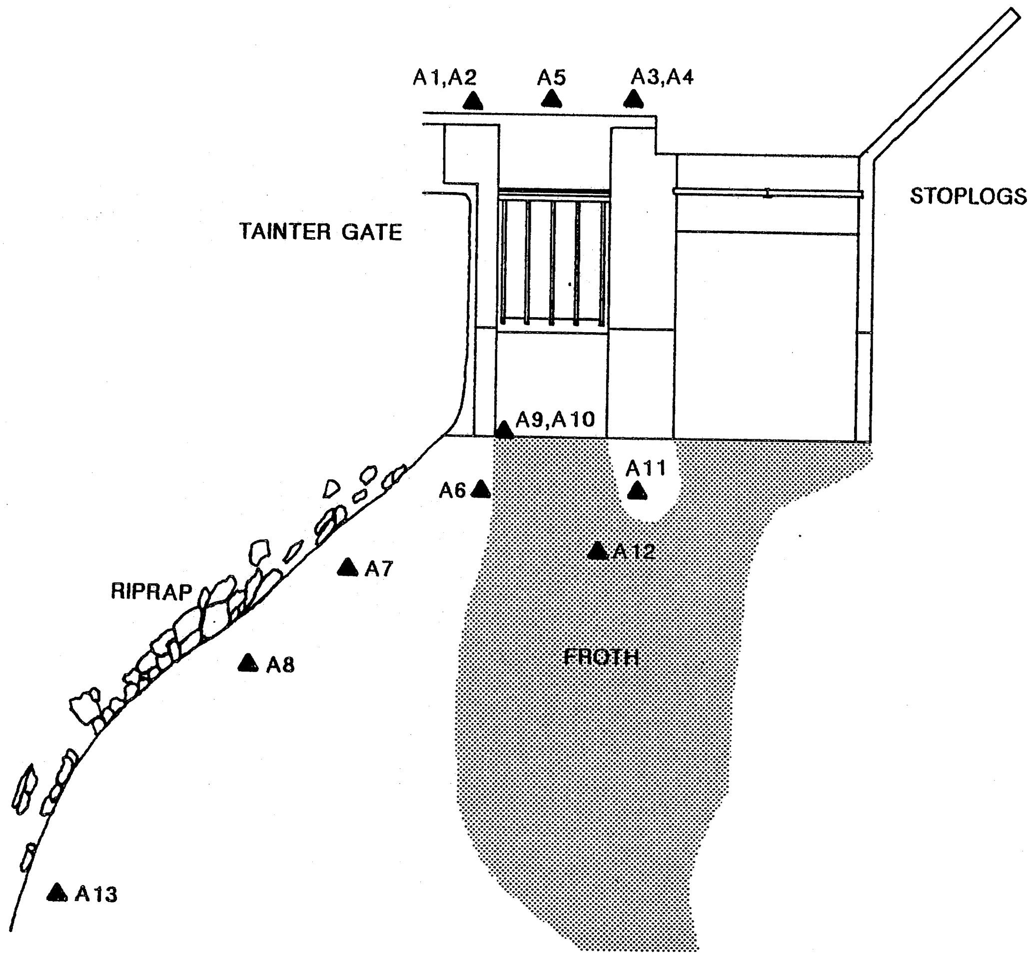


Fig. VII–1. Plan view of Amery Dam with February 16, 1985, sampling locations.

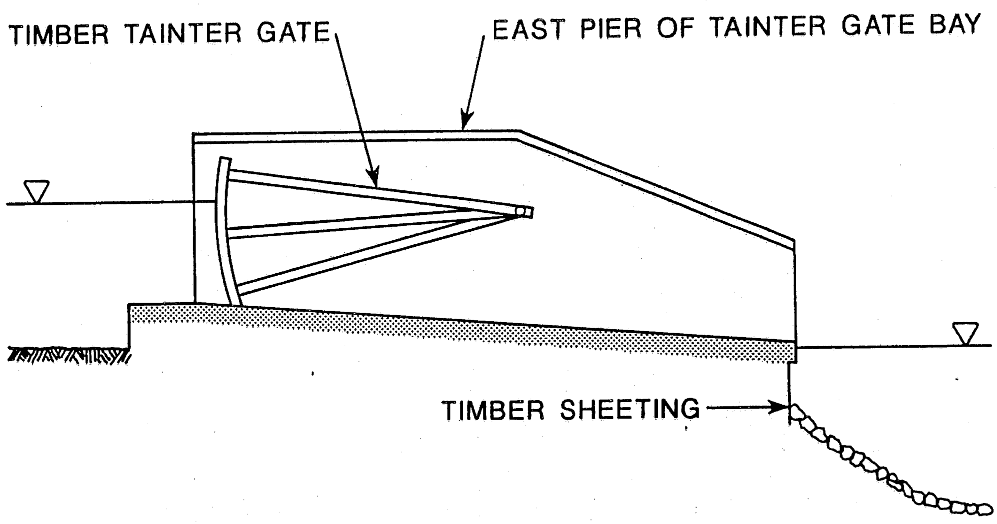


Fig. VII–2. Cross section of Amery Dam tainter gate spillway.

Photo VII–1. Flow leaving the Amery Dam tainter gate spillway.

VIII. COON RAPIDS DAM

A. PHYSICAL DESCRIPTION

The Coon Rapids Dam is located approximately 13 miles upstream from Minneapolis, Minnesota, at river mile 865.5 on the Mississippi River. The structure, upstream pool and surrounding area is owned and operated by the Hennepin County Parks Commission for recreational purposes.

The Coon Rapids Dam consists of several hydraulic structures separated by an earthen dam as shown in Fig. VIII–1. Gas transfer at this structure was investigated at the tainter gate control structure on the right side of the dam. This control structure consisted of twenty eight, 33 ft. wide tainter gate spillways. Downstream from this structure two different types of stilling basins shown in Fig VIII–2 and Fig VIII–3 are used to dissipate the excess kinetic energy of the flow. Fig. VIII–2 represents the ogee spillway and stilling basin downstream of bays 1–12, and Fig VIII–3 represents bays 13 through 28. Thus it was possible to investigate two different types of stilling basins at this structure: either a simple hydraulic jump as found downstream of Bays 1 through 12 or a hydraulic jump run up against the spillway as found in Bays 13 through 28.

It was not possible to investigate the affect gate openings have on gas transfer at this structure due to the current operating policy. The Coon Rapids Dam operating plan calls for the tainter gates to be raised out of the water during the winter months to minimize ice loads on the structure and flush ice downstream. Because of this operating policy gas transfer was only examined at these structures as a free overfall spillway. Gas transfer at the other structures located on the east bank could also have been interesting to investigate; however, by reducing the upstream pool during the winter months, the other structures, such as the flip bucket spillway or the fish ladder adjacent to the old powerhouse, do not discharge water.

B. DISCHARGE MEASUREMENTS

The rating curve shown in Fig. VIII–4, taken from Coon Rapids Dam Operating Plan, will be used to estimate the discharge at the Coon Rapids Dam during the winter months. It was unlikely that this method gave very accurate estimates of the discharge at this site primarily because of the contorted ice caps which would cover the spillways as shown in Photo, VIII–1. These ice caps forced the upstream flow to become pressurized upstream of the tainter gate spillways, causing the discharge to be like a jet issuing from an orifice instead of free discharge over a spillway crest. It is impossible to estimate a better discharge, since the ice did not form uniformly over the crest of the spillway. In addition, in some bays the ice effectively sealed the bay preventing the discharge of water. Hence, though it was possible to obtain discharge measurements from a downstream gauging station, it is still impossible to estimate the discharge from each individual bay, due to the unique ice formation which occurred in each tainter gate.

C. GAS TRANSFER MEASUREMENTS

Three dissolved oxygen surveys were performed at this site: January 22, 1985, February 12, 1985 and January 9, 1986. The February 12 survey was discarded because the D.O. sampler broke and samples taken by hand were not sufficiently accurate. The results from the first and last survey are presented in Tables VIII–1, and VIII–2. Sampling location maps are shown for these sites as Figures VIII–1, and VIII–5, respectively.

Due to the strange downstream ice formations downstream and upstream from the Coon Rapids Dam, the gas transfer measurements collected may not give a very good indication of the actual gas transfer which could occur. During most of the measurements, downstream ice formation distorted the flow pattern of the hydraulic jump. In addition, ice was found to buildup on the crest of the dam. As previously noted, several bays during each set of measurements were completely blocked due to ice formation on the spillway crest. This resulted in increased water levels upstream to pass the excess water through the remaining open gate structures. In addition the ice which formed across the openings of the gate structures distorted the flow discharging over the crest of the dam, and also the flow downstream of the dam. Thus, very unique flow patterns occurred downstream from the left bank. The right bank due to greater depths did not appear to be significantly impacted by this problem.

Finally during the winter of 1985–1986 a frazil ice jam formed just downstream of the dam as shown in Photo VIII–2. This ice jam caused a significant increase in the water level just downstream from the dam and decreased the water surface elevation difference from approximately 12 feet (normal flow) to approximately 7 feet. In addition the ice jam caused the flow just downstream from the dam to be highly three–dimensional and distorted.

It is unlikely the data collected herein is representative of what could occur during the summer months at this dam due to the significantly distorted flow patterns caused by the upstream and downstream ice formations.

TABLE VIII–1 Results from Coon Rapids Site Survey. January 22, 1985

Atmospheric Pressure:	737.1 ± 0.10 mm of Hg
Water Temperature:	0.5 ± 0.30 °C
Saturation Concentration:	13.69 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	825.34 ± 0.03 ft
Downstream Water Surface Elevation:	812.93 ± 0.05 ft
Headloss:	12.41 ± 0.05 ft
Head on Crest:	2.54 ± 0.03 ft
Discharge/Unit Crest Width:	13.853 ± 0.15 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Efficiency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	11.15	6	0.055	0.06	12.68	2	0.035	0.31	.60	0.14	13.6	0
Left Bank	11.15	6	0.055	0.66	12.41	4	0.149	0.24	0.50	0.11	3.1	0

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table VIII–1 (Cont'd). Data from Coon Rapids Site Survey, January 22, 1985

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
11.20	10:50	A1	Upstream Left Bank approx. 300 ft Upstream
11.20	10:50	A1	Upstream Left Bank approx. 300 ft Upstream
11.20	10:55	A1	Upstream Left Bank approx. 300 ft Upstream
11.10	10:55	A1	Upstream Left Bank approx. 300 ft Upstream
11.10	10:58	A1	Upstream Left Bank approx. 300 ft Upstream
11.10	10:58	A1	Upstream Left Bank approx. 300 ft Upstream
12.35	11:20	A2	Downstream Left Bank
12.60	11:20	A2	Downstream Left Bank
12.25	11:20	A2	Downstream Left Bank
12.45	11:20	A2	Downstream Left Bank
12.65	13:00	A3	Downstream Right Bank
12.70	13:00	A3	Downstream Right Bank

TABLE VIII–2 Results from Coon Rapids Site Survey, January 9, 1986

Atmospheric Pressure:	29.058 ± 0.01 mm of Hg
Water Temperature:	0.3 ± 0.30 °C
Saturation Concentration:	13.78 ± 0.28 mg O_2/ℓ
Upstream Water Surface Elevation:	825.93 ± 0.03 ft
Downstream Water Surface Elevation:	818.71 ± 0.05 ft
Headloss:	7.22 ft. ± 0.05 ft
Head on Crest:	3.13 ± 0.03 ft
Discharge/Unit Crest Width:	19.26 ± 1.00 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Efficiency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Left Bank	11.88	6	0.026	0.05	12.86	4	0.038	0.06	0.51	0.09	8.9	0

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table VIII–2 (Cont'd). Data from Coon Rapids, January 9, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
~~11.85~~	~~9:55~~	~~B1~~	~~Left Bank 75 ft Upstream from Left Bank Spillway~~
11.85	9:55	B1	Left Bank 75 ft Upstream from Left Bank Spillway
11.90	9:58	B1	Left Bank 75 ft Upstream from Left Bank Spillway
11.90	9:58	B1	Left Bank 75 ft Upstream from Left Bank Spillway
11.90	10:00	B1	Left Bank 75 ft Upstream from Left Bank Spillway
11.90	10:00	B1	Left Bank 75 ft Upstream from Left Bank Spillway
12.85	11:00	B2	Left Bank Downstream Through Ice Bubbles still in the Flow
12.80	11:00	B2	Left Bank Downstream Through Ice Bubbles still in the Flow
12.85	11:05	B2	Left Bank Downstream Through Ice Bubbles still in the Flow
12.85	11:05	B2	Left Bank Downstream Through Ice Bubbles still in the Flow
12.90	11:10	B2	Left Bank Downstream Through Ice Bubbles still in the Flow
12.90	11:10	B2	Left Bank Downstream Through Ice Bubbles still in the Flow

