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Coastal and Hydraulics Laboratory

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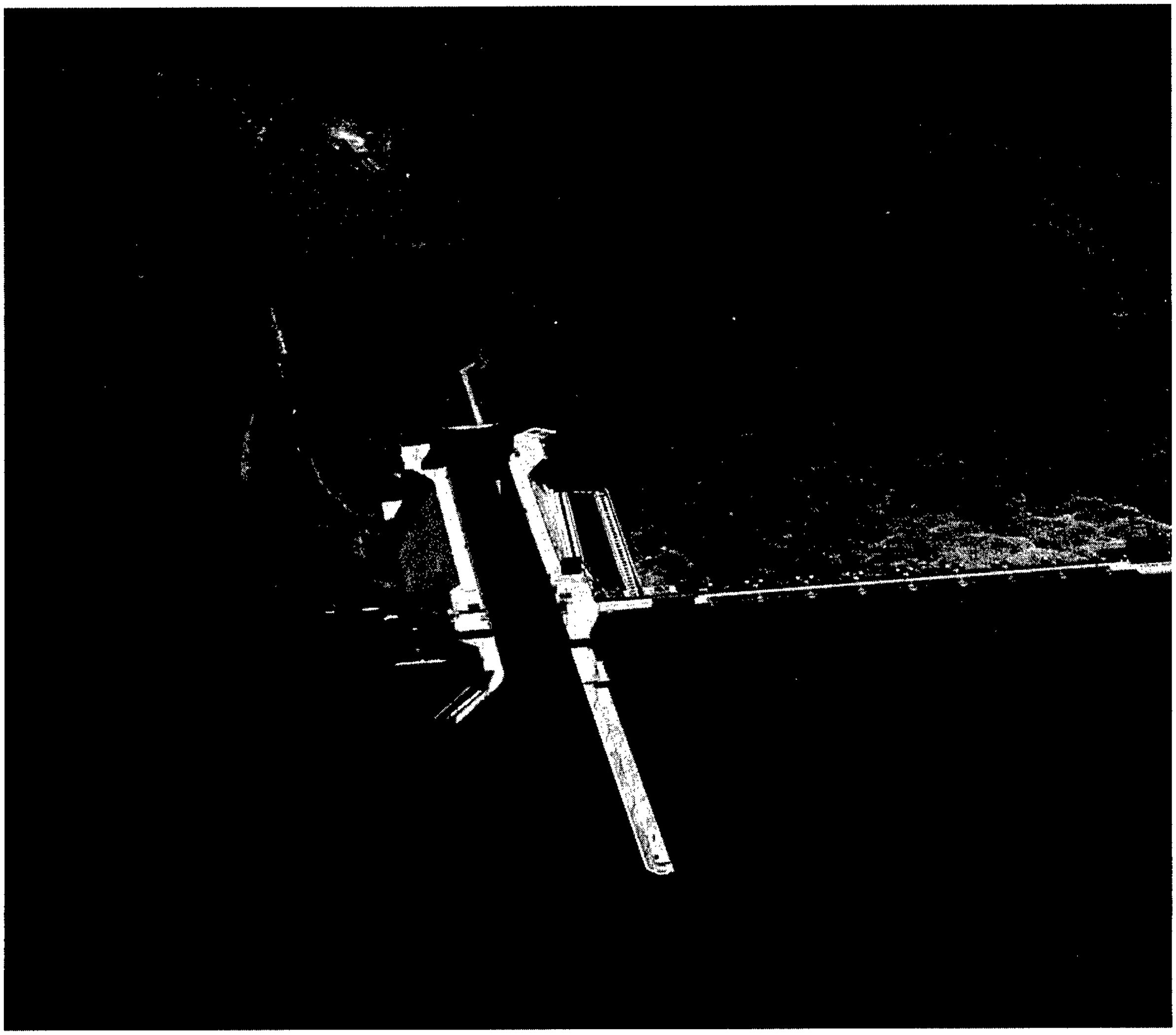
September 2003



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Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

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ABSTRACT: A 1:40 Froudian Scale model was used to investigate the hydraulic performance of the Lower Monumental Dam spillway, stilling basin, and tailrace for dissolved gas reduction and stilling basin apron scour. The model reproduced a 2-1/2 bay section of the spillway and portion of the non-overflow section between the spillway and navigation lock. Performance characteristics of two spillway deflectors were evaluated. The existing deflector (12.5 ft long horizontal with small fillet radius for transition from spillway to deflector) was recommended at el 434.0 because of its slightly wider tailwater range for operation in skimming flow. However, for fish passage over the deflector, the Type I deflector (12.5 ft horizontal with 15-ft radius transition) can likely be adopted with little degradation in dissolved gas uptake. Loadings on the deflector were estimated with pressure measurements on the horizontal and vertical faces. Instantaneous cavitation pressures were measured on the vertical face of the deflector due to flow separation. Only minor cavitation damage has been observed at other spillway deflectors, and thus, significant damage is not expected. Pressure measurements on the stilling basin flow show potential uplift pressure as high as 3,300 lb/ft^2. If these pressures have a pathway beneath the stilling basin apron, significant uplift force could result, ultimately causing a catastrophic failure of the apron. Debris was transported from the tailrace into the stilling basin for discharges above about 6.7 kcfs per spill bay (4.0-ft gate opening), when skimming flow occurred in the stilling basin. A numerical model of flow in the stilling basin showed a significant circulation cell on the stilling basin floor near the site of apron erosion, when operating the outside bay without a deflector. With a deflector on the outside bay, the circulation cell was nonexistent, indicating potential for significant reduction in apron scour. Experiments in the physical model verified the numerical model indications. Even with the outside bay deflector, some movement of debris in the stilling basin occurred. Thus, debris should be excluded from the stilling basin to completely eliminate apron scour. Several alternatives were investigating including armoring or grouting the tailrace to stabilize the debris, stilling basin wide debris trap, elevated end sill, and stilling basin splitter walls. Any alternative should be investigated in a general model.

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List of Symbols

D	Characteristic hydraulic length, usually depth, ft
F	Froude Number, dimensionless
G	Gravitational acceleration, 32.2 ft/sec^2
L_m	Length in model, ft
L_p	Length in prototype, ft
L_r	Model-to-prototype length ratio, dimensionless
tr	Model-to-prototype time ratio, dimensionless
tm	Time in model, seconds
tp	Time in prototype, seconds
v	Kinematic viscosity, ft^2/sec
Qm	Discharge in model, ft3/sec
Qp	Discharge in prototype, ft3/sec
Qr	Model-to-prototype discharge ratio, dimensionless
Re	Dimensionless Reynolds number
$\overline{V}$	Velocity, ft/sec
Vm	Velocity in model, ft/sec
Vp	Velocity in prototype, ft/sec
$\overline{V}_p$	Prototype velocity, ft/sec
Vr	Model-to-prototype velocity ratio, dimensionless
γs	Specific weight of rock, lb/ft3
γw	Specific weight of water, lb/ft3

Conversion Factors Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
feet	0.3048	meters
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	Newtons

Preface

The U.S. Army Engineer District, Walla Walla authorized the hydraulic modeling research effort reported herein. The study was initiated in 1999 with the construction of the section model with experimental work continuing until March 2002. Mr. Dan M. Katz, hydraulic engineer, was the technical point of contact in the Walla Walla District. Messrs. Mark F. Lindgren Chief, Hydrology and Hydraulics Branch and Lynn Reese, Chief, Hydraulic Design Section, Walla Walla District helped direct the study.

Dr. Steven C. Wilhelms and Mr. Thomas E. Murphy, Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), were the principal investigators for this study. They designed the model, developed and conducted a testing program, analyzed model data, and developed recommendations. Ms. Laurin Yates (CHL) assisted in the study with data collection, analysis, and presentation. Mr. Calvin Buie (CHL) assisted in the data collection effort. Dr. Wilhelms, Mr. Murphy, and Ms. Yates developed this report.

Mr. John F. George, former Chief, Inland Hydraulics Structures Branch, CHL, and Mr. Charles H. Tate, Jr., Chief, Inland Hydraulics Branch, CHL, directed the study and helped coordinate the effort. Mr. Thomas W. Richardson and Dr. William D. Martin were Director and Deputy Director, respectively, CHL.

COL James R. Rowan, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

1 Introduction

Background

During many spill operations at Lower Monumental Dam, total dissolved gas (TDG) levels exceed state and national standards in the river downstream of the project. To address this issue, structural and operational alternatives that reduce the dissolved gas levels were investigated in the Dissolved Gas Abatement Study (DGAS[1]). As part of the DGAS effort, existing flow conditions that contribute to TDG exchange and flow patterns under various alternatives were investigated in physical hydraulic models. Additionally, in the Lower Monumental stilling basin below the spillway, scour has occurred on the stilling basin floor, resulting in significant erosion of the concrete apron. The high level of erosion prompted concerns regarding the stability of the stilling basin apron. It seemed likely that debris, transported into the stilling basin from the tailrace contributed to the erosion.

To more completely understand these issues, the hydraulic performance of the Lower Monumental spillway and stilling basin was investigated for several alternative designs and configurations in a 1:40-scale model of a longitudinal section of the Lower Monumental structure.

The goals of this investigation were to identify operational and structural changes that could reduce stilling basin erosion, ensure stilling basin stability, and reduce downstream dissolved gas concentrations, while minimizing impacts on other river uses. The following areas were investigated:

a. Hydraulic performance of spillway deflectors.

b. Forces on the spillway deflectors.

c. Uplift pressures on the stilling basin floor.

d. Debris transport into and around the stilling basin.

e. Alternatives to reduce debris transport into the stilling basin.

f. Alternatives to reduce debris movement in the stilling basin.

The experimental studies and results from each of these areas are presented in later sections of this report.

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[1] Investigations conducted by the U.S. Army Engineer Districts, Portland and Walla Walla on the U.S. Army Corps of Engineers' projects on the Snake and Columbia Rivers.