Misc. Comments: C2 is approx. 50 ft Downstream in the Submerged Jump

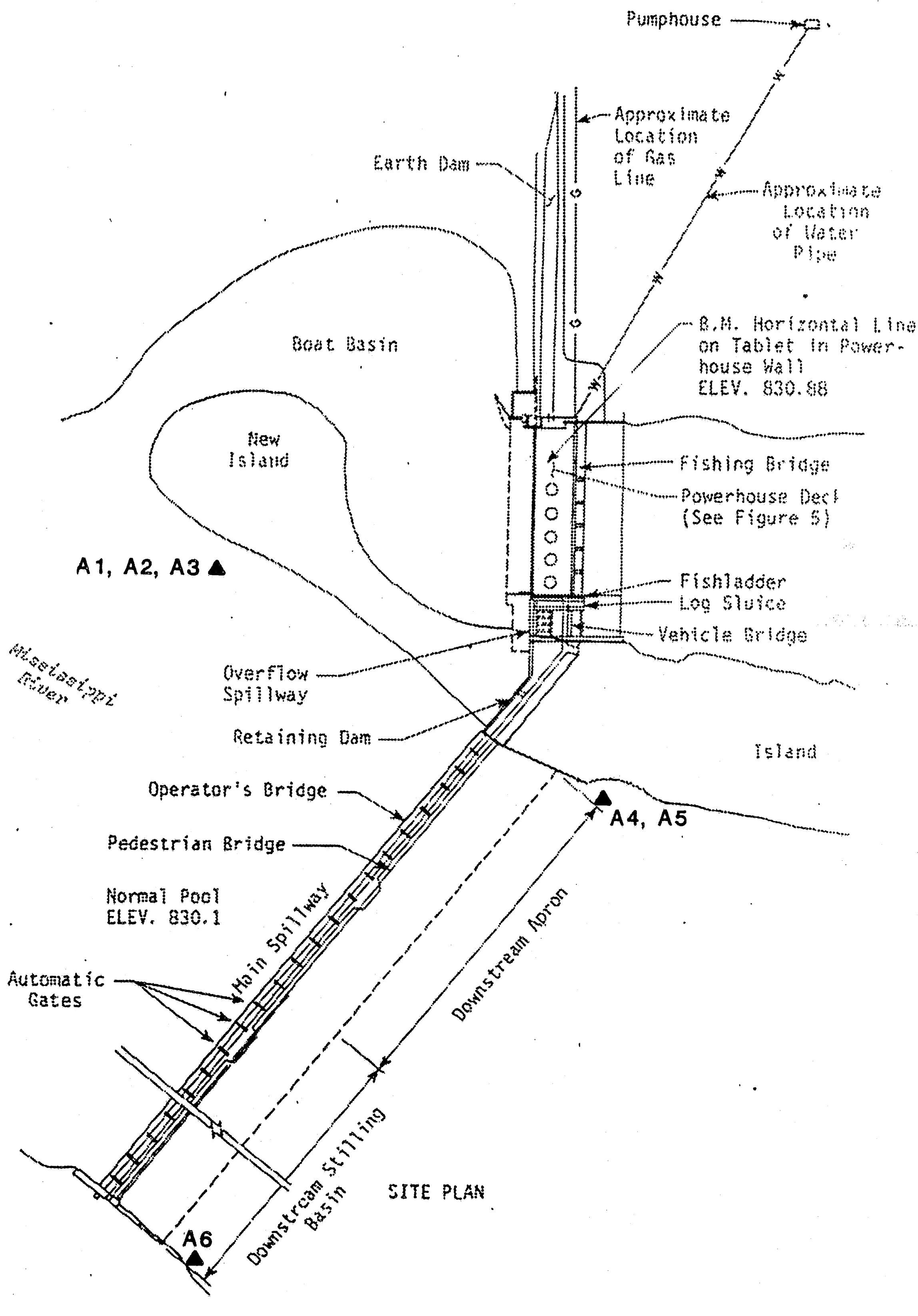


Fig. VIII–1. Plan view of Coon Rapids Dam and January 22, 1985, sampling locations.

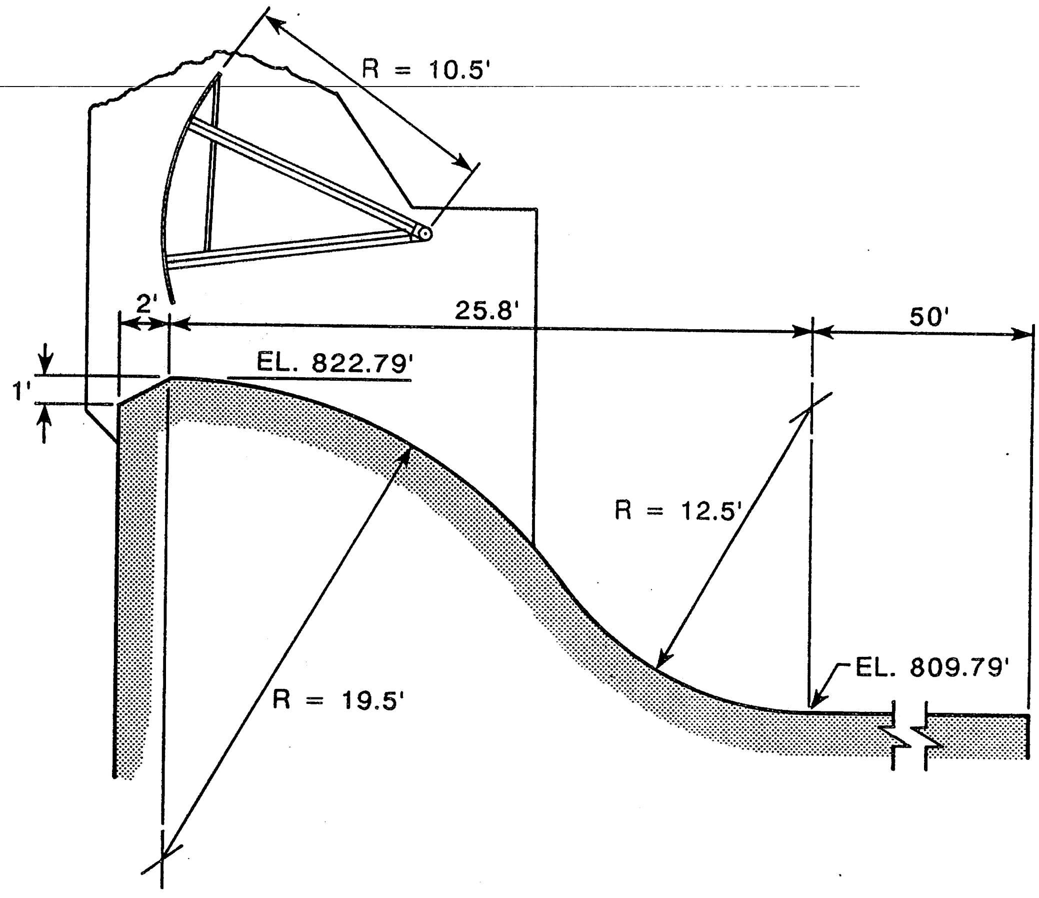


Fig. VIII–2. Cross section of tainter gate spillway bay 1–12, left bank.

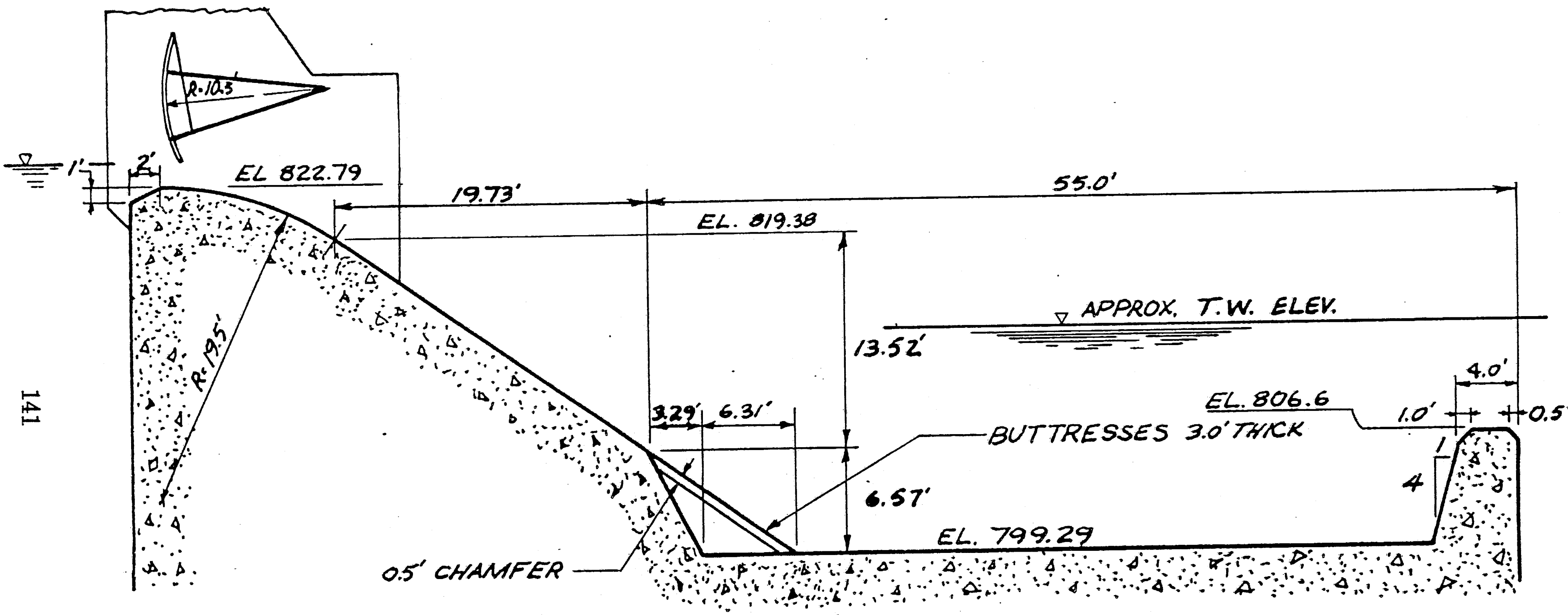


Fig. VIII–3. Cross section of tainter gate spillway Bay 13–28, right bank.

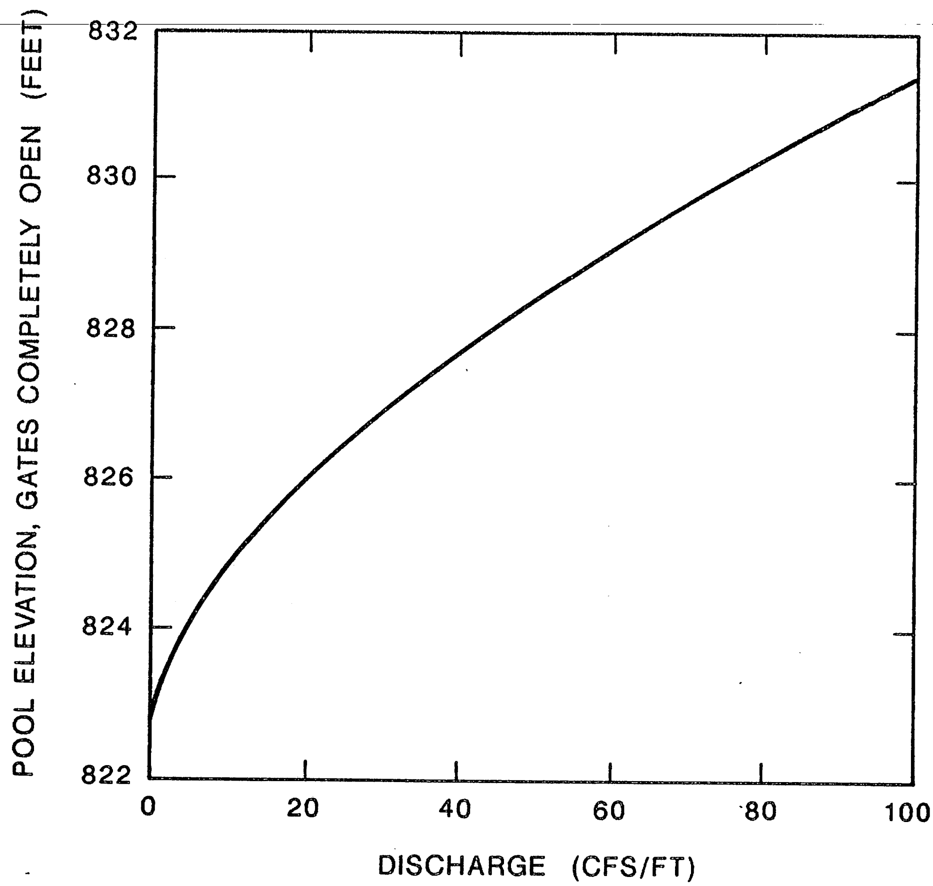


Fig. VIII–4. Coon Rapids discharge rating curve.

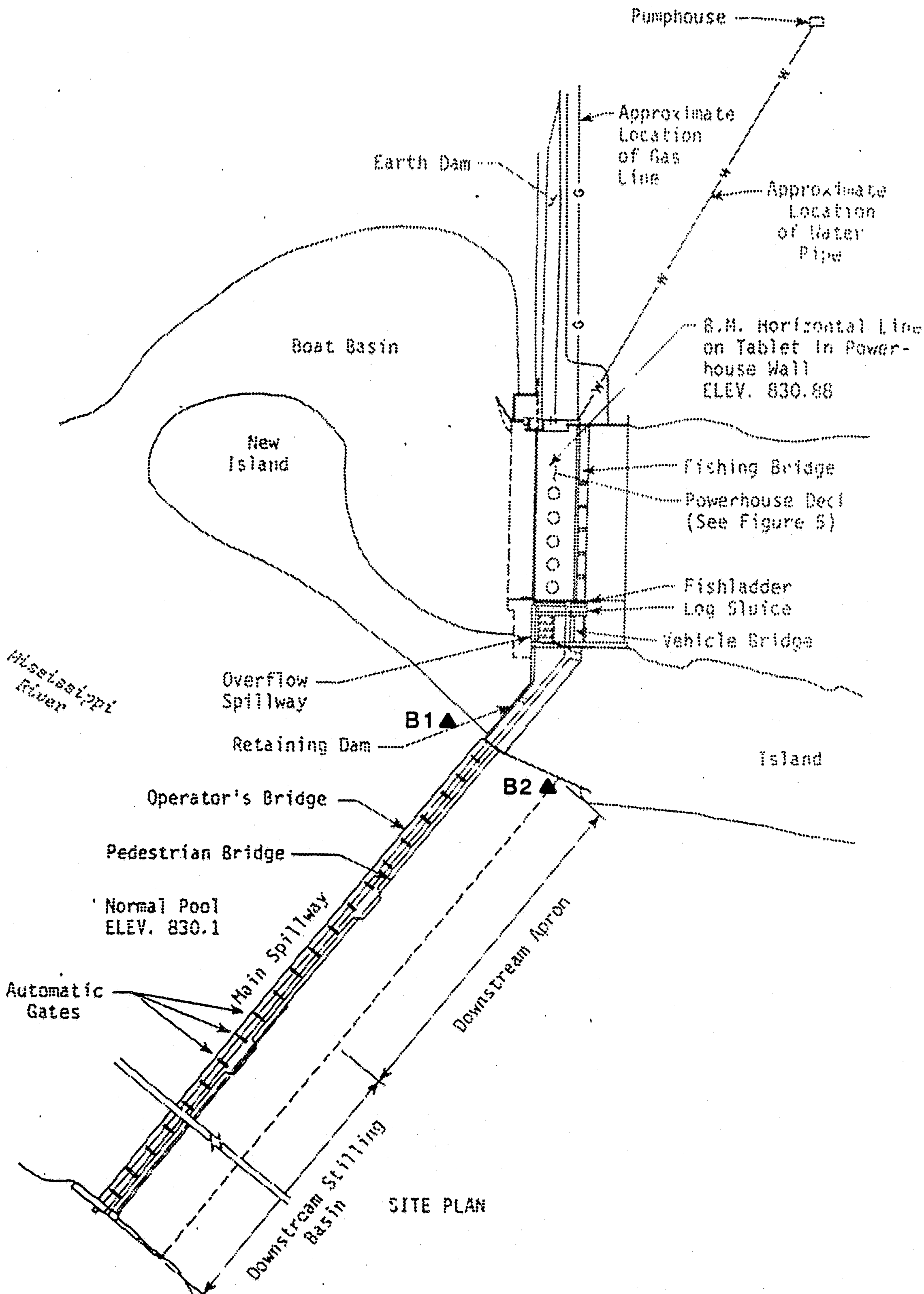


Fig. VIII–5. Plan view of January 9, 1986, sampling locations.

Photo VIII–1. Spillway crest ice caps, January 22, 1985.

Photo VIII–2. Frazil ice jam tailwater increase, January 9, 1986.

IX. SHADY LAKE DAM

A. PHYSICAL DESCRIPTION

The Shady Lake Dam consists of five 20 ft tainter gates and a 50 ft fixed crest spillway shown in Fig. IX–1 and in Photo IX–1 for a combined width of approximately 165 feet. The dam is located within the City of Oronoco, in Ohlmsted County, Minnesota, on the Middle Branch Zumbro River Basin immediately downstream of the confluence of the Middle Branch Zumbro River and the South Fork Middle Branch Zumbro River.

Since the tainter gates were inoperable due to ice, gas transfer measurements focused on the right bank spillway shown by Section A–A in Figure IX–1. The spillway does not have a stilling basin but relies on the spillway's flow impact with the underlying bedrock to dissipate the excess kinetic energy of the flow.

B. Discharge Measurements

Discharge of the Shady Lake Dam was determined using the Bureau of Reclamation, Engineering Monographs No. 9, *Discharge Coefficients for Irregular Overfall Spillways.* The crest shape of this spillway matched that of a spillway with a discharge coefficient of 3.9. Since the upstream head did not change during the two samplings, this discharge coefficient was used according to the following equation to estimate the discharge at this site.

$$Q = 3.9 \ L \ H^{3/2}$$

where L is the length of spillway, and H the difference between headwater elevation and spillway crest elevation. The uncertainty of this measurement will be assumed to be ±10%.

C. GAS TRANSFER MEASUREMENTS

Two dissolved oxygen surveys were performed at this site: January 22, 1986, and February 14, 1986. The results from these surveys are presented in Tables IX–1 and IX–2, respectively.

Since the measurements were collected in early winter, ice formed on the crest of the Spillway. This required the removal or chipping away ice off the crest of the dam on both sampling dates. It was possible to chip away all the ice for the January 22 sampling. It was not possible, however, to chip away all the ice during the February 14 measurement, as shown in Photo IX–2. The ice was found to have hardened to the face of the dam, specifically around the exposed rock anchor bolts which tie the spillway to the underlying bedrock.

However, other than this problem, water flowed smoothly over the structure, appearing to aerate at the point where the radius of the crest meets the face of the spillway. This aeration length was estimated to be 11 feet. Due to the depth of the tailwater, the jump which formed represented a hydraulic jump run up against the spillway and the aerated spillway flow plunged into a roller below the spillway.

TABLE IX–1. Results of the Shady Lake Site Survey, January 22 1986

Atmospheric Pressure:	29.5 ± .1 mm of Hg
Water Temperature:	0.1 ± .1°C
Saturation Concentration:	14.05 ± .28 mg02/ℓ
Upstream Water Surface Elevation:	948.9 ± .03 ft
Downstream Water Surface Elevation:	932.0 ± .05 ft
Headloss:	16.9 ± .05 ft
Head on Crest:	0.59 ± .03 ft
Discharge/Unit Crest Width:	1.36 ± .22 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi– ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	11.76	5	0.089	0.10	13.2	6	0.068	0.07	0.64	0.10	~4	11
Left Bank	11.72	6	0.052	0.05	13.3	6	0.061	0.06	0.66	0.09	~4	11
	Mean for site								0.65	.08	~4	11

LEGEND:
$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table IX–1 (Cont'd). Results of the Shady Lake Site Survey, January 22, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
11.8	11:00	A1	Upstream 12 ft from right bank approx. 3 ft deep
11.8	11:00	A1	Upstream 12 ft from right bank approx. 3 ft deep
11.8	11:00	A1	Upstream 12 ft from right bank approx. 3 ft deep
11.8	11.00	A1	Upstream 12 ft from right bank approx. 3 ft deep
11.6	11:00	A1	Upstream 12 ft from right bank approx. 5 ft deep
11.8	11:00	A2	Upstream just off of Left bank approx. 3 ft deep
11.7	11:00	A2	Upstream just off of Left bank approx. 3 ft deep
11.7	11:10	A2	Upstream just off of Left bank approx. 3 ft deep
11.65	11:10	A2	Upstream just off of Left bank approx. 3 ft deep
11.7	11:13	A2	Upstream just off of Left bank approx. 3 ft deep
11.75	11:13	A2	Upstream just off of Left bank approx. 3 ft deep
13.2	11:30	A3	Downstream from first sampling location – swift current noted
13.1	11:30	A3	Downstream from first sampling location – swift current noted
13.3	11:35	A3	Downstream from first sampling location – swift current noted
13.2	11:35	A3	Downstream from first sampling location – swift current noted
13.25	11:40	A3	Downstream from first sampling location – swift current noted
13.25	11:40	A3	Downstream from first sampling location – swift current noted
13.3	11:50	A4	Downstream from second sampling location – very little current
13.3	11:50	A4	Downstream from second sampling location – very little current
13.3	11:51	A4	Downstream form second sampling location – very little current
13.25	11:51	A5	Downstream approx. midway between the two upstream locations
13.3	11:52	A5	Downstream approx. midway between the two upstream locations
13.15	11:52	A5	Downstream approx. midway between the two upstream locations

TABLE IX–2. Shady Lake Site Survey, February 14, 1986

Atmospheric Pressure:	29.2 mm of Hg
Water Temperature:	0.1 ± .1°C
Saturation Concentration:	13.96 ± .28 mg02/1
Upstream Water Surface Elevation:	948.9 ± .05 ft
Downstream Water Surface Elevation:	932.3 ± .05 ft
Static Head:	16.61 ± .05 ft
Head on Crest:	0.54 ± .03 ft
Discharge/Unit Crest Width:	1.55 ± .22 ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	10.01	4	0.063	0.09	12.6	6	0.049	0.07	0.64	.06	~4.3	11
Left Bank	9.98	4	0.096	0.13	12.8	6	0.089	0.12	0.71	.06	~4.3	11
Center	9.93	4	.065	.09	12.7	11	.138	.09	.68	.06	~4.3	11
	Mean for site								0.68	.05	~4.3	11

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table IX–2 (Cont'd). the Shady Lake Site Survey, February 14, 1986

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
10.1	12:20	B1	Upstream Right bank on Crest approx. .5 ft deep
9.95	12:20	B1	Upstream Right bank on Crest approx. .5 ft deep
10	12:20	B1	Upstream Right bank on Crest approx. .5 ft deep
10	12:20	B1	Upstream Right bank on Crest approx. .5 ft deep
9.95	12:20	B2	Upstream Center on Crest approx. .5 ft deep
9.85	12:20	B2	Upstream Center on Crest approx. .5 ft deep
10	12:30	B2	Upstream Center on Crest approx. .5 ft deep
9.9	12:30	B2	Upstream Center on Crest approx. .5 ft deep
9.9	12:35	B3	Upstream Left bank on Crest approx. .5 ft deep
10.1	12:35	B3	Upstream Left bank on Crest approx. .5 ft deep
10	12:40	B3	Upstream Left bank on Crest approx. .5 ft deep
9.9	12:40	B3	Upstream Left bank on Crest approx. .5 ft deep
12.8	1:05	B4	Downstream left bank approx. 4.5 ft deep
12.7	1:05	B4	Downstream left bank approx. 4.5 ft deep
12.85	1:10	B4	Downstream left bank approx. 2.5 ft deep
12.9	1:10	B4	Downstream left bank approx. 2.5 ft deep
12.7	1:13	B4	Downstream left bank just below ice
12.55	1:13	B5	Downstream Right Bank approx. 1 ft deep
12.5	1:20	B5	Downstream Right Bank approx. 1 ft deep
12.6	1:20	B5	Downstream Right Bank approx. 1 ft deep
12.6	1:25	B5	Downstream Right Bank approx. 1 ft deep
12.5	1:25	B5	Downstream Right Bank approx. 1 ft deep
12.6	1:27	B5	Downstream Right Bank approx. 1 ft deep

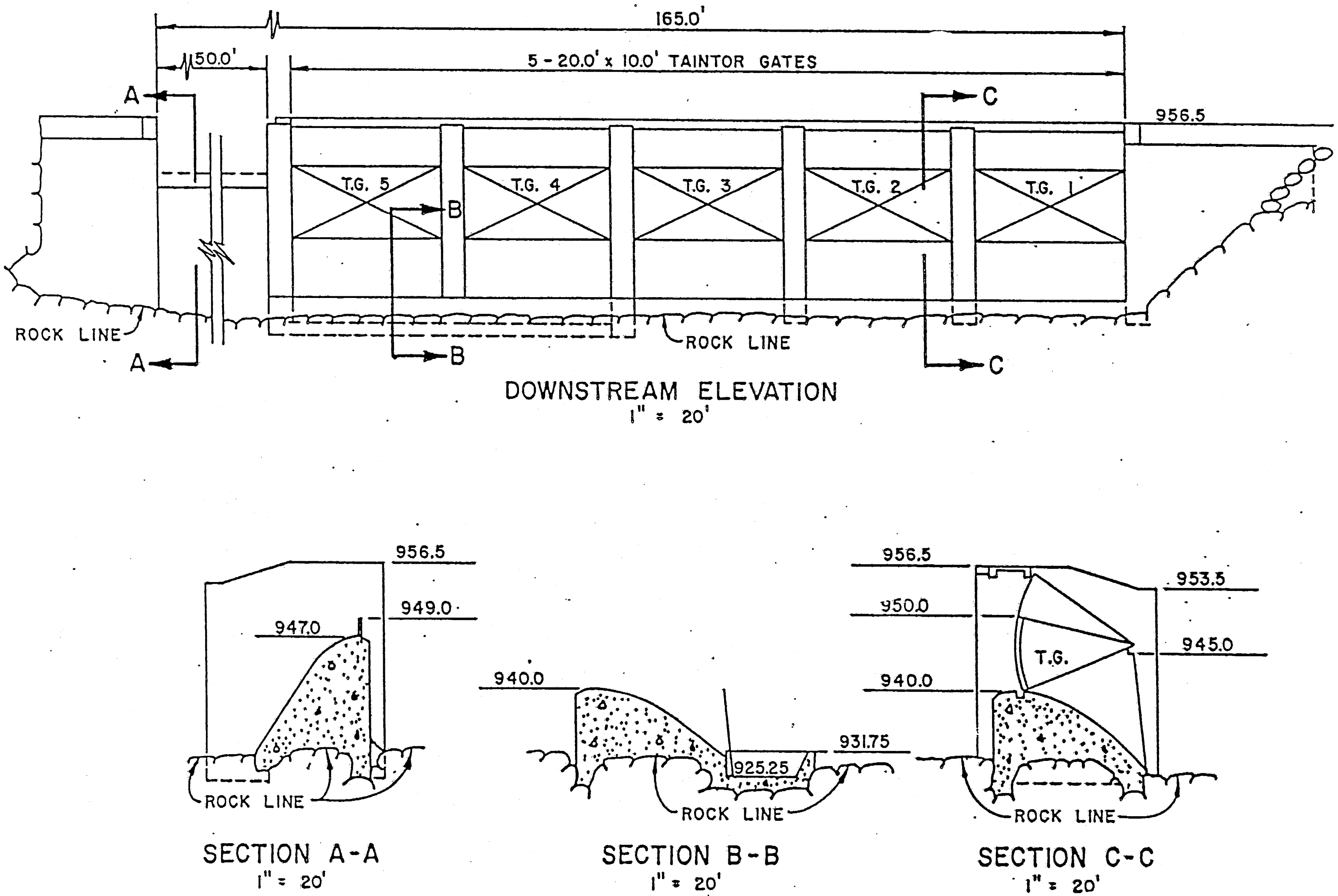


Fig. IX–1. The Shady Lake Dam.