Project Description

Lower Monumental Dam is located at river mile 41.6 on the Snake River in Franklin and Walla Walla Counties, WA. The dam is about 3,800-ft long and includes a powerhouse, spillway, navigation lock, and two fish ladders (Figure 1). The powerhouse on the north end of the dam consists of six Kaplan turbines, each with a 135,000-kW generator. Maximum discharge through the powerhouse is approximately 120 kcfs[1]. The spillway is 512-ft long and has eight 50-ft-wide by 60-ft-high tainter gates. The spillway crest is at elevation[2] 483.0 with a normal pool elevation of 540.0.

As originally designed, excess energy in the spillway discharge was dissipated by a hydraulic jump in a horizontal apron-type stilling basin with a sloping end sill as shown in Figure 2. Spillway bays 2 through 7 have added deflectors that are 12.5-ft long and located at el 434. The deflectors act to deflect the spill flow across the surface of the tailwater. The stilling basin is 198.0 ft long with an invert elevation of 392.0. The tailwater elevation may range from near 437.0 to 465.1 for the Lower Monumental spillway design flood of 850 kcfs. For many operations, the tailwater elevation will range from 440.0 up to 452.0, which results in an average depth of flow in the stilling basin of 48 to 60 ft. The lock is a single-lift type, with a clear plan dimension of 86 ft by 650 ft and a 15-ft minimum depth. The lock discharges into the tailwater channel about 400 ft downstream of the end of the stilling basin.

The tailrace of the Lower Monumental spillway and powerhouse was excavated to create greater depths of flow and provide greater energy dissipation. The channel downstream of the powerhouse slopes upward from the draft tube inverts at el 344.5 to el 420 within 200 ft of the powerhouse and then to el 425 at the end of the lock guide wall (Figure 3). The tailwater channel downstream of the stilling basin is highly irregular ranging in elevation from 390 to 425. At the end of the stilling basin, the channel bed abruptly slopes from el 392 to just over 400. This "bench" runs for about 80 ft with elevations ranging from 390 to 405. A second bench with a mean elevation of about 415 runs parallel to the spillway. The average channel bed elevation ranges from 415-420 for a half-mile downstream of the dam. A slight bend in the river then starts with greater depths and conveyance on the north half of the channel.

Problem definition

To reduce the absorption of dissolved gas during spill releases, spillway deflectors were added to the six interior bays of the Lower Monumental spillway. The deflectors cause the nappe of flow on the spillway to be deflected across the surface of the tailwater, thereby reducing the plunging action of the highly aerated flow. By reducing the plunging, the absorption of dissolved gas is significantly reduced. However, deflectors were not added to the exterior bays. Thus, bays 1 and 8 continued to demonstrate the deeply plunging flow that

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[1] kcfs is thousand feet per second.

[2] All elevations (el) referenced to the National Geodetic Vertical Datum (NGVD). To convert feet to meters, multiply by 0.3048.

causes high levels of TDG. Based on field measurements (Schneider 1996), the outside bays contributed noticeably to the dissolved gas level measured in the downstream channel compared to the bays with deflectors on the interior. The logical extension of this observation is that deflectors should be installed in the outside bays to reduce the level of TDG absorption.

In recent years, the stilling basin floor has been scoured in two locations (Figure 4). A ball-mill grinding action that transports rock and debris around the stilling basin floor is the likely cause of the scouring. The debris probably originates in the downstream channel and is transported into the basin by circulation cells in the tailrace. Because the damage to the stilling basin could pose a potential threat to the stability of the stilling basin floor, operational and structural alternatives were investigated to reduce or eliminate the potential for scour.

Objective and scope

The objective of this model investigation was to identify operational and structural changes that may reduce stilling basin erosion and downstream dissolved gas concentrations, while minimizing impacts on other river uses. To this end, the 1:40 scale section model was developed to investigate stilling basin performance for different deflector designs. Deflector-performance studies were aimed at defining the deflector design and flow conditions that minimize plunging flows. Flow conditions that contribute to debris transport and stilling basin erosion, were investigated, as well as those conditions and structural designs that would reduce debris movement. Stilling basin scour has penetrated the concrete apron thickness resulting in the potential for uplift pressures on the stilling basin apron monoliths because of flow between the monoliths and the underlying bedrock. Stilling basin floor pressures due to plunging flows were also investigated. To achieve these objectives, the hydraulic performance of the deflectors and stilling basin were experimentally evaluated over a range of spillway discharges and tailwater elevations. Likewise, debris transport and stilling basin uplift pressures were evaluated for a range of discharges. Detailed scopes of work for this research effort are presented in Appendix A.

Hydraulic model

Similitude. Similitude relationships between model and prototype units and dimensions are required for accurate transfer of model conditions to prototype events. Dimensional analysis indicates that the dominant forces in a free-surface hydraulic flow situation are inertial (velocities) and gravitational (potential energy). Similitude requires that the relationship of these forces in the prototype be reproduced in the model, typically referred to as Froudian Scale Modeling, where the Froude Number of the model is equal to the Froude Number of the prototype. The Froude Number (Equation 1) is described by

$$F = \frac{\vec{V}}{\sqrt{gD}} \tag{1}$$

where F is the dimensionless Froude Number, the ratio of inertial forces to gravity forces; $\vec{V}$ is velocity; g is gravitational acceleration; and D is a characteristic hydraulic length, usually depth.

Similitude also requires that the ratio of inertial forces (velocities) to viscous forces (turbulence) be retained between model and prototype. This is Reynolds scale modeling, where the Reynolds Number (Equation 2) of the model is equal to the Reynolds Number of the prototype.

$$\mathrm{Re} = \frac{\vec{V}D}{\nu} \qquad (2)$$

where Re is the dimensionless Reynolds Number, the ratio of inertial forces to viscous forces; and ν is kinematic viscosity.

It is impossible, however, to meet both of these criteria for most Froudian scale models, since a Froudian model will be less turbulent than the prototype or the level required by Reynolds modeling. The solution to this conundrum is to size the Froudian scale model such that the flow conditions of interest will be turbulent with Reynolds Numbers greater than 5,000. With turbulent flow, the model distortion introduced by not rigorously meeting the Reynolds similitude requirements is not significant.

To develop similarity relationships between model and prototype for a Froudian scale model, the Froude Number for the model is equated to the set full-scale Froude Number. From this equation, the prototype-to-model scale relationships can be developed to transfer model dimensions and hydraulic data to prototype equivalents.

The following ratios for scaling model quantities to prototype dimensions were used for the 1:40-scale section model.

Dimension	**Scale Ratio**	**Scale Relation**
Length	$L_r = L_m/L_p$	1:40
Time	$t_r = t_m/t_p - L_r^{1/2}$	1:6.325
Velocity	$\vec{V}_r = \vec{V}_m/\vec{V}_p = L_r^{1/2}$	1:6.325
Discharge	$Q_r = Q_m/Q_p - L_r^{5/2}$	1:10,119
Note: L_m, L_p - length in the model and length in the prototype, respectively.		

Measurements of distance, water-surface elevations, flow, velocities, and time can be transferred quantitatively from the model to the prototype equivalents by means of these scale relations.

Description. The section model of Lower Monumental reproduces approximately 600 ft of approach, 178 ft of spillway, two and one-half 50-ft-wide spillway bays with tainter gates, two 14-ft-wide piers, the 198-ft-long stilling basin, end sill, and about 100 of the nonoverflow section on the south end of the spillway (Figure 5). About 600 ft of exit channel is reproduced. The spillway and tainter gates were fabricated from sheet metal with a painted finish. The stilling basin was fabricated from plastic-coated plywood; the end sill was painted wood. The upstream and downstream approach channels were constructed from plastic-coated plywood.

The flume, in which the model was tested, was constructed from steel box channels. One-in.-thick clear Plexiglas viewing panels extended for 20 ft upstream and downstream of the model structure. Water was supplied to the model with three 12-in.-diam lines. The flow was monitored with a Data Industrial® Model 2100 flow monitor with a Model 220BR flow sensor (paddle type meter).

Calibration. The flow monitor was calibrated against a volumetric tank measurement over time. Seven calibration points were taken at discharges up to about 5.6 ft^3/sec. The actual discharge as measured with the calibration tank was compared to the metered discharge as displayed by the flow monitor. The calibration data and relationship between measured flow rate and monitored flow rate are given in Appendix B.

Several water-surface measurements were made using stilling wells outside of the model flume rather than an in-flow staff gage. Piezometers were also used to measure average pressures at different locations along the stilling basin floor and at other locations on the structure. The pressures were recorded as a water-surface elevation. The elevations for the water-surface measurements and pressure measurements were referenced to the elevation of the spillway crest.

2 Experimental Tasks and Results

Hydraulic Performance of Spillway Deflectors

This section summarizes the results from experiments to evaluate two deflector designs: the existing spillway deflector (Type I), which is located at el 434.0 and consists of a 12.5-ft-long deflector with a small fillet radius toe curve (Figure 6) and a modified design (Type II) that was also located at el 434.0. The Type II deflector consisted of a 12.5-ft-long deflector with a 15.0-ft radius toe curve (Figure 7). Presented in this section is classification of the stilling basin and tailrace flow conditions based on hydraulic action and photographs to document the flow conditions.

Experimental conditions and procedures

For deflector evaluation, flow conditions over the deflectors and through the stilling basin were investigated for gate openings ranging from 1.0 to 12 ft. With the Lower Monumental pool elevation set at el 537.0, for these gate openings, the discharge per spill bay ranged from about 1.8 kcfs to 21.9 kcfs (Table 1). Also

Table 1
Gate Openings and Corresponding Discharges

Gate Opening ft	Discharge Per Spill Bay kcfs	Spillway Discharge[1] kcfs	Total River Discharge with Max Powerhouse Flows kcfs
1	1.8	14.4	134.4
2	4.2	33.6	153.6
3	5.6	44.8	164.8
4	6.7	53.6	173.6
5	8.5	68.0	188.0
6	10.2	81.6	201.6
7	12.0	96.0	216.0
8	13.8	110.4	230.4
10	18.2	121.6	241.6
12	21.9	175.2	295.2

[1] Bays in uniform operation with pool el 537.0

given in Table 1 is the total spillway discharge assuming eight bays are operating uniformly and total river flow assuming that maximum powerhouse flows (120 kcfs) are also being released. This range covered total river flows from about 14 kcfs (no powerhouse flows) up to about 295 kcfs.

For each experiment, a discharge was set and the upper pool was stabilized at el 537.0. Tailwater elevation was then adjusted from as low as el 435.0 up to as high as el 468.0. The critical tailwater elevations, where a change in performance was indicated, were also approached from higher tailwater elevations to assess the stability of the hydraulic conditions. For each discharge, as the tailwater was increased, the flow conditions at the deflector, in the stilling basin, and in the tailrace were observed, documented in a written description and with video, and photographed.

Flow classification

In previous studies of deflectors (USAEWES 1996a; USAEWES 1996b; USAEWES 1999; Wilhelms 2002), hydraulic performance was classified into several categories depending upon the action in the stilling basin. Similar categories were adopted to describe the performance of Lower Monumental deflectors as described as follows:

a. Category 1: *Plunging flow* (Figure 8) includes *aerated plunging flow*, which occurred when the underside of the surface jet was vented at the downstream end of the deflector; *unstable aerated plunging flow,* which occurred when the underside venting of the surface was inconsistent and *non-aerated plunging flow,* which occurred when the underside aeration ceased.

b. Category 2: *Unstable or surging flow* occurred with the flow alternately attempting to ride the surface of the tailwater, but then plunging to the stilling basin floor with tailwater surging over the plunging flow (Figure 9).

c. Category 3: *Skimming flow or surface jet* (Figure 10) occurred when the spillway jet remained along the surface of the tailwater with a relatively flat water surface with no plunging action and little downwelling.

d. Category 4: *Undulating flow or an undulating surface jet* (Figure 11) occurred when the spillway jet coming off the deflector would ride over the downstream water surface forming an undulating surface with standing waves.

e. Category 5: *Ramped surface jet* occurred when the spillway jet coming off the deflector would "ramp up" steeply on the downstream water surface forming an undulating surface with significant downwelling at the standing waves (Figure 12).

f. Category 6: *Surface jump* (Figure 13) occurred when a hydraulic roller formed at the deflector, resulting in a hydraulic jump that was elevated off the stilling basin floor. This includes an *unstable surface jump*, which occurs when the sloping upstream face of the surface jet attempts to break over into a "surface jump," but retreats and starts again.

g. Category 7: *Submerged surface jump* (Figure 14) occurred when, with higher tailwater, the surface jump was inundated on the deflector, resulting in a submerged hydraulic jump that was elevated off the stilling basin floor.

With the deflector at el 434.0, at low tailwater elevations for even small discharges, the spillway jet was classified as plunging flow (Category 1). Although the jet trajectory angled downward after leaving the deflector, for low discharge (2- to 4-ft gate openings), the deflected jet stayed higher in the tailwater (Figure 15). For higher discharges (6- to 10-ft gate openings), the jet plunged to the depth of the stilling basin (Figure 16). This plunging condition would transport air to the full depth of the stilling basin. In general, this is an undesirable condition relative to TDG absorption. As the tailwater was increased, a mildly unstable flow condition developed where the underside of the spillway jet was intermittently vented at the deflector and the spillway jet alternately plunged to the basin floor and attempted to ride the surface of the tailwater (Video 1).

With higher tailwater, a skimming flow or surface jet (Category 3) developed for all of the flows tested including the 6-ft gate opening with 10.3 kcfs per bay (Video 2, Video 3). With any of the surface flows, the tailwater causes the jet to "lift" off of the deflector. To help quantify the occurrence of surface flows, the angle that the jet makes with the horizontal was measured. The most desirable flow condition for dissolved gas (based on maintaining the jet nearest the surface) occurred with a lift angle of up to about 5 deg from the horizontal. With this surface jet, a strong longitudinal circulation cell developed in the stilling basin and, in some cases, extended downstream into the tailrace. However, this elongated circulation cell was not strongly evident far down the Lower Monumental tailrace, although velocities on the bottom of the tailrace channel were in an upstream direction.

For higher relative tailwater, an undulating surface jet formed (Figure 17), which was classified in Category 4. The lift angle for an undulating surface jet varied over a range from about 5 deg up to 20 deg. For this flow condition, the jet remained essentially on the surface, even though the surface was undulating. Thus, the effects on dissolved gas should be similar to the surface jet.

With additional tailwater, the jet began to "ramp" upward on the tailwater as it left the deflector (Category 5) with a lift angle greater than 20 deg (Figure 18). This flow condition produced turbulence and surface waves that transported dye and air bubbles to the full depth of the tailrace. This flow classification may be considered undesirable relative to dissolved gas absorption because of the plunging action downstream of the standing wave and the deeper tailwater required to cause this performance. However, data supporting this theoretical assessment, have not been collected and analyzed. Spillway operation in this flow classification is tentatively judged to be more desirable than in the plunging-flow category.

Additional increases in tailwater caused a surface jump to form immediately downstream of the deflector (Figure 19). With extremely high tailwater, a submerged jump formed over the deflector, resulting in a plunging nappe with a submerged roller triggered by the submergence of the deflector (Figure 20). Field observations have indicated that, next to discharge, tailwater depth is the dominant parameter in determining the TDG absorption (Schneider and Wilhelms 1998). Although significant amount of the energy in the discharge is dissipated in the surface jump, and downstream velocities are significantly reduced, because of the high tailwater required, this condition may contribute undesirable levels of dissolved gas production. Appendix C is a photo album of flow conditions with the Type I and Type II deflectors.

The performance of the Lower Monumental spillway and deflectors was analyzed based on a submergence parameter and discharge per spill bay. Deflector submergence was defined as the difference between tailwater elevation and deflector elevation. Thus, with a tailwater at el 440.0 and deflector at el 434.0, the submergence was 6.0 ft. While the performance of each deflector is discussed separately, all of the observations are presented in Appendix D.

Type I deflector

The performance of the Type I deflector is shown in Figure 21. For flows up to 7.0 to 10.0 kcfs per spill bay[1], tailwater could vary by about 5-7 ft, while maintaining a skimming or undulating surface jet. A surface jet is our recommended performance category to help minimize potential plunging action and the resulting dissolved gas levels. The tailwater range[2] for Lower Monumental for river discharges from about 28 kcfs (8 bays at ~3.5 kcfs/bay and no powerhouse flows) to 200 kcfs (8 bays at ~10.0 kcfs/bay with 120 kcfs powerhouse) is given in Table 2.

Table 2
Lower Monumental Tailwater Ranges

Spill Discharge Per Spill Bay kcfs	Spill Discharge for 8 bays kcfs	Minimum[1] Tailwater Elevation ft	Maximum[2] Tailwater Elevation ft
3.5	28.0	440.0	443.2
5.0	40.0	440.1	444.0
7.0	56.0	440.3	444.3
10.0	80.0	440.7	445.2

[1] Minimum tailwater for river flow – spill.
[2] Maximum tailwater for river flow - spill + 120 kcfs powerhouse flow.

For the tailwater ranges given in Table 2, the performance curves in Figure 21 show that skimming and undulating surface jet categories are prevalent for discharges up to 7.0 kcfs per spill bay. It appears that the Type I Lower Monumental deflector is likely near its optimum position at el 434.0 to provide surface-jet performance for discharges up to nearly 7.0 kcfs per spill bay.

For discharges between 7.0 and 10.0 kcfs per spill bay, the tailwater range is slightly smaller (~ 6 ft) and additional tailwater is required for skimming or undulating surface jet performance. For 10 kcfs per spill bay, minimum submergence must be about 11.0 ft for surface jet performance. Table 3 shows combinations of spill (10 kcfs per spill bay) and powerhouse flows, resulting

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[1] Likely maximum spill to avoid exceeding 120 percent TDG, based on field studies of TDG exchange.

[2] Based on normal pool at Ice Harbor Dam and total river flow, provided by Walla Walla District.

Table 3
Deflector Elevation as Function of Total River Flow for Submergence of 11.0 ft

Spill Discharge kcfs 8 bays @ 10 kcfs per bay	Power Discharge kcfs	Tailwater Elevation ft[1]	Deflector Elevation ft[2]
80	0	441.5	430.5
80	35	442.0	431.0
80	80	443.5	432.5
80	115	445.0	434.0[3]

[1] Assuming a submergence of 11.0 ft.
[2] Based on normal pool at Ice Harbor Dam and total river flow.
[3] Existing deflector elevation.

tailwater (based on total river flow), and deflector elevation assuming a submergence of 11.0 ft. Thus, if the design flow for Lower Monumental spillway deflectors is 10.0 kcfs per spill bay, then the deflectors could be 2-4 ft lower than the existing design and still provide adequate skimming performance. However, because of the depth of the Lower Monumental stilling basin (50–60 ft), field studies (Schneider and Wilhelms 1998) indicate that total dissolved gas criteria will likely be exceeded at discharges lower than 10.0 kcfs per spill bay. Therefore, the recommended design elevation for the Type I deflector is 534.0 (existing design) for discharges up to 7.0 kcfs per spill bay. The transition from the spillway to the deflector for skimming flow or an undulating surface jet was extremely rough, which could pose survival problems for migrating fish. Based on these results, testing should include a Type II deflector with a 15-ft radius toe curve.

Type II deflector

In general, the transition of the flow from the spillway to the deflector was much smoother than the Type I deflector. The performance of the Type II deflector is shown in Figure 22. For flows of 3.5 to 10.0 kcfs per spill bay, tailwater could vary by 6-7 ft, while maintaining a skimming or undulating surface jet. For the tailwater ranges given in Table 2, the performance curves in Figure 22 show that skimming and undulating surface jet categories are prevalent for discharges from 5.0 to 7.0 kcfs per spill bay, but for lower discharges (<5.0 kcfs per spill bay), the deflector is located about 3 ft too deep in the tailwater. However, on the other end of the design range at 10.0 kcfs per spill bay, the deflector could be lowered by 2-4 ft. Although at the lower discharges deflector performance would be categorized as a "ramped" or a "surface jump," the impact on dissolved gas is likely small since the discharge is relatively low and plunging is limited for these categories. As with the Type I deflector, the depth of the Lower Monumental stilling basin (50–60 ft) will cause the TDG to exceed maximum at discharges lower than 10.0 kcfs per spill bay. Therefore, the recommended design elevation for the Type II deflector is 534.0 for discharges up to 7.0 kcfs per spill bay. Because of the more-limited range of tailwater elevations over which the Type II deflector provides surface jet conditions, the Type I deflector is recommended. However, fish survival or injury concerns may dictate the smoother transition from spillway to tailwater provided by the Type II deflector.