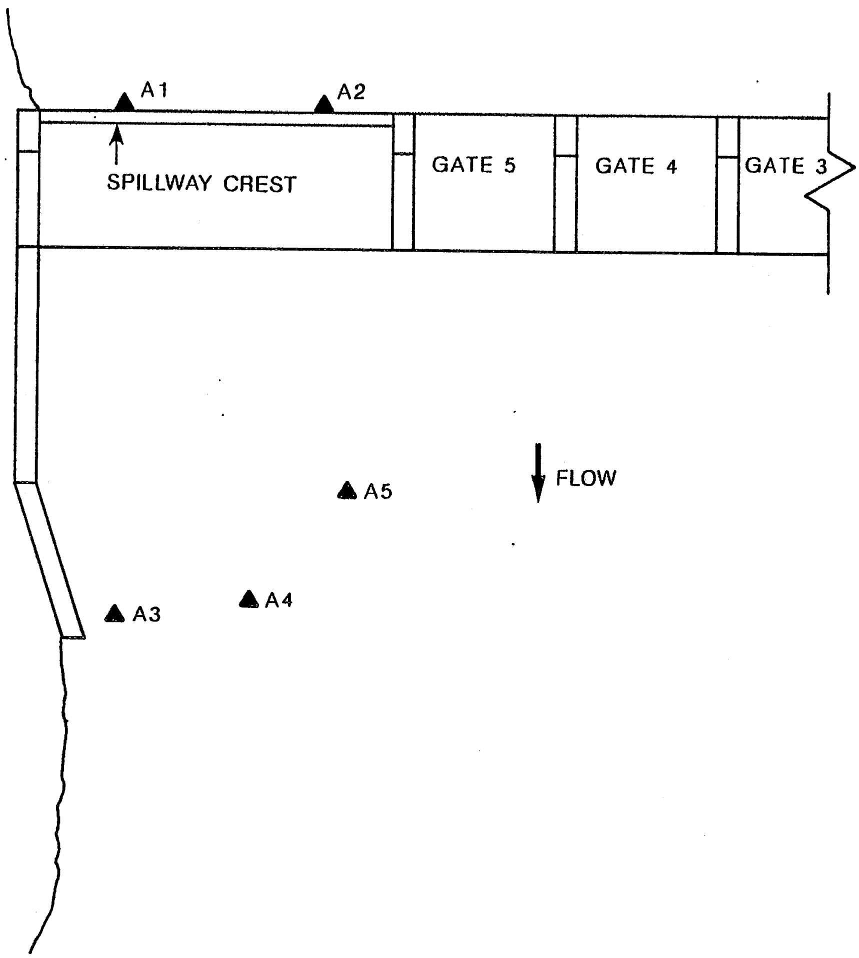


Fig. IX–2. Plan view of January 22, 1986, sampling locations.

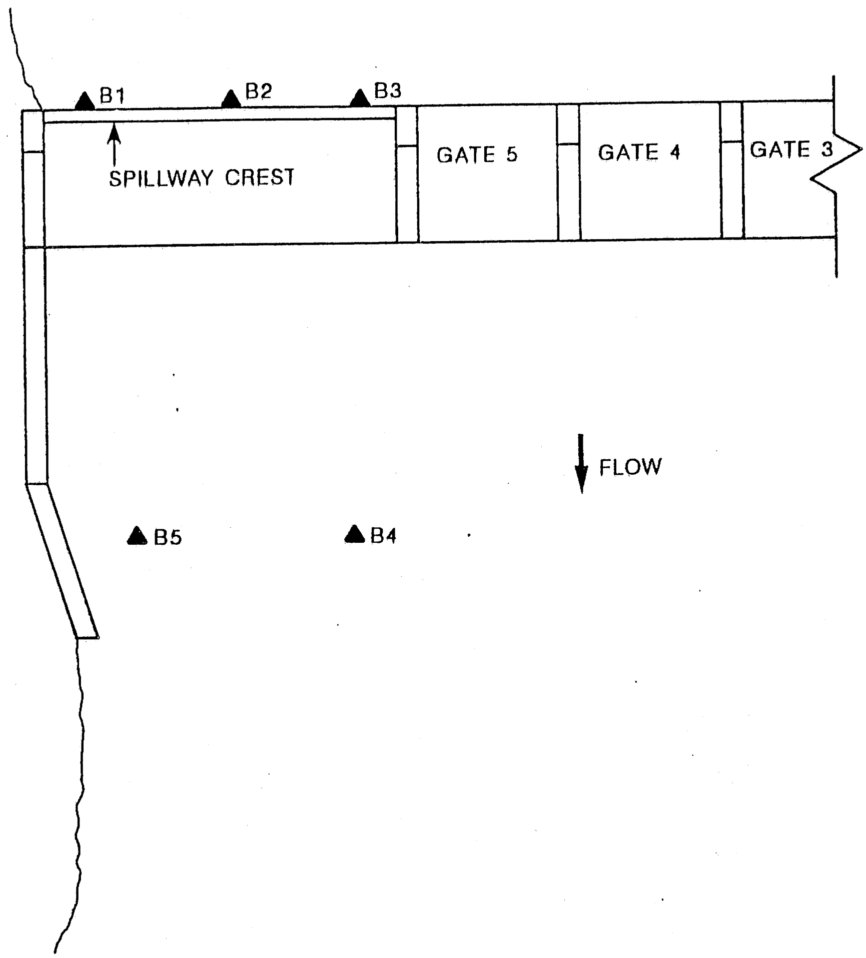


Fig. IX–3. Plan view of February 14, 1986, sampling locations.

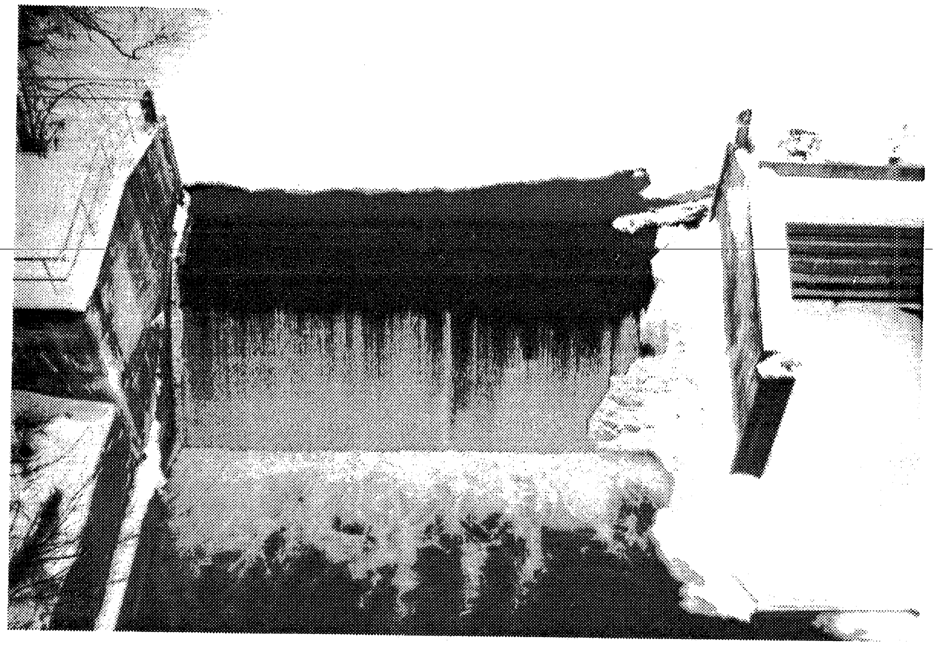


Photo IX–1. Shady Lake Dam, January 22, 1986, ice formation.

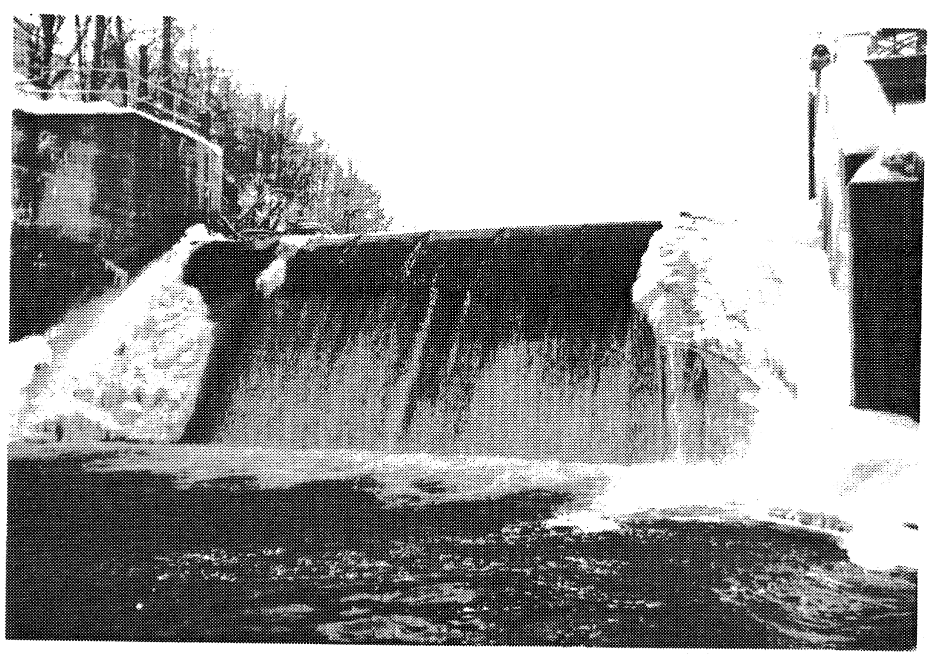


Photo IX–2. Shady Lake Dam, February 14, 1986, ice formation.

X. NEW RICHMOND DAM

A. PHYSICAL DESCRIPTION

The New Richmond Dam is located on the Willow River in New Richmond, Wisconsin, and maintains a small impoundment for recreational purposes within the city limits. The dam consists of two parts: a concrete control structure and a 245 ft. long earth dike off the right abutment. The concrete control structure, shown in Fig X–1 and Photo X–1 consists of five stoplog bays each 7 ft wide and two needle bays each 15.3 feet wide. The base of the stoplog bays and needle bays consists of a small ogee spillway as shown in Figure X–1. Since the needle bays are only used for large floods, gas transfer was investigated at the stoplog bay.

The water leaving the stoplog bay does not have great depths to plunge to. Excess kinetic energy of the flow after passing through the stoplogs is dissipated by splashing on the stilling basin below.

B. DISCHARGE MEASUREMENTS

It was not possible to obtain very good discharge measurements at this structure. Water was leaking through the stoplogs causing considerable spray to occur downstream of the stoplog structure. The quantity of this leakage was impossible to estimate and was ignored in the final estimate of discharge. In addition the stoplogs were not level. To estimate the discharge, the discharge coefficients given in Brater and King (1976) for a .5 ft wide broad–crested wier are used with the standard weir formula presented previously. Since the elevations of both ends of the stoplogs were measured, this equation is integrated across the width of each stoplog. This calculation resulted in an estimated discharge of approximately 40 cfs for the structure on the date of the survey.

C. GAS TRANSFER MEASUREMENTS

Gas transfer measurements were only collected once at this site on February 19, 1985. The results from this survey are presented in Table X–1. The sampling locations are given in Fig. X–2. Sampling was discontinued here after the original field trip due to the leakage encountered through the stoplogs, and the nonuniformity of the structure. The result from these measurements are an estimate of the overall gas transfer at this structure. This structure should not be classified as a simple weir due to the splashing which occurs on the floor of the stilling basin but will be classified as a shallow stilling basin weir.

TABLE X–1. Results from New Richmond Dam Site Survey, February 19, 1985

Atmospheric Pressure:	743 ± .1 mm of Hg
Water Temperature:	0.2 ± .1°C
Saturation Concentration:	14.0 ± .28 mg02/ℓ
Upstream Water Surface Elevation:	assumed 100
Downstream Water Surface Elevation:	89.87 ± .05 ft
Headloss:	10.13 ± 05 ft
Head on Crest:	0.5 ± .2 ft
Discharge/Unit Crest Width:	1.2 ± .1 ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi– ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Mean of Bays 2,3 and 4	9.95	6	.065	.065	11.89	10	.091	.064	0.48	0.04	5	15

LEGEND:
$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table X–1 (Cont'd). Data from New Richmond Site Survey February 19, 1985.

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
9.90	9:40	A1	Upstream of stoplog Bay 4, just below water surface
9.90	9:40	A1	Upstream of stoplog Bay 4, just below water surface
9.95	9:45	A2	Upstream of stoplog Bay 3, just below water surface
10.05	9:45	A2	Upstream of stoplog Bay 3, just below water surface
10.00	9:50	A3	Upstream of stoplog Bay 5, just below water surface
10.00	9:50	A3	Upstream of stoplog Bay 5, just below water surface
9.95	9:55	A4	Upstream of stoplog Bay 2, just below water surface from right
9.85	9:55	A4	Upstream of stoplog Bay 2, just below water surface from right
11.85	10:00	A5	D.S. below Falls at hydraulic jump below Bay 4
11.80	10:00	A5	D.S. below Falls at hydraulic jump below Bay 4
12.00	10:10	A6	D.S. Below Falls at Bay 2–3 Pier
11.90	10:10	A6	D.S. Below Falls at Bay 2–3 Pier
11.80	10:30	A7	Off of Right Bank Ledge Approx. 20 ft Downstream
11.90	10:30	A7	Off of Right Bank Ledge Approx. 20 ft Downstream
11.95	10:40	A8	Off of Right Bank Ledge Approx. 35 ft Downstream
12.05	10:40	A8	Off of Right Bank Ledge Approx. 35 ft Downstream
11.80	10:50	A9	Approx. 60 ft downstream in the Center of the River
11.80	10:50	A9	Approx. 60 ft downstream in the Center of the River

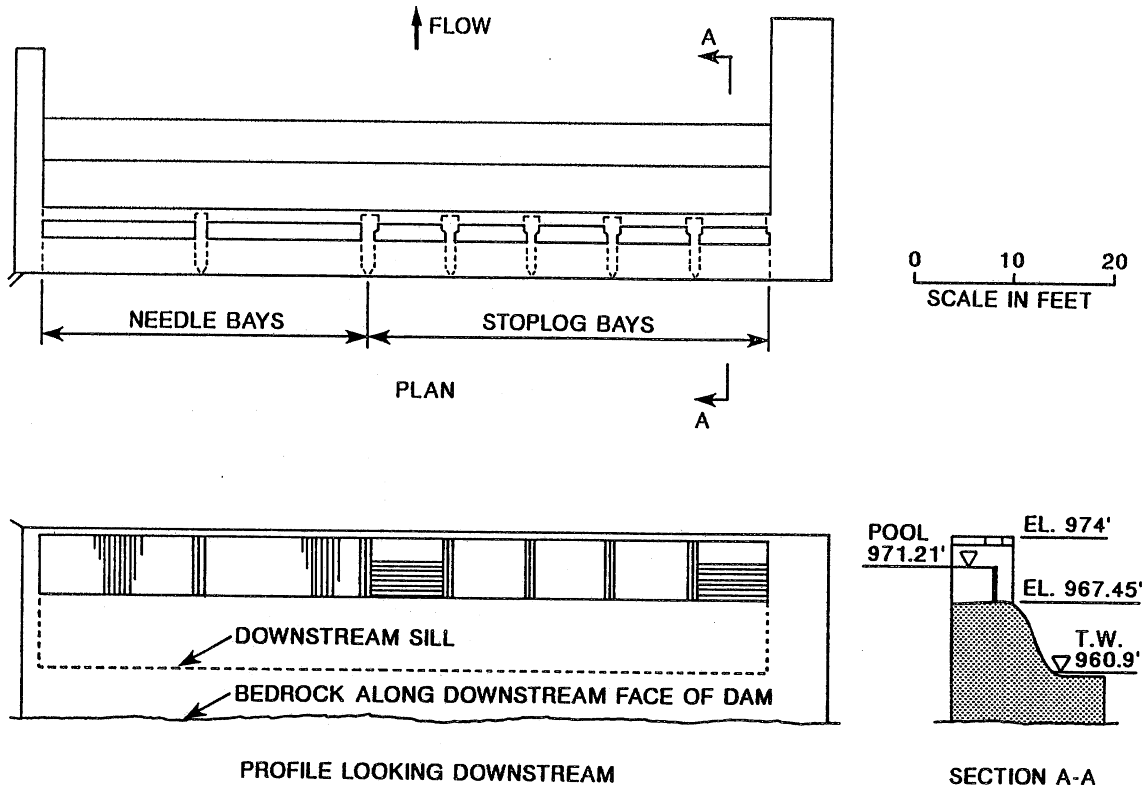


Fig. X–1. Plan and section view of New Richmond Dam.