Pressures and Forces on Spillway Deflectors and Stilling Basin Apron

The observations presented in the following paragraphs represent our investigation into the pressures on the horizontal and vertical faces of the Type I deflector. A piezometer was located on the vertical face of the deflector (Figure 23) to assess the potential for cavitation on the vertical face. Pressures were also measured with high-frequency response pressure transducers at two locations: (a) near the center line of the bay on the horizontal face approximately 1.6 ft upstream of the deflector end and (b) near the center line of the bay on the vertical face about 1.6 ft below the horizontal face. The objective of these measurements was to estimate the forces on the deflector due to large spill flows and to evaluate the potential for cavitation in any low-pressure regions.

Average piezometric pressures

The measured piezometric pressures, given in Appendix E (piezometer No. 8), represent averages and are expressed as a water-surface elevation. For these observations, tailwater elevation ranged from 435.0 to 465.0 providing deflector performance over all categories. Normally, in physical modeling, cavitation is considered likely if the local piezometric pressure is more than 20 ft lower than the elevation at the piezometer. Table 4 shows the difference in pressures measured by the piezometer and the elevation of the deflector, with a negative pressure meaning that the piezometric pressure was lower than the elevation of the piezometer. In general, average pressures on the vertical face of the deflector were positive, although for a few conditions, the pressures dropped to near 0.0 (near atmospheric). These data indicate that cavitation should not be a significant problem on the deflector face. However, mean pressures do not always adequately show the potential for severe negative pressure fluctuations. Thus, instantaneous pressure may drop to cavitation levels causing some level of cavitation.

Instantaneous pressures

The pressure transducers were flush-mounted on the vertical and horizontal surfaces of the magnetically attached deflector with the surface of the transducer sensing plate oriented to measure pressures normal to the surface. In these tests, the pressures on the faces of the deflector were measured for gate openings of 28.0 ft and fully opened. For the 28-ft gate opening the pool was set at el 539.0, giving a discharge of 50.0 kcfs per bay. For the full-open gate, the pool was set at el 544.0, giving a discharge of 106 kcfs per bay (Table 5).

Table 4
Difference between Piezometer Pressure on Deflector Face and Piezometer Elevation

Gate Opening ft	Discharge/ Bay Prototype kcfs	Headwater ft	Tailwater ft	Pressure Difference ft	Gate Opening ft	Discharge/ Bay Prototype kcfs	Headwater ft	Tailwater ft	Pressure Difference ft
2	4.2	537	437.0	6.5	8	13.8	537	442.0	6.5
2	4.2	537	439.0	12.0	8	13.8	537	444.0	9.5
2	4.2	537	447.0	13.3	8	13.8	537	446.0	20.0
2	4.2	537	449.0	7.0	8	13.8	537	450.0	3.0
4	6.7	537	438.0	0.0	8	13.8	537	452.0	1.0
4	6.7	537	440.0	1.0	8	13.8	537	456.0	0.8
4	6.7	537	442.0	7.5	8	13.8	537	458.0	17.2
4	6.7	537	446.0	1.0	8	13.8	537	460.0	16.0
4	6.7	537	448.0	10.7	10	18.2	537	449.0	8.3
4	6.7	537	450.0	24.0	10	18.2	537	451.0	6.0
6	10.2	537	440.0	3.0	10	18.2	537	453.0	7.0
6	10.2	537	443.5	6.0	10	18.2	537	455.0	3.0
6	10.2	537	444.0	22.5	10	18.2	537	457.0	10.6
6	10.2	537	446.0	8.6	10	18.2	537	459.0	3.4
6	10.2	537	448.0	11.0	10	18.2	537	461.0	6.1
6	10.2	537	450.0	9.2	10	18.2	537	463.0	6.0
					10	18.2	537	465.0	26.0

Table 5
Gate Openings and Corresponding Discharges[1]

Gate Opening ft	Discharge Per Spill Bay kcfs	Pool Elevation ft	Tailwater Elevation ft
28.0	50.0	539.0	453.0
Full	106.0	544.0	461.0

[1] All bays in operation.

Before collecting data, the transducers' calibration[1] was checked onsite to establish zero pressure. To begin data collection, one of the selected discharges was set and the upper pool was stabilized at the appropriate elevation. Tailwater elevation was then adjusted to the specified elevation and the model was allowed to stabilize. Pressure measurements were collected continuously for 2 min at a rate of 25 samples per sec, which translates to a prototype collection frequency of about 4 samples per sec. The measurements were repeated for the same flow conditions. At the end of the day, a post calibration check for zero-pressure was conducted to verify that no substantial "drift" had occurred since the initial calibration of the transducers.

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[1] Pressure transducers were calibrated in the instrumentation laboratory using a dead-weight pressure chamber.

The 3,000 pressure measurements from the 2 min of data collection were analyzed based a frequency of occurrence. Figures 24 and 25 show the frequency of the measured pressures. Figures 26-27 show the cumulative frequency distributions from the two pressure cells. The frequency distributions provide a visual indication of the distribution of pressures around the mean. The cumulative frequency distributions give a measure of exceedence, i.e., the portion of time that the pressures were greater than a given level. For example, the mean pressure on the horizontal deflector face for a 28.0-ft gate opening was 15.4 ft of water. Figure 26 shows that the pressures on the horizontal face exceed 17.0 ft of water 20 percent of the time. Replicated data are shown in the plots, indicating that the measured pressures were accurately reproduced between replicated tests.

The highest pressures were measured on the horizontal face with negative pressures being measured in the flow separation zone on the vertical face of the deflector. Table 6 gives the low, mean, and maximum pressures, standard deviation of the pressure frequency distribution, and the 20 percent and 80 percent exceedence pressures.

Table 6
Deflector Pressure Data Summary

Discharge kcfs	Location	Low Pressure ft-water	Mean Pressure ft-water	High Pressure ft-water	Standard Deviation ft-water	20 Percent Exceedence Pressure ft-water	80 Percent Exceedence ft-water
50	Horizontal face	7.6	15.4	20.8	1.8	17.0	13.9
	Vertical face	-25.5	-11.1	-1.7	3.1	-9.0	-14.0
106	Horizontal face	20.5	29.1	36.8	2.1	30.9	27.5
	Vertical face	-12.0	1.3	13.0	3.3	3.9	-1.7

The minimum pressures measured on the vertical face were as low as –25.5 ft of water. In most model studies, pressures lower than about –20.0 ft to –25.0 ft of water would indicate that cavitation potential exists. However, for a cavitation pressure study, the structure model would usually be designed at a scale larger than the 1:40 scale of this model. Regardless of modeling considerations, these pressures imply that cavitation potential is an actuality. It is likely that these kinds of pressures are experienced at nearly all of the spillways with deflectors on the Lower Columbia and Snake Rivers. Only minor cavitation damage has been reported at other projects with spillway deflectors. Thus, while the measurements indicate low pressures, cavitation is not expected to be a serious problem.

From these experiments, the loading on the deflector should be the vector sum of the pressure forces measured on the horizontal and vertical faces of the deflector. Referring to the exceedence curve for the 28-ft gate opening (50 kcfs): The 80 percent exceedence pressure from the vertical face is –14.0 ft of water, while the 20 percent exceedence pressure from the horizontal face is 17.0 ft of water. If the entire area of the deflector (12.5 ft by 50.0 ft) is acted upon by these pressures, the total load on the horizontal face caused by the 50 kcfs flow is approximately 663,000 lbs acting in a direction toward the deflector surface. For the vertical face, the load is approximately 546,000 lbs acting away from the deflector face. Since these forces act at a 90-deg angle with each other, the vector sum of 858,900 lbs, at an angle of 39.5 deg with the vertical, represents the resultant force acting on the deflector's horizontal face at about 1.1 ft from the intersection of the deflector with the spillway. The force acting parallel to the spillway surface is approximately 854,950 lbs.

The force caused by the 106 kcfs discharge is approximately 1,206,900 lbs acting at an angle off the vertical of 3.15 deg resulting in a force of 899,000 lbs acting parallel to the spillway surface. Table 7 summarizes the calculations for the loadings on the deflector using the 80 percent and 20 percent exceedence pressures for the vertical and horizontal faces, respectively. The average or maximum pressure differences between the horizontal and vertical faces can also be used to compute the potential loading to the deflector.

Table 7
Deflector Loading Calculations for 12.5 ft by 50 ft Deflector

Discharge kcfs	Loading Horizontal Face lbs	Loading Vertical Face lbs	Resulting Force lbs	Force Direction/ Angle from Vertical deg	Resulting Force Parallel to Spillway lbs
50	663,000	-546,000	858,900	39.5	854,950
106	1,205,100	-66,300	1,206,900	3.15	899,000

Very low local pressures, caused by high velocities on the stilling basin apron, may result in cavitation. Conversely, plunging flow may significantly increase the pressures on the stilling basin apron caused by the impingement of the water jet. These high pressures, if exposed to joints or crevasses between the apron and underlying bedrock could produce significant uplift force. To assess pressures and forces on the stilling basin apron, piezometers were placed on the stilling basin floor to measure average pressures and to evaluate the potential for cavitation on the apron. In later experiments, high-frequency response pressure transducers were placed on the apron and in the apron scour hole. The transducer measurements were used to investigate the instantaneous pressures that could be experienced on the apron or in the scour hole.

Piezometric stilling basin pressures

Seven piezometers, numbered 1-7 from upstream to downstream, were located on the stilling basin floor along the center line of the middle bay as shown in Figure 28. The piezometric pressure measurements along the stilling basin floor and on the deflector are given in Appendix E. They represent average pressures and are expressed as a water-surface elevation. Figures 29-33 show selected sets of stilling basin pressures plotted as a function of distance along the stilling basin.

Table 8 shows the difference between the local piezometric pressure and the piezometer elevation on the stilling basin apron. As previously stated, in physical modeling, if these pressure differences approach –20 ft of water, then cavitation is considered likely.

Uplift Pressures on Stilling Basin Floor

Hydrostatic pressure in the stilling basin tends to "hold" the apron down, while the pressure caused by the impingement of a plunging jet tends to "lift" the apron, if exposed to cracks and crevasses in or under the apron. The pressure that can cause apron uplift is the difference between the localized pressure measurements and the hydrostatic pressure over the stilling basin. If these pressures have a pathway beneath the stilling basin apron, significant uplift force could result. If the apron monoliths were lifted sufficiently to allow flow under them, additional hydraulic forces could cause a catastrophic failure of the apron.

The instantaneous pressures experienced by the stilling basin apron and the surface of the scour hole in the apron were investigated with two placements of pressure transducers in the model: (a) transducers located on the undamaged apron along the center line of bay 2 and (b) on the damaged surface of the year 2000 (Y2K) scour hole. The former provided a baseline of stilling basin pressures to compare to those with the boundary of the scour hole.

For the first placement, five high frequency pressure transducers were flush-mounted at the surface of the stilling basin apron (el 392.0) along the center line of bay No. 2 (Figure 34). For the second placement of transducers, the scour hole for the year 2000 was added to the model using concrete mortar molded to sheet metal templates. Four transducers were mounted along the center line of the Y2K scour hole (Figure 35). The transducers were mounted flush with the surface of the hole with the sensing plate of the transducer oriented to measure pressures normal to the surface. Pressures were collected for several discharges and tailwater elevations to examine the range of pressures that the stilling basin could experience for various flow regimes in the stilling basin.

In these tests, the pressures along the stilling basin floor were measured for gate openings of 3.5 ft to fully opened. The Lower Monumental pool elevation ranged from el 537.0 to el 540, giving a range of discharge per spill bay from 6.5 kcfs to 84.0 kcfs (Appendix G). Tailwater elevations ranged from as low as el 441.0 up to as high as el 468.0. Table 9 gives the spillbay discharges, total spillway discharge, and the tailwater range.

Before collecting data, the transducer calibration[1] was checked onsite to establish zero pressure. To begin data collection, one of the selected discharges was set and the upper pool was stabilized at el 537.0. Tailwater elevation was then adjusted to specified elevations and the model was allowed to stabilize. Pressure measurements were collected continuously for 2 min at a rate of

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[1] Pressure transducers were calibrated in the instrumentation laboratory using a dead-weight pressure chamber with a zero calibration check once installed in the model.

Table 8
Difference Between Stilling Basin Piezometer Pressure and Pressure due to Tailwater

Gate Opening, ft	Discharge/bay kcfs	Headwater Elevation, ft	Tailwater Elevation, ft	Piezometer 1 ft	Piezometer 2 ft	Piezometer 3 ft	Piezometer 4 ft	Piezometer 5 ft	Piezometer 6 ft	Piezometer 7 ft
2	4.2	537	435.0	38.5	N/A	38.0	38.5	39.0	40.8	40.0
2	4.2	537	437.0	48.5	N/A	48.2	48.2	48.0	52.2	49.0
2	4.2	537	439.0	53.5	N/A	53.0	52.7	52.6	58.3	54.5
2	4.2	537	441.0	36.5	36.5	38.5	42.0	46.0	61.0	48.0
2	4.2	537	443.0	38.0	N/A	37.2	37.4	38.7	43.0	41.5
2	4.2	537	445.0	37.0	N/A	36.0	38.5	41.0	48.0	45.5
2	4.2	537	447.0	54.5	55.2	54.7	54.1	55.2	56.8	57.1
2	4.2	537	449.0	47.0	N/A	45.5	47.0	48.5	51.5	52.0
4	6.7	537	438.0	41.2	N/A	40.0	40.0	42.6	49.0	48.0
4	6.7	537	440.0	42.0	N/A	40.5	41.0	43.0	49.0	47.0
4	6.7	537	442.0	48.2	48.0	47.8	47.8	48.2	49.0	49.6
4	6.7	537	444.0	40.0	39.0	39.5	43.0	48.0	54.0	50.0
4	6.7	537	446.0	41.8	41.0	40.5	41.0	43.5	47.0	49.8
4	6.7	537	448.0	51.8	51.5	51.0	50.8	51.2	53.0	53.5
4	6.7	537	450.0	63.0	N/A	63.5	65.0	68.0	69.0	68.0
6	10.2	537	440.0	44.0	N/A	43.0	43.7	43.0	49.0	47.0
6	10.2	537	443.5	46.5	45.5	45.5	45.5	46.0	47.5	49.5
6	10.2	537	444.0	63.5	63.2	62.5	63.5	63.5	65.5	65.5
6	10.2	537	446.0	50.5	N/A	50.2	50.2	50.3	55.5	51.2
6	10.2	537	448.0	53.1	N/A	53.0	53.2	53.3	58.0	54.0
6	10.2	537	450.0	55.6	N/A	55.5	55.5	55.8	56.5	51.5

(Continued)

Table 8 (Concluded)

Gate Opening, ft	Discharge/bay kcfs	Headwater Elevation, ft	Tailwater Elevation, ft	Piezometer 1 ft	Piezometer 2 ft	Piezometer 3 ft	Piezometer 4 ft	Piezometer 5 ft	Piezometer 6 ft	Piezometer 7 ft
8	13.8	537	442.0	43.5	43.5	41.5	42.5	43.5	48.0	50.5
8	13.8	537	444.0	49.5	N/A	49.0	49.0	49.0	52.0	54.0
8	13.8	537	446.0	59.0	N/A	59.3	59.5	63.5	63.5	64.0
8	13.8	537	448.0	41.0	N/A	40.5	40.5	41.0	43.0	41.5
8	13.8	537	450.0	45.3	N/A	45.0	45.3	45.0	40.0	45.4
8	13.8	537	452.0	39.5	N/A	44.0	43.0	48.5	53.5	54.5
8	13.8	537	458.0	58.0	57.8	57.3	57.7	58.1	59.3	59.8
8	13.8	537	460.0	56.0	N/A	55.5	55.5	56.5	58.0	60.0
8	13.8	537	454.0	40.2	N/A	39.5	39.3	40.5	44.4	43.0
8	13.8	537	456.0	42.5	N/A	41.8	41.6	41.5	45.5	43.7
10	18.2	537	447.0	43.2	N/A	43.0	43.0	42.8	45.5	43.5
10	18.2	537	449.0	45.5	N/A	50.1	50.0	50.2	55.0	50.6
10	18.2	537	451.0	46.5	N/A	46.0	46.0	46.0	50.0	48.0
10	18.2	537	453.0	48.0	N/A	48.0	47.0	47.0	52.0	49.0
10	18.2	537	455.0	43.0	N/A	43.0	44.0	47.0	41.0	54.0
10	18.2	537	457.0	53.0	N/A	51.5	51.5	52.0	53.0	56.0
10	18.2	537	459.0	44.7	N/A	44.6	44.3	44.2	48.3	45.6
10	18.2	537	461.0	47.6	N/A	47.2	47.0	46.8	51.3	47.5
10	18.2	537	463.0	45.0	N/A	43.0	54.0	46.0	49.5	53.0
10	18.2	537	465.0	9.0	N/A	11.0	26.0	29.0	30.0	36.0

Table 9
Gate Openings and Corresponding Discharges for Stilling Basin Uplift Pressure Experiments

Gate Opening ft	Discharge Per Spill Bay kcfs	Spillway Discharge[1] kcfs	Tailwater Range ft
3.5	6.5	52.0	441.0
16.5	29.0	232.0	451.0-454.0
20.0	34.0	272.0	447.0-468.0
28.0	50.0	400.0	457.0-465.0
Full	84.0	672.0	456.0-466.0

[1] Eight bays in uniform operation.

50 samples per sec. The measurements were repeated, then the discharge or tailwater elevation was changed, and data were collected again, using the same procedure. At the end of the day, a post-calibration check for zero-pressure was conducted to verify that no substantial drift had occurred since the initial calibration of the transducers.

The 6,000 pressure measurements from the 2 min of data collection were analyzed based a frequency of occurrence. An example plot of the frequency curves from the five pressure cells is shown in Figure 36. The cumulative frequency distribution was also computed and plotted (Figure 37). All of the experimental data are shown in similar plots in Appendix H. The frequency distributions provide a visual indication of the distribution of pressures around the mean. The cumulative frequency distributions give a measure of exceedence, i.e., the portion of time that the pressures were greater than a given level. For example, the mean and standard deviation of the cell 5 data, shown in Figure 37, are 40.11 ft of water and 2.59 ft of water, which indicates a relatively large spread around the mean. Figure 37 also shows that the pressures measured by cell 4 exceed 52 ft of water 20 percent of the time. The statistical properties of the frequency distributions are given in Appendix I.

Figures 38 and 39 show replicated data collection, indicating that pressure frequency distribution may vary slightly. These, and other replicate observations, indicate that the measured pressures vary by about 2 ft of water but are reasonably reproduced between replicated tests.