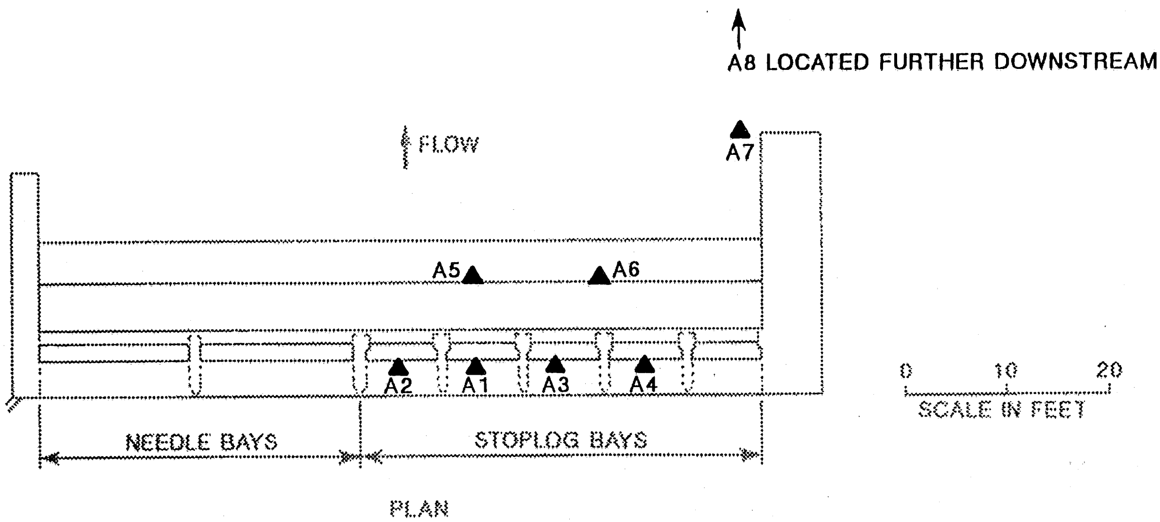


Fig. X–2. Plan of February 19, 1985, sampling locations.

Photo X–1. New Richmond Dam, February 19, 1985, discharge characteristics.

XI. NORTHFIELD DAM

A. PHYSICAL DESCRIPTION

The Northfield Dam is a located approximately 100 ft upstream of the 4th Street bridge over the Cannon River within the City of Northfield, Minnesota. The dam consists of an ogee spillway which is 165 ft long and uncontrolled. The existing dam was constructed to supply water power to the mill adjacent to the river on the left bank. Today, however, the dam serves solely to maintain an impoundment for aesthetic purposes on the Cannon River.

The dam shown in Figure XI–1 is further described by a concrete fixed crest spillway 10.7 ft high and 164.8 ft wide. It is flanked on the right bank by a concrete retaining wall and left bank by the Malt–O–Meal Corporate headquarters. A cross section representing the dam after construction is shown in Figure XI–1; however, due to significant concrete removal, a result of concrete spalling, this cross section inaccurately describes the dam which is shown in Photo XI–1.

B. DISCHARGE CHARACTERISTICS

The discharge at this site are estimated by the following equation developed using stream gage measurements at this site.

$$Q = 157\ (3.3)H^{3/2}$$

where H is headwater elevation minus spillway crest elevation.

C. GAS TRANSFER MEASUREMENTS

Table XI–1, which presents the results of the dissolved oxygen measurements collected at this site on February 16, 1985, shows considerable variation across the width of the river downstream from the dam. This variation is probably caused by increased spillway aeration over the spalled areas and is demonstrated by the .5 mg/ℓ difference between location A4 and A5. The white water shown in Photo XI–1 indicates aeration near the center location (A4) to be much greater than the aeration at the right bank location (A5). Due to the non–uniformity in the downstream D.O. concentrations, additional field surveys were not performed.

TABLE XI–1. Results from Northfield (Malt–0–Meal) Dam Site Survey, February 16, 1985.

Atmospheric Pressure:	745.7 mm of Hg.
Water Temperature:	0.5 ± 1°C
Saturation Concentration:	13.85 ± .28 mg02/ℓ
Upstream Water Surface Elevation:	100.3 ± .1 ft
Downstream Water Surface Elevation:	91.31 ± .1 ft
Headloss:	9.00 ± .05 ft
Head on Crest:	0.32 ± .2 ft
Discharge/Unit Crest Width:	0.56 ± .1 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Overall	9.45	6	0.063	0.07	11.7	12	0.198	0.13	0.50	0.05	2.3	9

LEGEND:
$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table XI-1 (Cont'd). Data from Northfield (Malt–O–Meal) Dam Site Survey Feb. 16, 1985.

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
9.40	10:25	A1	40 ft Upstream of the Crest, 6 ft from Right Bank
9.50	10:25	A1	40 ft Upstream of the Crest, 6 ft from Right Bank
9.50	10:30	A2	40 ft Upstream of the Spillway Crest Centerline
9.50	10:30	A2	40 ft Upstream of the Spillway Crest Centerline
9.35	10:35	A3	Just Upstream of the Spillway Crest off of Right Bank
9.45	10:35	A3	Just Upstream of the Spillway Crest off of Right Bank
11.55	12:45	A4	25 ft Downstream, 10 ft from Left Bank
11.55	12:45	A4	25 ft Downstream, 10 ft from Left Bank
12.00	12:50	A5	25 ft Downstream, of Spillway Centerline
12.05	12:05	A5	25 ft Downstream of Spillway Centerline
11.75	1:00	A6	25 ft Downstream, 15 ft from Right Bank
11.80	1:00	A6	25 ft Downstream, 15 ft from Right Bank
11.55	1:05	A7	30 ft Downstream, 5 ft from Right Bank
11.50	1:05	A7	30 ft Downstream, 5 ft from Right Bank
11.50	1:30	A8	9 ft Downstream, 8 ft from the Right Bank.
11.55	1:45	A9	5 ft Downstream, 6 ft from the Right Bank.
11.55	1:45	A9	5 ft Downstream, 6 ft form the Right Bank.

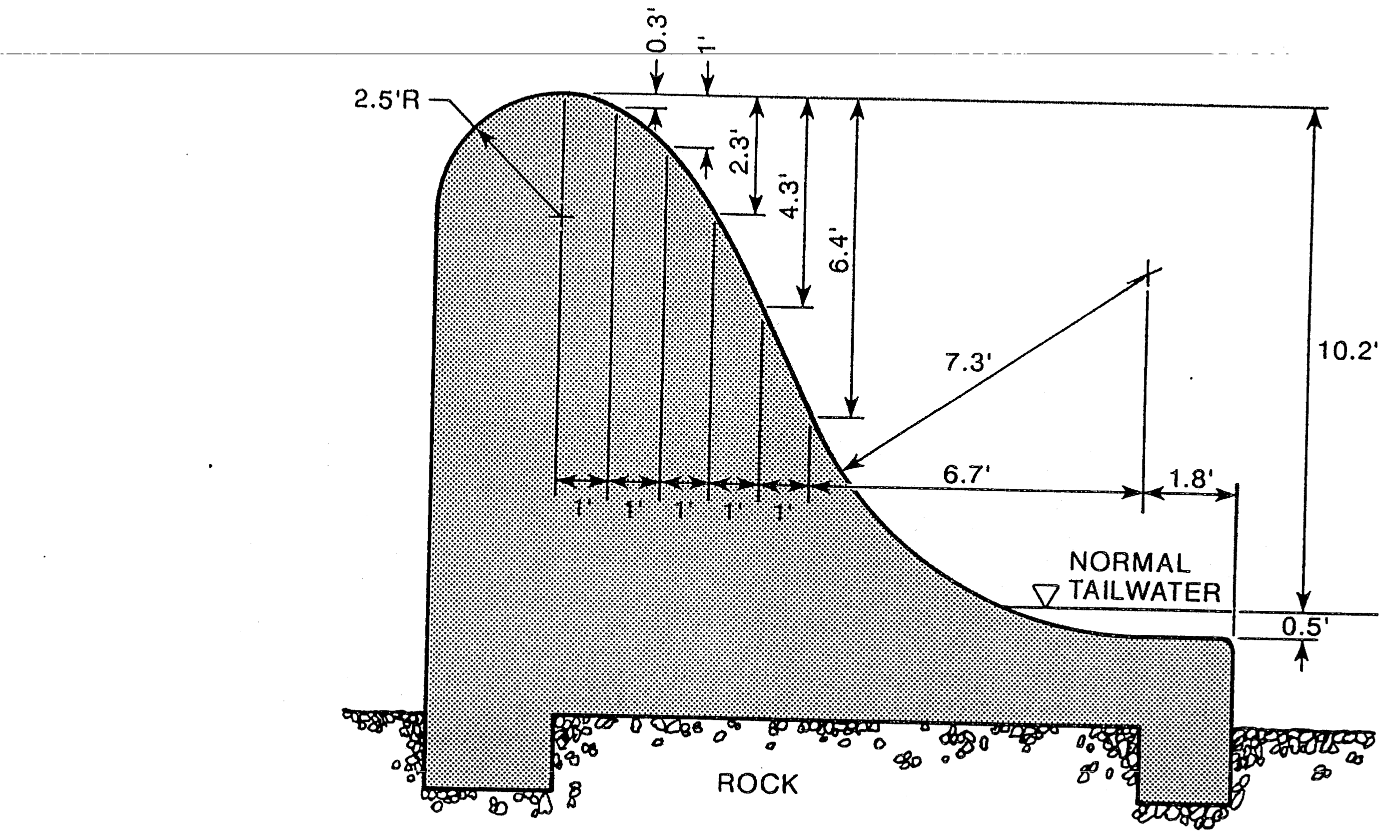


Fig. XI–1. Faribault Woolen Mill Dam original cross section.

Photo XI–1. Northfield Dam, A1 sampling location. Note: the large variation of aerated flow due to the large portions of concrete removed by concrete spalling.

XII. MINNEHAHA CREEK HEADWATERS CONTROL STRUCTURE

A. PHYSICAL DESCRIPTION

The Minnehaha Creek Headwaters Control Structure is located on the headwaters of Minnehaha Creek on the Grays Bay of Lake Minnetonka. The dam consists of a 200 ft wide sheet pile dam, and a 40 ft wide tainter gate control structure. This latter control structure consists of three 10 ft wide tainter gates as shown in plan Figure XII–1 and in section Figure XII–2.

This control structure relies on a free hydraulic jump and downstream riprap to dissipate excess kinetic energy.

B. DISCHARGE CHARACTERISTICS

Since this site was investigated only once, the discharge for this day was estimated without the creation of a rating curve. Because the width of the tainter gate opening was very small (approximately 0.15 feet) and the tailwater not submerged, the discharge at this site was estimated using Torricelli's equation for orifice flow. This resulted in a discharge of approximately 21 cfs at the time of sampling.

C. GAS TRANSFER MEASUREMENTS

Gas transfer measurements were collected at this site on February 15, 1984, just after the tainter gates were opened by the Watershed District. The results of these measurements and the data collected are presented in Table XII–1, and the sampling locations are shown on Figure XII–1. This was the first site where data was collected on hydraulic structures gas transfer. As such, the measurements did not have the standard methods sampler, to cut down on measurement collection error. The samples collected were taken by submerging a 300 mℓ Winkler bottle in the flow to fill. A large variation in the oxygen transfer measurements collected was observed. This large spread was not the consequence of only measurement error due to the sampling technique, but also due to the physics of the flow field at this site. As shown in Figure XII–1, Location A4 was collected in a region which appeared to be in a sheltered backwater of a large rock. This region was picked because of the different flow pattern which appeared to cycle bubbles through the area. So it is likely that the larger value found is not representative of the tainter gate mass transfer process but of this cycling process, and was ignored in the computation of the transfer efficiency for this structure. The other measuring sites were located in areas of flowing water and did not experience this difficulty.