The highest pressures collected for each flow rate are summarized in Table 10. Given are the low, mean, and maximum pressures, standard deviation of the pressure frequency distribution, and the 20-percent exceedence pressure. Pertinent hydraulic information is also included. Video 4 and Figure 40 show the plunging nature of flow that causes the increased pressures on the stilling basin floor. Table 10 shows that the highest stilling basin pressures occurred for the highest discharge of about 84 kcfs per spill bay. The average pressure for transducer No. 5 was about 85 ft of water, a maximum instantaneous pressure of about 130 ft of water, and a 20 percent exceedence pressure of 91.2 ft of water. The far field tailwater elevation for these flow conditions was 466.0, giving a hydrostatic pressure of about 74.0 ft above the stilling basin floor. However, because of the high velocity in the stilling basin for these flow conditions, the water-surface

Table 10
Highest Pressure Summary Data

Test No.	Average Pressure ft H2O	Figure Number	Discharge kcfs/bay	Gate Opening ft	Pool El, ft	Tailwater El, ft	Cell Number ft H2O	Minimum Pressure ft H2O	Average Pressure ft H2O	Maximum Pressure ft H2O	Standard Deviation of Pressure Measurements ft H2O	20 Percent Exceedence Pressure ft H2O	Hydrostatic Pressure at Scour Hole,[1] ft H2O
Pressures Along Center Line of Bay [2]													
Im01	41.7	H1	29.0	16.5	537.0	451.0	4	37.06	49.54	65.60	3.43	52.00	40.0
Im05	36.1	H5	6.5	3.5	537.0	441.0	4	36.81	39.48	43.32	0.88	40.20	N/A
Im12[2]	45.4	H12	29.0	16.5	537.0	454.0	4	29.22	43.22	56.93	2.91	45.40	54.0
Im20	54.8	H20	34.0	20.0	540.0	463.0	5	50.85	63.21	75.42	2.63	65.20	60.0
Pressures In Y2K Scour Hole													
Im26	38.2	H25	29.0	16.5	537.0	451.0	5	16.3	49.3	74.9	6.6	54.1	N/A
Im31	39.3	H30	6.5	3.5	537.0	441.0	2	37.5	41.4	46.3	1.3	42.5	N/A
Im38	51.9	H37	50.0	28.0	539.0	465.0	5	17.8	61.4	92.2	6.0	65.8	N/A
Im41	61.6	H40	84.0	Full	540.0	461.0	5	55.7	79.1	116.5	7.8	84.6	37.0
Im43	64.6	H42	84.0	Full	540.0	466.0	5	57.1	81.0	117.0	7.7	86.8	37.0
Im46	48.0	H45	84.0	Full	540.0	456.0	5	43.7	69.3	118.2	10.3	76.9	22.0
Im48	67.1	H47	84.0	Full	540.0	466.0	5	63.9	85.6	129.8	7.9	91.2	39.0

[1] Estimated with local water-surface elevation at scour hole was scaled from photographs documenting flow conditions.
[2] Extremely high measurements, but no apparent error.

elevation was less than the far field tailwater elevation. Thus, the hydrostatic pressure on the stilling basin apron at the scour hole was actually approximately 39.0 ft of water with the local water surface elevation[1] at the scour hole of 431.0. The resulting difference of 52.2 ft of water between the hydrostatic pressure and the measured 20 percent exceedence pressures could cause apron uplift. Thus, this pressure difference or the difference between the maximum pressure and hydrostatic should be used for estimating the potential uplift forces on the stilling basin apron.

Debris Transport in Tailrace

Stilling basin and tailrace performance was investigated regarding debris transport from downstream into the stilling basin. The threshold discharge above which rock debris is transported from the tailrace into the stilling basin was determined. Since this effort was initiated immediately after the Type II deflector performance experiments, the section model was configured with the Type II spillway deflectors installed on all bays. The model reproduced the circulation patterns downstream of the south side of the stilling basin around the training wall and under the fish ladder. The tailrace was roughened by gluing pea gravel to the tailrace surface, thereby simulating its rough characteristics. Figure 41 shows the model layout for these experiments.

Crushed limestone was sized (Appendix F) for model experiments based on 1-ft-diam[2] rock debris in the Lower Monumental tailrace. The limestone was painted green, yellow, and blue and then placed across the width of the tailrace at 20, 40, and 80 ft, respectively, downstream of the end sill. The transport of this material was tested for a range of discharges from 1.8 kcfs per spill bay to 10.2 kcfs per spill bay. Table 11 gives gate openings, spill bay discharges, and total spill based on eight bays with uniform spill. A range of tailwater elevations was also tested for each discharge to determine the effects of performance regimes.

Table 11
Gate Openings and Corresponding Discharges

Gate Opening, ft	Discharge per spillbay kcfs	Spillway Discharge[1] kcfs
1	1.8	14.4
2	4.2	33.6
3	5.6	44.8
4	6.7	53.6
5	8.5	68.0
6	10.2	81.6

[1] Eight bays in uniform operation.

The following procedure was followed for evaluating debris transport into the stilling basin. The tailrace was flooded from downstream to prevent tailrace debris movement while flow conditions stabilized. The Lower Monumental tainter gates were set and discharge was adjusted to provide a pool elevation of 537.0. Tailwater elevation was then adjusted in 1.0–2.0 ft increments from as high as el 468.0 to as low as el 435.0. At each tailwater elevation, the painted stone in the tailrace was observed to determine if movement occurred. If a stone

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[1] Local water-surface elevation at the scour hole was scaled from photographs documenting the flow conditions.

[2] Material size provided by Walla Walla district personnel.

fluttered or actually rolled or was swept toward the stilling basin, the combination of discharge and tailwater was deemed capable of debris transport.

A 4.0-ft gate opening (6.7 kcfs per spill bay) caused stones 20 ft downstream of the end sill to flutter, but not readily move upstream. However, if the spillway were operated at this condition for a sufficient length of time, rock would likely be transported into the basin during some flow conditions. A 5-ft gate opening provided the minimum discharge (8.5 kcfs per spill bay) required to move rock into the stilling basin. Movement of stone from the tailrace to the stilling basin occurred when the tailwater elevation produced a surface jet (either a skimming or undulating surface jet) with a strong upstream flow along the tailrace bottom. Even with this strong consistent circulation cell, individual rocks were moved in spurts of high velocity. For all surface jets, the bottom current generally continued from the tailrace into the stilling basin (Figure 42).

With these flow conditions, rock was transported into the basin whether the end bay (non-deflectored bay) was opened or closed. The rock that was placed 20 and 40 ft downstream from the end sill was moved upstream and piled against the back of the sill. Bursts of turbulence over the sill caused rocks to float and then be carried over the end sill by the upstream circulation. These rocks continued upstream along the stilling basin floor and generally congregated along the lower end of the spillway toe curve. Circulation and short-lived vortices and turbulent bursts in the stilling basin tended to move rock in a circular ball-mill grinding motion in this area. Strong bursts of turbulence would lift rocks from the stilling basin floor and deposit them some distance away. They would then be moved across the stilling basin back to the lower end of the spillway toe curve.

The majority of the rock placed 80 ft downstream of the end sill either remained in place, or was moved downstream with a 5-ft gate opening. However, a small amount of this rock was moved approximately 40 ft upstream and would eventually be moved into the stilling basin, if this flow condition existed for sufficient time. For these experiments, there was no set test duration time to investigate debris movement, thus, no time estimate for rock movement was made.

A 6-ft gate opening (10.2 kcfs per spill bay) tended to move rock into the basin at a faster rate than with a 5-ft gate opening. This was the highest discharge tested in this set of experiments.

Based on these results, clearly, larger gate openings with higher discharges will move rock into the basin at a faster rate, when flow conditions produce an upstream circulation cell along the tailrace bottom. The circulation cell that created the upstream velocity did not extend beyond about 120 ft downstream of the end sill. However, for higher discharges with a surface jet, the upstream circulation may extend farther.

Regardless of discharge, the flow conditions that move rock into the stilling basin are as follows:

a. Conditions where a surface jet produces a strong vertical circulation cell with upstream velocities along the tailrace bottom from the tailrace into the stilling basin.

b. Conditions where turbulence lifts rocks up and over the end sill.

c. Conditions where rock movement builds a ramp against the downstream face of the sill, which then allows rock to "roll over" over the end sill and into the basin.

Movement and Deposition of Debris in Stilling Basin

From the previous analysis, clearly, flow conditions are capable of transporting material into the stilling basin. With debris present in the stilling basin, hydraulic action would likely move the rock creating a ball-mill grinding action causing apron erosion. To assess this potential, a numerical model of stilling basin flow was developed. Physical model experiments were also conducted to visualize the movement of debris in the stilling basin.

Numerical modeling of stilling basin hydraulics

A three-dimensional (3-D) numerical model entitled MAC3D (Bernard 1998) was used to simulate the flow conditions in the stilling basin. The numerical model results provide a means to visualize the flow conditions near the stilling basin floor with and without the outside deflectors in place and determine the conditions contributing to stilling basin scour.

Figure 43 shows a schematic representation of the velocity vectors on the stilling basin floor for skimming flow in bays 2-4. Bay 1 had no deflector, resulting in plunging flow. The deflected flow creates a demand for lateral entrainment that draws the plunging flow through bay 1 laterally under the deflected jet. This causes a circulation cell on the stilling basin floor on each side of the stilling basin in the location similar to the scour area. By inference, a similar circulation cell should exist below bays 7 and 8 on the other side of the stilling basin. Numerical model simulations with deflectors on the outside bays showed velocity vectors in the upstream direction eliminating the circulation cell caused by the entrainment of the outside bay plunging flow (Figure 44). Based on these simulations, it seems likely that the operation of the outside bays without deflectors has contributed to the ball-mill grinding that caused the apron scour. By simply installing deflectors on the outside bays, apron scour may be significantly reduced, eliminating the severe horizontal circulation on the stilling basin floor.

Physical modeling of stilling basin hydraulics

The movement and deposition of rock debris in the stilling basin was investigated in the section model for the following configurations:

a. *Configuration 1.* Type II deflectors at el 434.0 on two interior bays with no deflector on the outside bay, all bays in operation.

b. *Configuration 2.* Type II deflectors at el 434.0 on two interior bays with no deflector on the outside bay, two interior bays in operation.

c. *Configuration 3.* Type II deflectors at el 434.0 all spill bays with pier extensions, all bays in operation.

The model reproduced the south side of the stilling basin a part of the non-overflow section, and bathymetry under the south shore fish ladder. A scour hole was constructed in the stilling basin to observe the hydraulic action and debris movement in and around the scour hole. The scour hole was positioned in a similar location to the hole in the basin floor of the prototype (Figure 45). It covered the same general area as the prototype hole, but with a constant depth of 2.5 ft. The depth of the prototype hole was irregular and included some areas up to 8 ft deep.

The crushed limestone used in the previous experiments and pea gravel (more rounded grains than the crushed limestone) simulated rock debris in the stilling basin. Movement of this material in the stilling basin was observed for a range of gate openings from 2 ft to 12 ft. Table 12 gives gate openings, spill bay discharges, and total spill based on eight bays with uniform spill. A range of tail-water elevations was also tested for each discharge to determine the effects of performance regimes.

Table 12
Gate Openings and Corresponding Discharges

Gate Opening ft	Discharge Per Spill Bay kcfs	Spillway Discharge[1] kcfs	Tailwater Range ft
2	4.2	33.6	435.0-447.0
4	6.7	53.6	436.0-452.0
6	10.2	81.6	442.0-454.0
8	13.8	110.4	444.0-466.0
10	18.2	145.6	446.0-460.0
12	21.9	175.2	448.0-462.0

[1] Eight bays in uniform operation.

During these experiments, an assortment of rock debris was scattered across the stilling basin and placed in the scour hole. Tailwater elevation was adjusted in 1.0- to 2.0-ft increments from as low as el 435.0 to as high as el 468.0. With stabilized flow conditions at each tailwater elevation, debris in the stilling basin tailrace was observed to determine its movement and deposition.

Configuration 1. **Deflectors at el 434.0 on two interior bays with no deflector on the outside bay, all bays in operation.** There was slight movement of rock for all tailwater elevations with gate openings of 2 and 4 ft (Figure 46, Video 5). The fluttering and displacement of rock increased as the tailwater decreased. With high to midrange tailwater elevations (above el 450.0) and a 6-ft gate opening, the rock debris moved easily within the scour hole. Some stones were transported from the hole by bursts of turbulence from the adjoining nondeflectored bay. For lower tailwater elevations, rock movement increased and more stones were transported from the hole, while other stones moved in a ball-mill grinding fashion in the scour hole.

For gate openings of 8, 10, and 12 ft, rock debris rapidly moved around the basin and was washed through the scour hole in a generally clockwise circulation pattern caused by entrainment of water from the outside bay (Figure 47 and Video 6; Figure 48 and Video 7). Rocks remained in the scour hole for only a short duration and tended to accumulate and move about on the spillway toe curve.

Configuration 2. **Deflectors at el 434.0 on two interior bays with no deflector on the outside bay, two interior bays in operation.** For 2- and 4-ft gate openings, there was less movement of the rock in the scour hole than with the end bay in operation (Figure 49, Video 8). For gate openings of 6 and 8 ft with tailwater above el 443.0 and el 446.0, respectively, rock in the scour hole showed a small amount of movement (Figure 50, Video 9). At lower tailwater elevations, rock movement increased. With plunging flow, rock circulated in and out of the scour hole with significant collection and movement of rock about 40 ft to the north of the scour hole. Flow conditions with 10- and 12-ft gate openings were similar to those with an 8-ft opening, but with an attendant increase in velocity and debris movement along the floor of the basin (Figure 51, Video 10).

Configuration 3. **Deflectors at el 434.0 all spill bays with pier extensions, all bays in operation.** With a gate opening of 2 ft, turbulence and velocities on the basin floor were relatively low with very little debris movement in the scour hole at any tailwater elevation. With the gates at a 4-ft opening, there was slight movement of rock in the scour hole at higher tailwater. However, as tailwater was lowered, rock movement and fluttering in the scour hole increased and became continual at low tailwater.

Flow conditions with a 6-ft gate opening significantly increased the upstream velocity along the basin floor compared to lower gate openings. Rock movement in the scour hole occurred at high tailwater and some rocks were lifted from the upper end of the scour hole and circulated in the hole. With lower tailwater, velocities increased along the basin floor. Rock was plucked from the upstream end of the hole, but circulated back into the hole. The same pattern of higher velocity and rock movement continued as the gates were operated at 8-, 10-, and 12-ft openings.

Discussion of debris movement

For even a small 2-ft gate opening with the undeflected outside bay in operation (existing design and operation), debris in the basin fluttered and moved. For larger gate openings, movement became more violent. Without the outside bay in operation, the movement was reduced, even for 6- to 8-ft gate openings, but not eliminated. With a Type II deflector on the outer bay, rock movement seemed to be reduced further for gate openings up to 4 ft compared to the other tested operations. However, with a 6-ft gate opening, a large circulation cell tended to pluck debris from the scour hole, move it around the stilling basin, and then back to the hole. Plunging flow seemed to cause the worst conditions for debris movement with some deposition occurring to the north of the existing scour hole. Thus, operating with plunging conditions should be avoided to minimize debris transport within the stilling basin.

Based on these experiments, it seems likely that once debris is transported into the stilling basin, movement will occur for even small discharges. Thus, any engineering alternative should exclude rock debris from being transported from the tailrace into the stilling basin. While an engineering revision is being developed for Lower Monumental, the outside bay should not be operated. Based on the model study this operation should reduce debris movement and the ball-mill grinding action in the stilling basin. In addition to an attractive dissolved gas abatement alternative, deflector installation on the outside bays seems to reduce the in-stilling basin circulation that contributes to debris movement.

Because of the obvious 3-D effects of flow on debris movement, these conditions and conclusions should be verified in the Lower Monumental general model.

Alternatives to Reduce Debris Transport into Stilling Basin

The following alternatives were considered for stabilizing or capturing debris in the tailrace:

a. Grouting or armoring tailrace channel with riprap

b. Excavating a tailrace rock trap (trench)

c. Elevating the stilling basin end sill

d. Constructing in-stilling basin splitter walls

For some alternatives, model observations and measurements provided a basis for the assessment. Other alternatives were evaluated on a conceptual basis. The first three alternatives are aimed at reducing or eliminating the transport of debris from the tailrace into the stilling basin. The purpose of the last alternative is to reduce the swirling hydraulic action on the stilling basin apron that contributes to ball-mill grinding, when debris is present.

Because of the vertical circulation cell generated by the surface jet coming off the spillway deflectors, loose material in the tailrace may be transported upstream and into the stilling basin. Even the fractured basalt is susceptible to being plucked out of the surrounding rock and then transported with the flow. Of course, once this material is in the stilling basin, circular grinding action will wear-away at the concrete apron.

Grouting or armoring tailrace channel with riprap

Grouting the tailrace will anchor any loose material or cover fractured rock and thereby prevent any movement of material upstream. Of course, armoring the tailrace with a suitably sized riprap can likewise provide protection against the transport of bottom material into the stilling basin. For either of these alternatives, the looming design question is "How far downstream must the protection extend?" For the latter, there is the additional question of "What size of riprap material is suitable?"

Based on the initial debris experiments discussed earlier in this chapter, the circulation cell extended a distance of about 120 ft downstream of the stilling basin end sill. To avoid debris transport into the stilling basin, the tailrace should be protected for at least this distance. Velocity profiles, shown in Figure 52, were taken with an Acoustic Doppler Velocimeter (ADV) at the end sill for several discharges with surface jet performance. Table 13 gives the measured mean velocities and 95 percent confidence interval about the measured mean. Clearly, mean prototype velocities can range up to 10.0 to 12.0 ft/sec with bursts up to 13.0 to 14.0 ft/sec. Thus, these velocities should be used to design the armoring for the tailrace.

Table 13
Maximum Velocities Near End Sill for Surface Jet Flows

Gate Opening ft	Discharge Per Spill Bay ft^3/sec	Headwater El ft proto	Tailwater El ft proto	Water Surface Elevation at End Sill ft proto	El of Velocity ft proto	Mean Upstream Velocity ft/sec proto	Span of 95% Confidence Interval on Velocity ft/sec proto
4	6.7	537.0	448.0	439.0	407.0	10.1	0.3
6	10.2	537.0	452.0	444.0	414.0	11.3	0.3
8	13.8	537.0	457.0	446.0	412.0	12.2	0.4
10	18.2	537.0	459.0	445.0	411.0	8.2	1.9
12	21.9	537.0	460.0	453.0	427.0	10.6	1.2

Using the Ishbosh relationship (HQUSACE 1987)

$$D_{50}\Big|_p = \left\{ \frac{\vec{V}_p}{1.12\left[2g\left(\frac{\gamma_s - \gamma_w}{\gamma_w}\right)\right]^{1/2}} \right\}^2 \tag{3}$$

where $D_{50}\big|_p$ is the stable stone size; γ_s and γ_w are the specific weights of rock and water at 170 lb/ft^3 and 62.4 lb/ft^3, respectively; and $\vec{V}_p$ is the prototype velocity at 14.0 ft/sec. Substituting these values into Equation 3 gives:

$$D_{50}\big|_p = 1.4 \ ft$$

Thus, the minimum mean diameter for riprap protection is about 1.4 ft. However, the size could be significantly larger for plunging flow that impinges on the tailrace. Since the velocities decrease with distance downstream, the size of the riprap could be reduced further downstream from the end sill. Any design for riprap protection should be experimentally assessed in the general model over a wide range of flow conditions.

Rock and debris trap

A rock and debris trap would generally be located just downstream of the stilling basin end sill with the end sill forming the upstream wall of the trap. Fenwick (1989) investigated several alternative designs for a rock trap for the Kinzua Dam stilling basin with streamwise widths from 25.0 to 30.0 ft and depths of 8.0 to 14.0 ft. The final design recommended for Kinzua was for a 26.0-ft-wide by 10.0-ft-deep trap. Even under the "worst case" scenario with the strongest upstream currents, no material was transported into the stilling basin, although substantial volumes were transported into the trap.

Based on the Kinzua (Fenwick 1989) study, we recommend a 25.0 ft wide by 10.0-ft-deep trap located near the end sill that would run the entire width of the stilling basin as an initial design for Lower Monumental is recommended (Figure 53). Velocity measurements in the section model along the tailrace bottom in this vicinity ranged up to about 14.0 ft/sec. Based on the Ishbosh (HQUSACE 1987) relationship for stable riprap, these velocities could potentially move stone that has a mean diameter less than 1.4 ft. Thus, significant material could be moved into the trap, depending upon the volume of loose or erodible material in the tailrace. Some maintenance interval will likely be needed to remove trapped debris and maintain the effectiveness of the trap.