TABLE XII–1. Results from Minnehaha Creek Headwaters Control structure, February 15, 1984

Atmospheric Pressure:	751 ± .1 mm of Hg
Water Temperature:	0.1 ± .1° C
Saturation Concentration:	14.09 ± .28 mg02/ℓ
Upstream Water Surface Elevation:	929.1 ± .1 ft
Downstream Water Surface Elevation:	926.9 ± .1 ft
Headloss:	2.2. ± .1 ft
Gate Opening:	0.15 ± .05 ft
Discharge/Unit Gate Width:	2.15 ± .2 cfs/ft

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Tainter gate	4.80	4	0.178	0.28	7.43	4	0.299	0.39	0.28	.048	1.15	NA

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table XII–1 (Cont'd). Data from Minnehaha Creek Headwaters Control Structure, Feb. 15, 1984

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
4.6	11:00	A1	Upstream Center of Tainter Gate
4.7	11:00	A1	Upstream Center of Tainter Gate
4.95	11:00	A2	Upstream Center of Tainter Gate
4.95	11:00	A2	Upstream Center of Tainter Gate
7.8	11:00	A3	Samples taken by hand D.S. in Hydraulic Jump
7.45	11:00	A3	Samples taken by hand D.S. in Hydraulic Jump
9.35	11:00	A4	Samples taken by hand D.S. in Hydraulic Jump
9.3	11:10	A4	Samples taken by hand D.S. in Hydraulic Jump
7.1	11:10	A5	D.S. Taken By Hand ~ 3.4 ft deep
7.05	11:13	A5	D.S. Taken By Hand ~ 3.4 ft deep
7.6	11:13	A6	D.S. Taken By Hand ~ 3.2 ft deep
7.6	11:30	A6	D.S. Taken By Hand ~ 3.2 ft deep

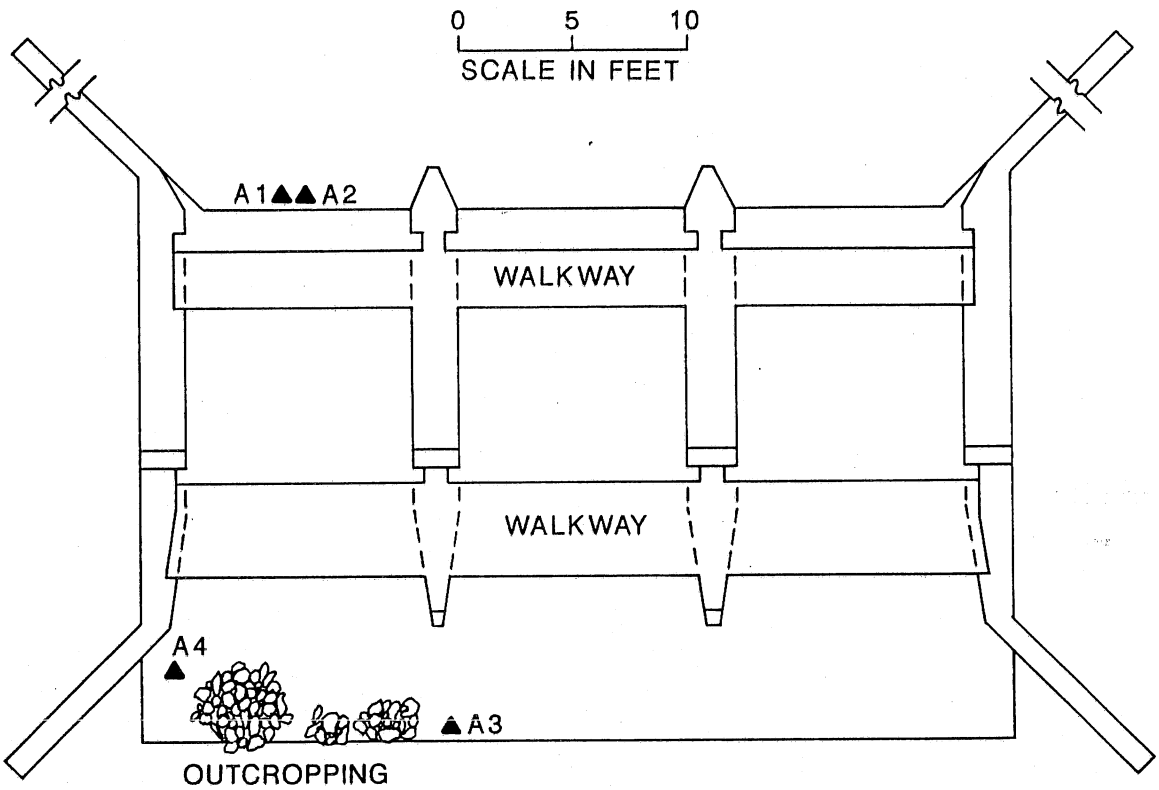


Fig. XII–1. Plan of the Minnehaha Creek headwaters control structure and February 15, 1984, sampling locations.

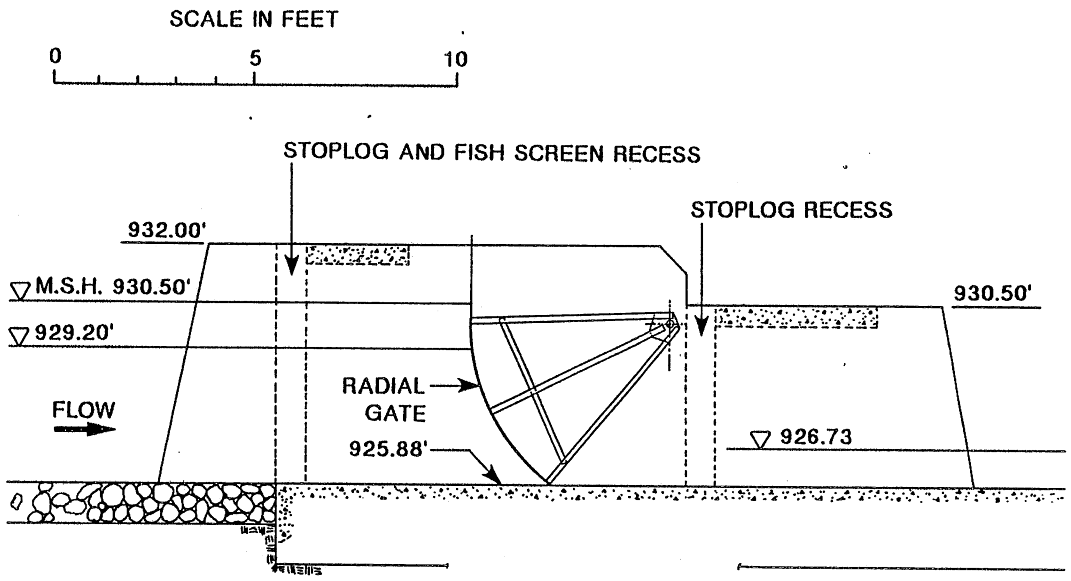


Fig. XII–2. Cross section of the Minnehaha Creek headwaters control structure.

XIII. RAPIDAN DAM

A. PHYSICAL DESCRIPTION

Rapidan Dam is located on the Blue Earth River just south of Mankato, Minnesota. The dam as shown in plan in Figure XIII–1 and in cross section in Figure XIII–2 consists of an Ambursen Dam, powerhouse, and seven tainter gate spillways. The tainter gate spillway shown in Fig. XIII–2 was of interest to this study.

B. DISCHARGE MEASUREMENTS

The discharge measurements collected at this site were only estimates. It was not possible with the measuring devices at this dam to estimate the gate opening without further analysis and field survey work. It should be noted that the turbines were inoperational during the sampling, and the only flow through this dam was due to the tainter gate.

C. GAS TRANSFER MEASUREMENTS

One site survey was performed at this site on March 9, 1985. The results of the measurements are presented in Table XIII–1. A Photograph of the spillway flow is shown in Photo XIII–1. Water samples were collected upstream of the gates and downstream in an area where the river naturally narrows, and along the north and south bays. After this date, further sampling in 1985 was suspended due to ice–out upstream of the dam. 1986 measurements were not collected due to turbine operation.

TABLE XIII–1. Rapidan Site Survey, March 9, 1985

Atmospheric Pressure:	743.8 mm of Hg	
Water Temperature:	1.1 ± 1°C	0.3
Saturation Concentration:	13.62 ± .28 mg02/ℓ	0.28
Upstream Water Surface Elevation:	868.7 ft	0.1
Downstream Water Surface Elevation:	810.7 ft	0.1
Headloss:	58 ft	0.05
Head on Crest:	N.A.	0.03 ft
Discharge/Unit Crest Width:	200 cfs/ft	ESTIMATE

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	8.95	6	0.045	.05	13.3	2	0.035	.31	0.926	.10	~ 1	60
Left Bank	8.95	6	0.045	.05	13.4	2	0.071	.31	0.942	.10	~ 1	60
Overall–A5&A6	8.95	6	0.045	.05	13.3	6	0.080	.08	0.94	.08	~ 1	60
Average									0.93	.08	~ 1	60

LEGEND:
- $\bar{c}$ = mean of collected sample
- n = number of samples
- σ = standard deviation
- W = precision uncertainty of each set of measurements
- E = transfer efficiency
- U = transfer efficiency

Table XIII–1 (Cont'd). Data from Rapidan Site Survey, March 9, 1985

Dissolved Oxygen Conc. mg $0_2/\ell$	Time	Location	Comments
13.40	10:15	A1	D.S. of Powerhouse off left bank in Backwater Area
13.30	10:15	A1	D.S. of Powerhouse off left bank in Backwater Area
8.90	10:45	A2	Upstream of Gate 2 approx. 4 ft deep
8.90	10:45	A2	Upstream of Gate 2 approx. 4 ft deep
8.95	10:50	A3	Upstream of Gate 3 approx. 4 ft deep
9.00	10:50	A3	Upstream of Gate 3 approx. 4 ft deep
8.95	10:55	A4	Upstream of Gate 4 approx. 4 ft deep
9.00	10:55	A4	Upstream of Gate 4 approx. 4 ft deep Dist. from Left bank ~ 3 ft deep
13.40	12:50	A5	D.S. in River Contraction approx. 1/3 Dist. From Left bank ~ 3 ft deep
13.40	12:50	A5	D.S. in River Contraction approx. 1/3 Dist. From Left bank ~ 3 ft deep
13.20	1:00	A6	D.S. in River Contraction approx. 1/2 Dist. From Left bank ~ 1 ft deep
13.30	1:00	A6	D.S. in River Contraction approx. 1/2 Dist. from Left bank ~ 1 ft deep
13.35	1:10	A7	D.S. in River Contraction approx. 2/3 Dist. From Left bank ~ 1 ft deep
13.40	1:10	A7	D.S. in River Contraction approx. 2/3 Dist. From Left bank ~ 1 ft deep
13.30	1:00	A8	D.S. Off of Right Bank By Concrete Abutment.
13.25	1:00	A8	D.S. Off of Right Bank By Concrete Abutment

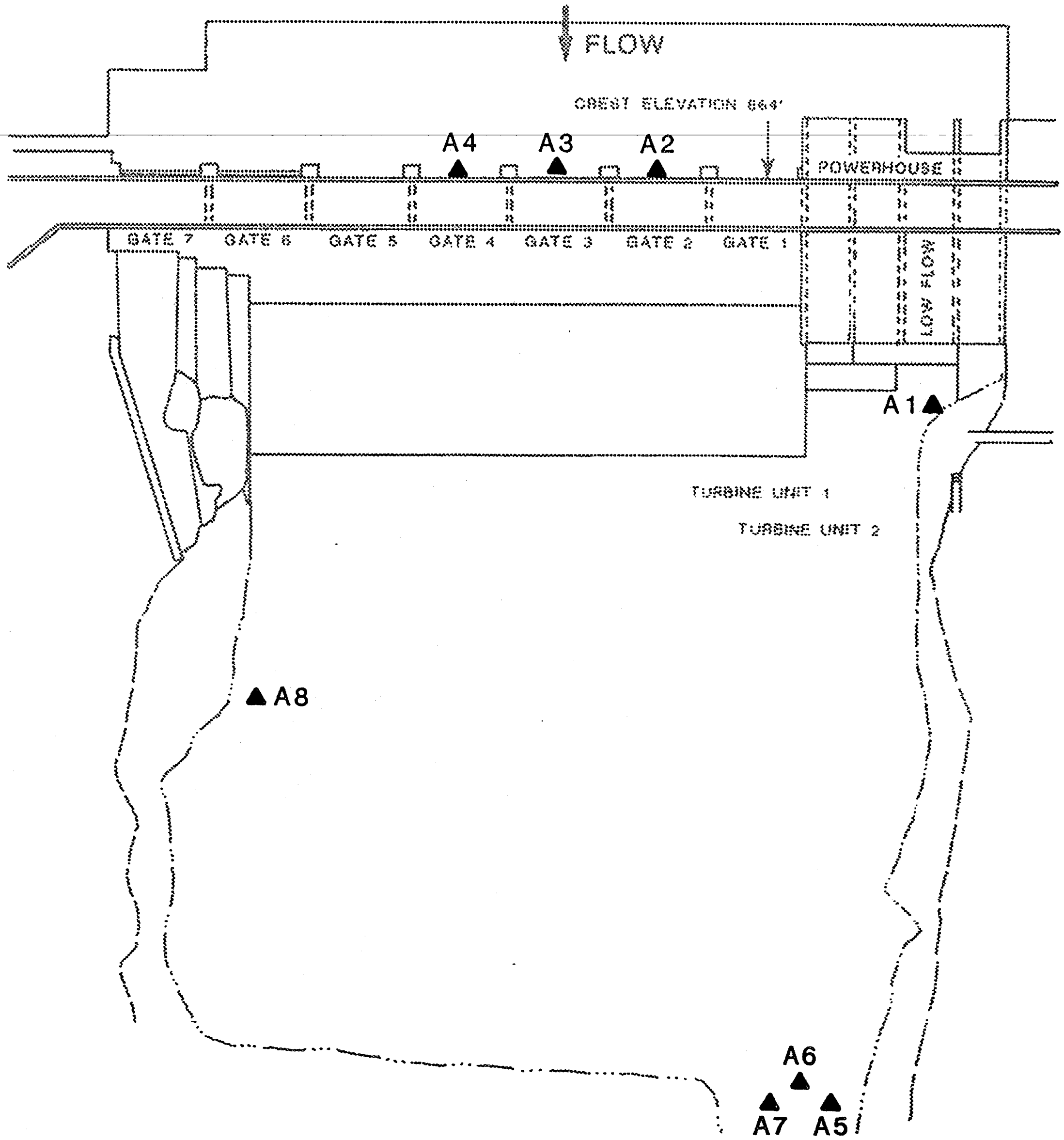


Fig. XIII–1. Plan of Rapidan Dam with March 9, 1985, sampling locations.

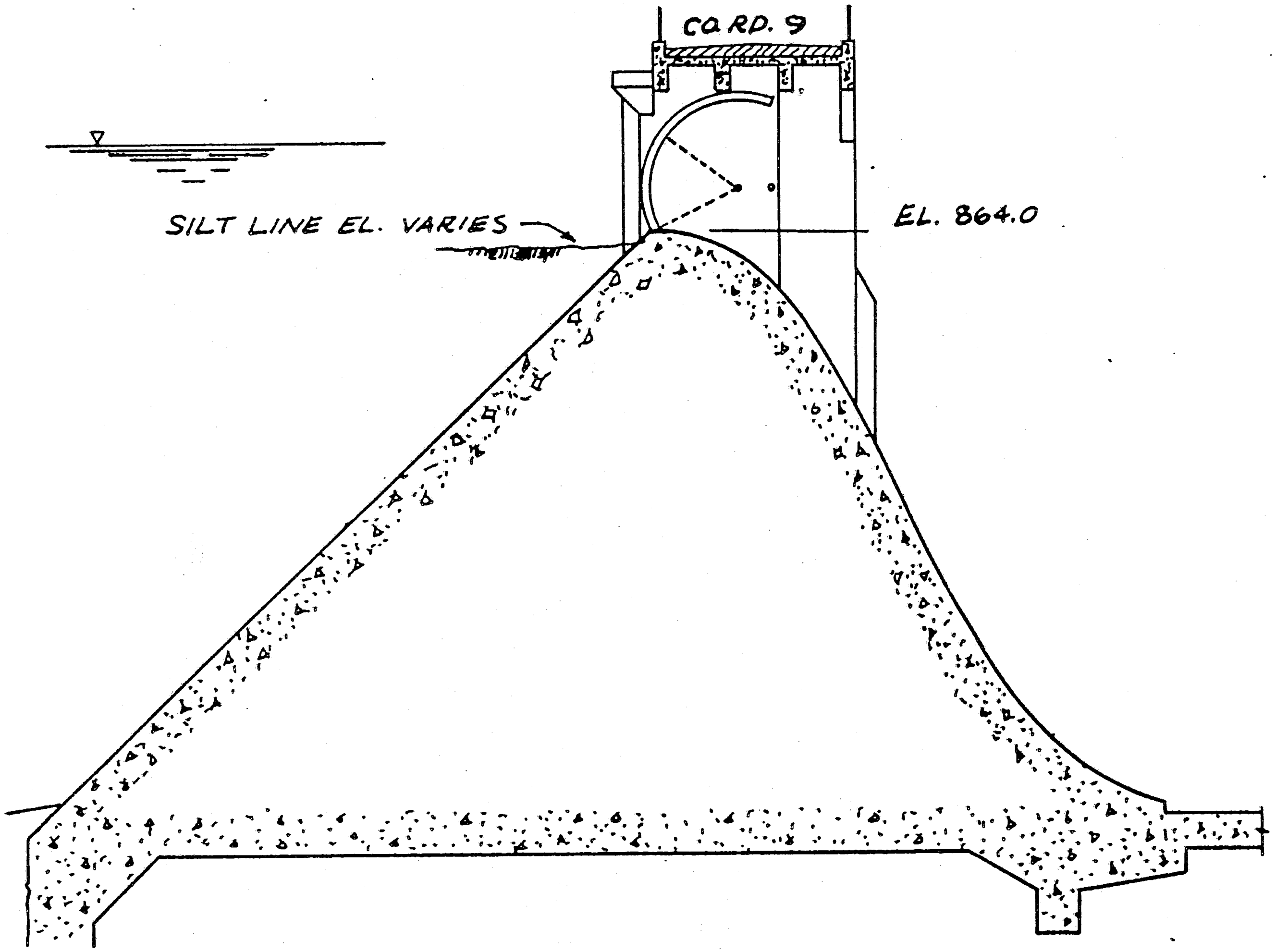


Fig: XIII–2. Cross section of the Rapidan Dam spillway.

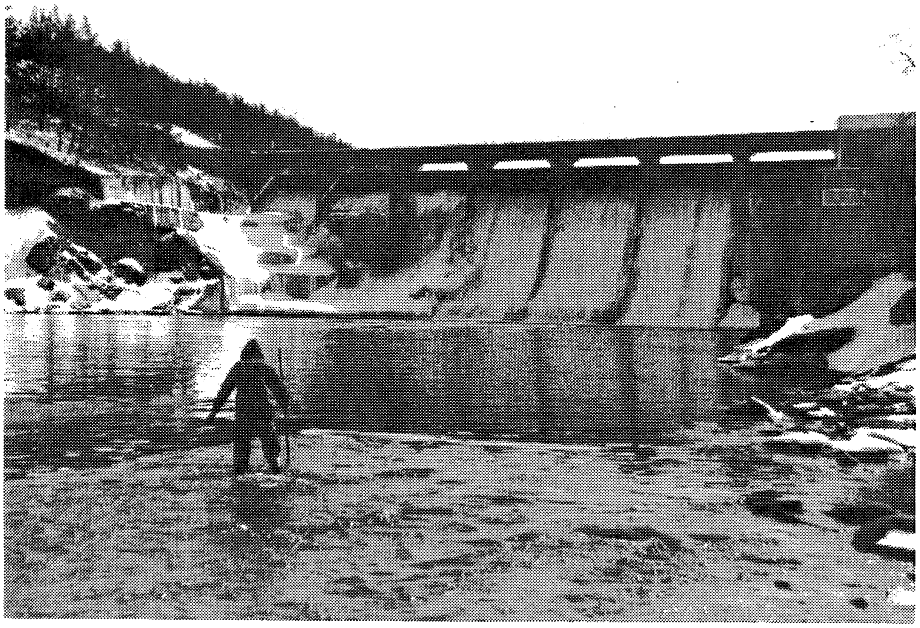


Photo XIII–1 Rapidan Dam tainter gate spillways.

XIV. BYLLESBY DAM

A. PROJECT DESCRIPTION

The Byllesby Dam is located on the Cannon River on the border between Goodhue and Dakota Counties, approximately 1 mile upstream from the City of Cannon Falls, Minnesota. The dam as shown in plan on Figure XIV–1 consists of the following structures: an Ambursen fixed crest spillway, main dam, and powerhouse. A typical cross section through the Ambursen fixed crest spillway main dam is shown in Figure XIV–2. However, the cross sections downstream of other sections of the spillway vary greatly due to the terraced rock stilling basin located on the right bank as shown in Photos XIV–1 and XIV–2.

B. DISCHARGE MEASUREMENTS

Discharge estimates were made using Figure XIV–3 developed by Barr Engineering for the spillway.

C. GAS TRANSFER MEASUREMENTS

One site survey was performed on February 23, 1985. The results of these measurements are presented in Table XIV–1. As shown in Figure XIV–1 dissolved oxygen measurements were collected upstream off the left and right abutments and downstream off the left and right banks.

The results of these measurements do not represent the oxygen transfer from the right bank spillway or the left bank spillway, but instead show the oxygen transfer from a combination of aerated spillway flow, splashing in the pool and riffle area on the terraced spillway, and also an aerated spillway flow and plunging hydraulic jump. Interestingly, the measurements collected downstream off the left and right bank have very little variability, indicating a well mixed condition exists downstream from the dam.

Further measurements on gas transfer at this structure were not collected due to the inability to distinguish between the oxygen transfer of the three structures represented.

TABLE XIV–1. Results from Byllesby Dam Site Survey, February 23, 1985

Atmospheric Pressure:	742.1 mm of Hg
Water Temperature:	1 ± .1°C 0.3
Saturation Concentration:	13.57 ± .28 mg02/ℓ
Upstream Water Surface Elevation:	855.05 ± 0.03 ft
Downstream Water Surface Elevation:	800.9 ± 0.05 ft
Headloss:	54.15 ± 0.05 ft
Head on Crest:	0.85 ± 0.03 ft
Discharge	1100 ± 50 cfs

Location	Upstream Concentration mg O_2/ℓ				Downstream Concentration mg O_2/ℓ				Transfer Effi–ciency		Tailwater depth ft	Aeration Length ft
	$\bar{c}$	n	σ	W	$\bar{c}$	n	σ	W	E	U		
Right Bank	10.30	2	0.071	0.64	13.3	6	0.029	0.05	0.93	0.12		
Left Bank	10.03	6	0.141	0.15	13.2	6	0.044	0.05	0.91	0.10		
Average									0.92	.09	NA	~54

LEGEND:

$\bar{c}$ = mean of collected sample
n = number of samples
σ = standard deviation
W = precision uncertainty of each set of measurements
E = transfer efficiency
U = transfer efficiency

Table XIV–1 (Cont'd). Data from Byllesby Dam Site Survey, February 23, 1985.

Dissolved Oxygen Conc. mg O_2/ℓ	Time	Location	Comments
10.00	9:20	A1	Upstream of left pier at surface
9.95	9:20	A1	Upstream of left pier at surface
10.20	9:20	A1	Upstream of left pier approx. 3 ft deep
10.20	9:20	A1	Upstream of left pier approx. 3 ft deep
9.90	9:23	A1	Upstream of left pier approx. 6 ft deep
9.90	9:23	A1	Upstream of left pier approx. 6 ft deep
13.20	10:00	A2	D.S. off of Left Bank approx. 3 ft deep
13.20	10:05	A3	D.S. off of Left Bank approx. 4 ft deep
13.20	10:05	A3	D.S. off of Left Bank approx. 4 ft deep
13.20	10:10	A4	D.S. below Powerhouse Walkway approx. 4 ft deep
13.25	10:10	A4	D.S. below Powerhouse Walkway approx. 4 ft deep
13.30	10:14	A5	D.S. off of Left Bank approx. 1 ft deep
13.30	10:14	A5	D.S. off of Left Bank approx. 1 ft deep
10.35	11:40	A6	U.S. Right Abutment just before crest 1 ft deep
10.25	11:40	A6	U.S. Right Abutement just before crest 1 ft deep
13.30	11:50	A7	D.S. Right bank just below last falls 2 ft deep
13.30	11:50	A7	D.S. Right bank just below last falls 2 ft deep
13.35	12:00	A7	D.S. Right bank just below last falls 2 ft deep
13.35	12:00	A7	D.S. Right bank just below last falls 2 ft deep

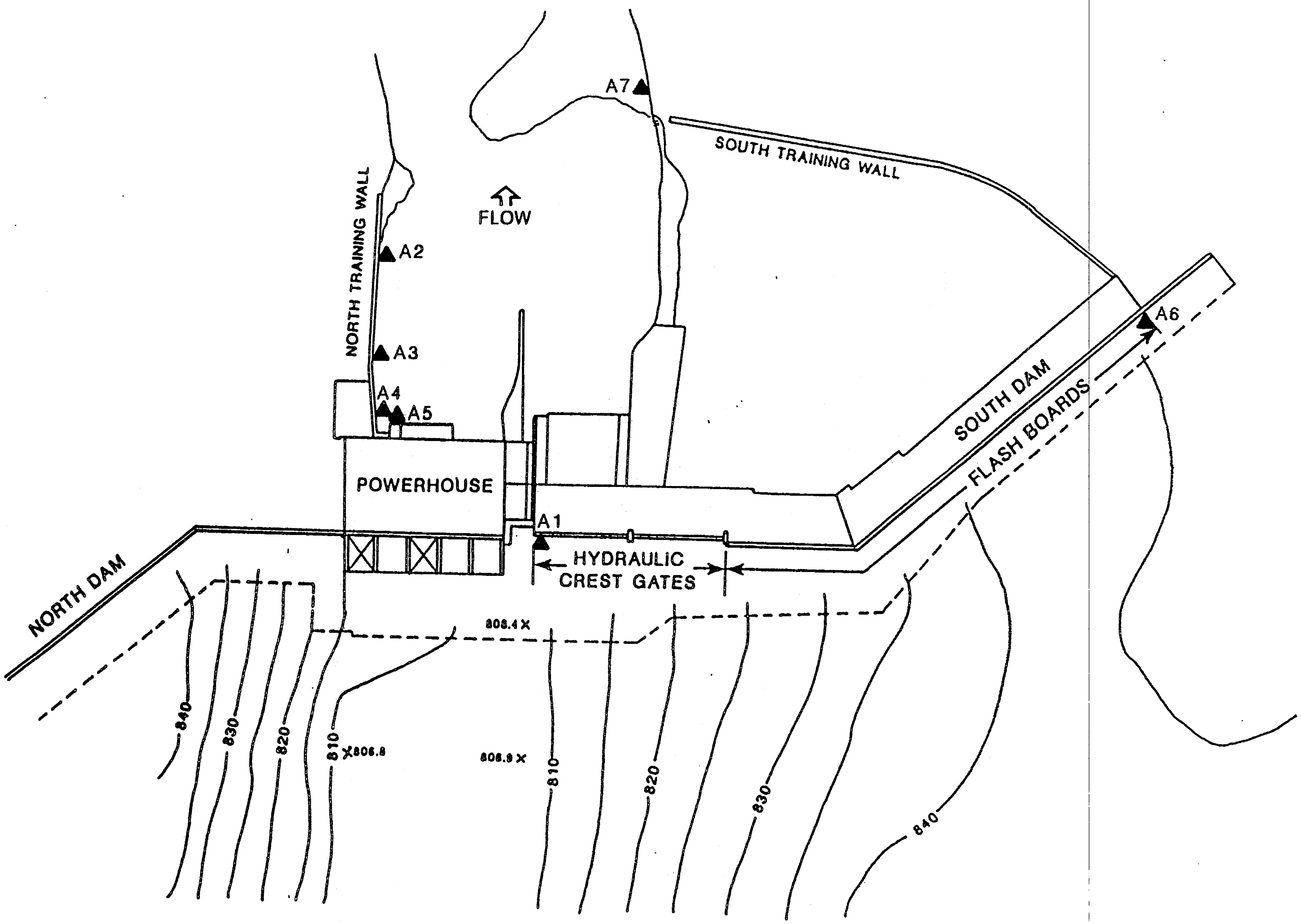


Fig. XIV–1. Sampling locations for the February 23, 1985, Byllesby Dam site survey.

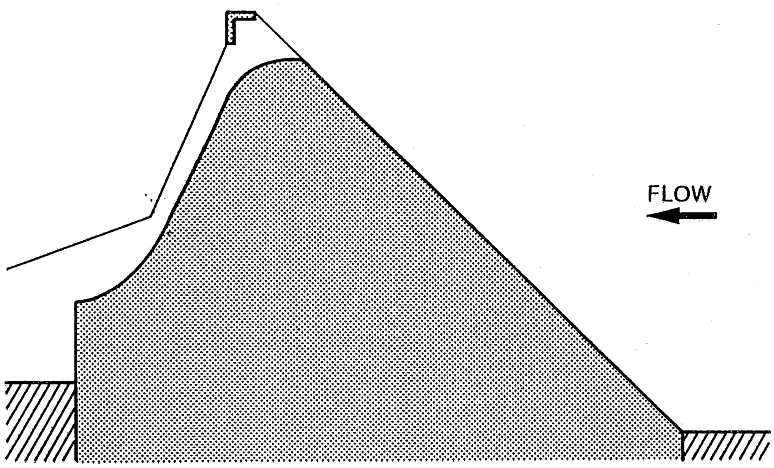
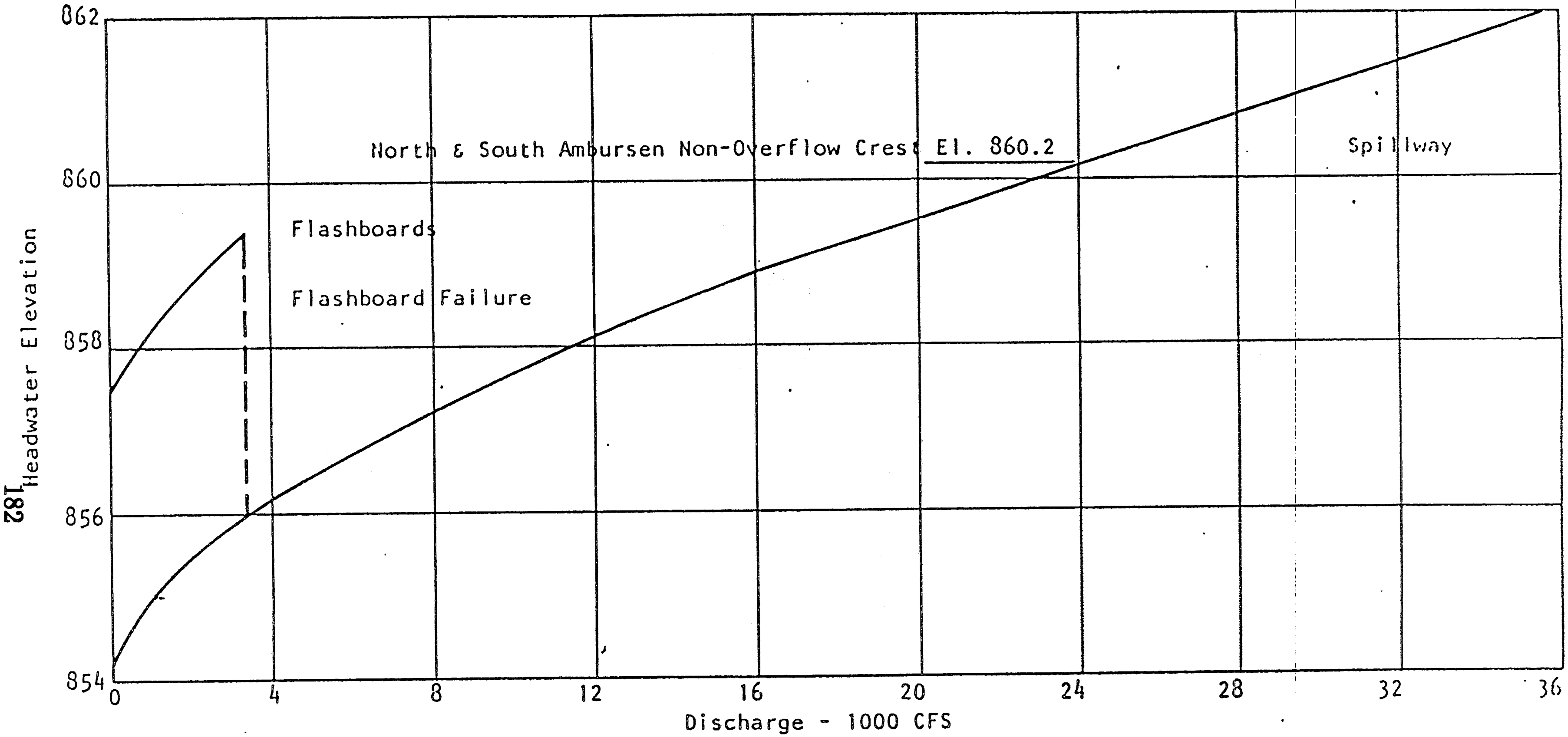


Fig. XIV–2. Typical section through the Byllesby Dam.



NOTE: Does Not Include Discharge Capacity of Sluice Gates.

Fig. XIV–3. Headwater rating curve for Byllesby Dam.

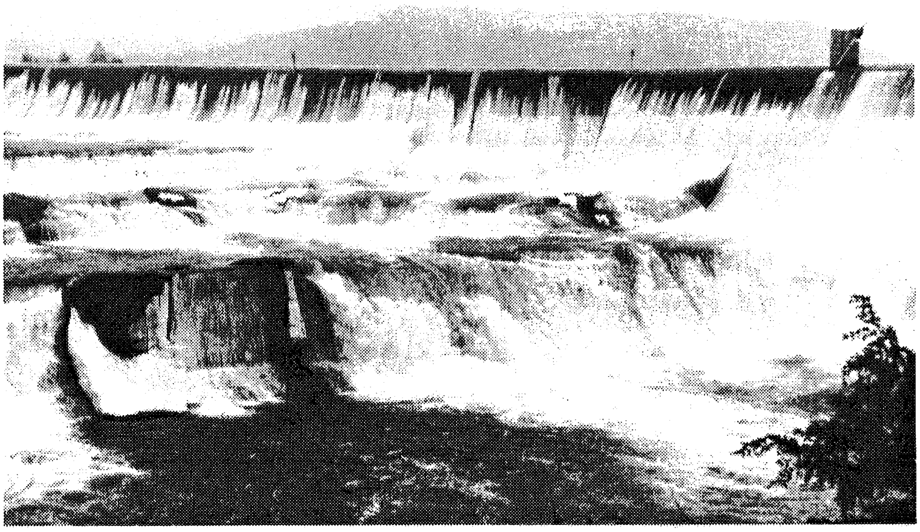


Photo XIV–1. Byllesby Dam, February 23, 1985, right spillway flow.

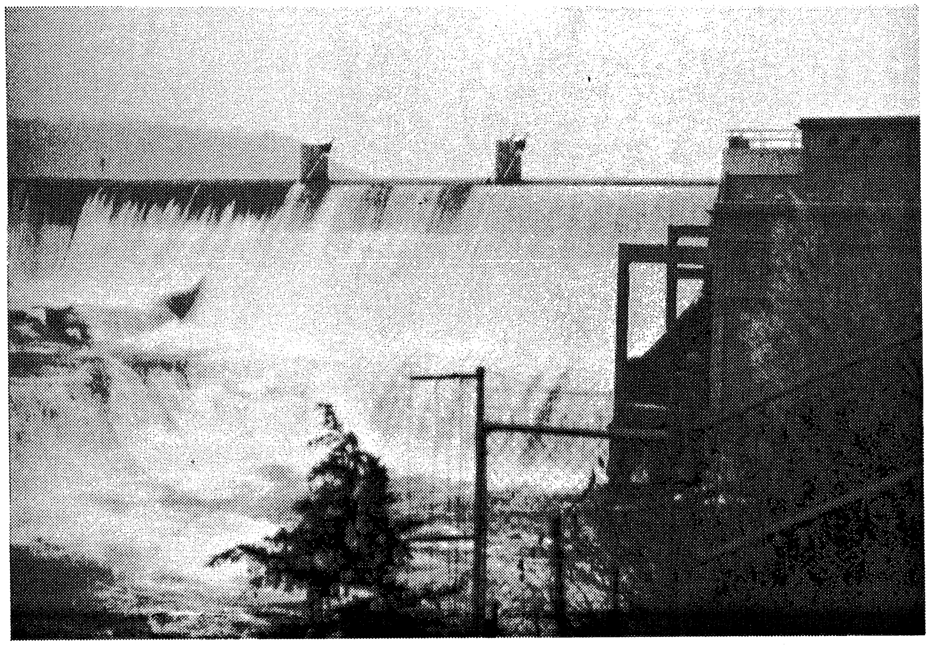


Photo XIV–2. Byllesby Dam, February 23, 1985, left rock spillway flow.

XV. SUMMARY AND CONCLUSIONS

Winter sampling proved to be an effective field measurement technique for gas transfer at many hydraulic structures in Minnesota. Measurements can be made using this technique at any structure where a significant ice cover forms upstream, such that the D.O. deficit is relatively large. Thirty four individual surveys at thirteen hydraulic structures are reported herein. These surveys were made over the '84–'85 and '85–'86 winter seasons. The measurements are summarized in Table XV–1.

TABLE XV–1. Summary of gas transfer measurements made with the winter sampling technique at 13 hydraulic structures in Minnesota.

Structure	Date	H (ft)	q (cfs/ft)	E	U	Tailwater Depth (ft)	Aeration Length (ft)	Comments
Kost Dam	2–2–85	13.16	1.35	0.41	0.04	0.8	~11	
	3–12–85	13.04	1.55	0.39	0.05	1.0	~11	
	12–13–85	12.97	1.75	0.41	0.02	1.1	~11	
	Spillway			0.18	0.02	NA	5	
	1–13–86	13.04	1.05	0.43	0.03	0.8	~11	
	Spillway			0.16	0.02	NA	11.2	
	Spillway			0.11	0.02	NA	5.2	
	2–21–86	12.93	0.88	0.45	0.03	1.0	~11	
	Spillway			0.14	0.01	NA	11.2	
	Spillway			0.12	0.01	NA	6.5	
	3–10–86	13.00	1.22	0.40	0.03	0.9	~11	
	Spillway			0.24	0.02	NA	10.8	
	Spillway			0.20	0.02	NA	10.0	
St. Cloud Dam	3–2–85	17.44	7.27	0.53	0.04	0.8	~19	
	3–14–85	17.55	8.91	0.55	0.04	0.9	~19	
	12–19–85	16.34	11.82	0.45	0.05	0.8	~10	
	1–17–86	17.16	10.55	0.50	0.05	1.5	~10	
Anoka Rum River	2–2–84	13.10	8.2	0.63	0.03	11.8	~1	
		13.00	11.3	0.65	0.03	11.4	~1	
		12.62	18.8	0.68	0.03	12.2	~1	
		12.26	26.0	0.54	0.02	12.4	~1	
		12.24	32.8	0.44	0.02	12.2	~1	
		11.90	35.6	0.40	0.02	12.3	~1	
		13.43	9.8	0.68	0.03	11.3	~1	
Anoka Rum River:	1–24–86							
Tainter gate		10.34	4.5	0.62	0.03	11.8	~1	
Amberson Spillway		10.34	2.03	0.57	0.03	NA	NA	
Amberson Spillway		10.34	2.03	0.59	0.03	NA	NA	
	3–14–86							
Tainter Gate		10.38	4.1	0.68	0.05	11.8	~1	
		10.27	6.8	0.59	0.04	11.9	~1	
Amberson Spillway		10.27	2.2	0.57	0.04	NA	NA	
		10.27	2.2	0.55	0.04	NA	NA	
Elk River Dam	1–16–85	13.68	1.5	0.67	0.03	5.5	~13.3	
	1–20–85	13.68	1.6	0.64	0.04	5.5	~13	
	1–24–85	14.18	1.4	0.58	0.03	5.0	~13	
	2–26–85	12.09	2.0	0.58	0.03	7.2	~13	
	12–6–85	14.66	2.3	0.56	0.03	4.7	~13	
	1–10–86	15.00	1.6	0.59	0.02	4.2	~13	
	1–31–86	14.83	1.9	0.56	0.02	4.5	~13	

TABLE XV–1. (Cont'd) Summary of gas transfer measurements made with the winter sampling technique at 13 hydraulic structures in Minnesota.

Structure	Date	H (ft)	q (cfs/ft)	E	U	Tailwater Depth (ft)	Aeration Length (ft)	Comments
Faribault Woolen Mill	1–26–85	9.07	0.9	0.28	0.04	1.0	~6	
	3–7–85	8.60	1.4	0.33	0.07	1.6	6	
	12–17–85	9.0	1.1	0.37	0.03	1.2	~6	
	Spillway			0.05	0.02	NA	~6	
	2–28–86	9.0	0.9	0.43	0.03	1.0	~6	
	Spillway			0.08	0.02	NA	~6	
Amery Dam	2–16–85	10.87	22.7	0.39	0.03	0	25	
	Spillway			0.24	0.42	NA	25	
Coon Rapids Dam	12–22–85	12.41	13.9	0.50	0.11	3.1	0	
				.60	0.14	13.6	0	
	1–9–86	7.22	19.2	0.51	0.09	8.9	0	
Shady Lake Dam	1–22–86	16.91	1.4	0.65	0.08	~4	~11	
	2–14–86	16.61	1.6	0.68	0.05	~4.3	~11	
New Richmond Dam	2–19–85	10.13	1.2	0.48	0.04	~5	~15	Spray from Stoplogs
Northfield Dam	2–16–85	9.00	0.6	0.50	0.05	2.3	9	
Minnehaha Control Structure	2–15–84	2.20	2.15	0.28	0.05	1.15	NA	Tainter Gate Structure–no spillway
Rapidan Dam	3–9–85	58.00		0.93	0.08	~1	60	
Byllesby Dam	2–23–85	54.15		0.92	0.09	NA	54	Spillway–weirs–etc. combined.

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