If this alternative is selected for further development, the trap design should be investigated in the Lower Monumental general model to determine the trap efficiency (material retained in trap compared to the total material transported from the tailrace into the trap).

Elevated end sill

As an alternative to reduce the movement of debris into the stilling basin, the stilling basin end sill was raised by 8.0 ft (Figure 54). This higher end sill would make debris movement into the stilling basin more difficult and increase the length of operation before debris would have to be removed compared to the existing end sill height (about 10.0 ft) above the tailrace channel. Based on the experiments, the study showed that debris tended to build a ramp as material was deposited just downstream of the end sill. Once the ramp was sufficiently high, debris was transported into the stilling basin. Velocities in the tailrace are shown in Figures 55-57. Upstream velocities at the end sill range up to 11.0 ft/sec compared to 14.0 ft/sec with the existing sill height. Although this alternative appears to reduce the velocities at the end sill, a clear recommendation cannot be made. The performance of an elevated end sill should also be assessed in the general model.

Stilling basin splitter walls

Walls that split the stilling basin into 50-ft-wide bays were installed downstream of each spill bay pier. The purpose of the splitter walls was to reduce the lateral circulation flows on the stilling basin floor to minimize or eliminate the ball-mill grinding action of debris. The top of each wall was set at the top of the stilling basin end sill (Figure 58).

With the splitter walls, the vertical circulation cell in the stilling basin consistently transported material upstream to the toe curve of the spillway. The horizontal circulation cell on the stilling basin flow was significantly reduced. However, lateral entrainment across the top of the splitter walls occurred, particularly between spill bays 1 and 2 where the wall intersected the toe curve (Video 11).

Stilling basin splitter walls will likely reduce the hydraulic conditions that contributed to the ball-mill grinding scour. However, splitter walls will not likely eliminate completely the horizontal circulation cells. Further, these experimental observations were conducted for discharges ranging from 9.3 to 22.4 kcfs per spill bay. The strength of the horizontal circulation cells would likely increase for higher discharges. Thus, this alternative is not recommend for further development, unless all other alternatives are discarded.

3 Conclusions

Based on the investigation into the hydraulic performance of the Type I and Type II spillway deflectors, the Type I deflector, which is the existing design at el 434.0, is recommended. Skimming and undulating surface-jet categories were prevalent for discharges up to 7.0 kcfs per spill bay for the operational range of tailwater elevation. It appears that the Type I deflector is likely near its optimum position at el 434.0 to provide surface-jet performance for discharges up to nearly 7.0 kcfs per spill bay. Although the transition of the flow from the spillway to the deflector was much smoother with the Type II deflector than the Type I deflector, the tailwater range for which surface-jet performance occurs with the Type II deflector at el 434.0 was smaller.

Pressure measurements on the spillway deflector showed positive pressures on the horizontal surface with negative pressures on the vertical face. Using the 20 percent exceedence pressure (only 20 percent of the measured pressures exceed this value) for the pressure on the horizontal face and the 80 percent exceedence (80 percent of the measured pressures exceed this value) for the vertical face, the force on the spillway deflector can be estimated. With these pressures, the force acting on the deflector (area of 12.5 ft by 50 ft) parallel to the spillway surface is approximately 899,000 lbs for the spillway design discharge of 106.0 kcfs per spill bay. The minimum pressures measured on the vertical face were as low as -25.5 ft of water. These pressures would indicate that cavitation potential exists, but only due to pressure fluctuations. It is likely that these kinds of pressures are experienced at nearly all of the deflectored spillways on the Lower Columbia and Snake Rivers. Only minor cavitation damage has been reported. Thus, while the measurements indicate cavitation potential, major damage due to cavitation is not expected to be a problem.

Pressure measurements were taken on the stilling basin floor to determine the potential uplift forces on the stilling basin apron. The pressure that can cause apron uplift is the difference between the localized pressure measurements and the hydrostatic pressure over the stilling basin. The hydrostatic pressure tends to hold the apron down, while the pressure caused by the impingement of a plunging jet tends to lift the apron, if exposed to crevasses under the apron. For 84 kcfs per spill bay, potential uplift pressure could be as high as 3,300 lb/ft^2. If these pressures have a pathway beneath the stilling basin apron, significant uplift force could result. If the apron monoliths were lifted sufficiently to allow flow under them, additional hydraulic forces could cause a catastrophic failure of the apron.

The discharge required to transport bottom debris (rock) was investigated by observing the movement of stone in the model tailrace. If a stone fluttered or rolled or was swept toward the stilling basin, the combination of discharge and tailwater was deemed capable of debris transport. A 4.0-ft gate opening (6.7 kcfs per spill bay) caused stones 20 ft downstream of the end sill to flutter, but not readily move upstream. A 5-ft gate opening provided the minimum discharge (8.5 kcfs per spill bay) required to move rock into the stilling basin. Whenever debris movement occurred, the hydraulic conditions were classified as a surface jet (either a skimming or undulating surface jet) with a strong upstream flow along the tailrace bottom. Larger gate openings tended to move rock into the basin at a faster rate. Although for these experiments, the circulation cell that created the upstream velocity did not extend beyond about 120 ft downstream of the end sill, for higher discharges and surface-jet flow conditions, the upstream circulation cell may extend farther downstream. These experiments show that the conditions that move rock into the stilling basin are as follows:

a. Conditions where a surface jet produces a strong vertical circulation cell with upstream velocities along the tailrace bottom from the tailrace into the stilling basin.

b. Conditions where turbulence lifts rocks up and over the end sill.

c. Conditions where rock movement builds a ramp against the downstream face of the sill, which then allows rock to "roll over" over the end sill and into the basin.

Experiments were also conducted to determine the conditions that caused the ball-mill grinding action that caused the apron erosion. A numerical model of flow along the stilling basin floor with and without the end bay deflector in place showed a prominent circulation cell downstream of bay 2. The installation of end bay deflectors is therefore recommended to reduce or perhaps eliminate the circulation cell on the apron. However, even with deflectors on the outside bays, it seems likely that once debris is in the stilling basin, some movement will occur. The severity of damage to the stilling basin will likely be significantly reduced. Frequent apron inspections should be conducted to gage the progress of apron scour, once deflectors have been installed. If damage continues at a significant rate, an engineering alternative should be developed that would exclude rock debris from being transported from the tailrace into the stilling basin.

Three alternatives were investigated to reduce transport of debris into the stilling basin: (a) grouting or armoring the tailrace channel, (b) the installation of a trench downstream of the end sill to act as a rock trap, and (c) a higher end sill elevation. For the first, whether grouting or riprap, protection would have to extend downstream of the end sill farther than the circulation cell (more than 120 ft), which transports material upstream. The minimum mean diameter for riprap protection in the tailrace is about 1.4 ft. However, the size could be significantly larger for higher spill rates with skimming flow or for plunging flow that impinges on the tailrace. Since the velocities decrease with distance downstream, the size of the riprap could be reduced with distance downstream. Any design for riprap protection should be experimentally assessed in the general model over a wide range of flow conditions before finalizing.

Based on a previous study (Fenwick 1989) at a different project, a 25.0-ft-wide by 10.0-ft-deep trap is recommended, located near the end sill that would run the entire width of the stilling basin as an initial design for Lower Monumental. The relative high velocities along the tailrace bottom could potentially move significant amounts of loose material into the trap. Depending upon the volume of loose or erodible material in the tailrace, some maintenance interval will likely be needed to remove trapped debris and maintain the effectiveness of the trap. The trap design should be investigated in the Lower Monumental general model to determine the trap efficiency (material retained in the trap compared to the total material transported from the tailrace into the trap).

A higher end sill was investigated that would make debris movement into the stilling basin more difficult. Based on the experiments, a higher end sill would only increase the length of time compared to the existing end sill before debris was transported over the end sill into the stilling basin. The study showed that debris tended to build a ramp as material was deposited just downstream of the end sill. Once the ramp was sufficiently high, debris was transported into the stilling basin.

To reduce the lateral circulation on the stilling basin floor and thereby minimize or eliminate the ball-mill grinding action, walls were installed in the stilling basin that split the stilling basin into 50-ft-wide bays. Although the vertical circulation cell that extended well downstream consistently transported material up to the toe curve of the spillway, the horizontal circulation cell on the stilling basin floor was significantly reduced. Stilling basin splitter walls will likely reduce the hydraulic conditions that contributed to the ball-mill grinding scour. However, splitter walls are not likely to completely eliminate horizontal circulation. Further, these experimental observations were conducted for discharges ranging from 9.3 to 22.4 kcfs per spill bay. The strength of the horizontal circulation cells will likely increase for larger discharges.

4 Recommendations

The following recommendations are made based on the results of this investigation:

- Type I spillway deflectors, which is the existing design at el 434.0, are recommended, because of a slightly wider operating range for surface jets. However, the transition of the flow from the spillway to the deflector is much smoother with the Type II deflector than the Type I deflector. Thus, the Type II deflector should be adopted if fish injury is a concern for the Type I. Significant differences in TDG exchange characteristics are not expected.

- The force acting on the deflector (area of 12.5 ft by 50 ft) parallel to the spillway surface is approximately 899,000 lbs for the spillway design discharge of 106.0 kcfs per spill bay and should be used as an estimate of deflector loading.

- Minimum pressures on the vertical face of a deflector may indicate potential for cavitation. However, only minor cavitation damage has been noted at other deflectors. Thus, significant cavitation damage is not expected to be a problem and protection from cavitation damage need not be included in project design.

- Transducer measurements on the stilling basin apron showed uplift pressures of approximately 3,300 lb/ft^2 could possibly occur for a discharge of about 84 kcfs per spill bay. These pressures could potentially cause significant uplift force and as a result, catastrophic failure of the apron. Protection from apron uplift should be instituted as soon as possible.

- A 5-ft gate opening provided the minimum discharge (8.5 kcfs per spill bay) required to move rock into the stilling basin. To minimize debris transport, the discharge per spill bay should be minimized. Although surface-jet conditions cause debris transport, the hydraulic conditions that provide surface jets should be sought to minimize plunging (high uplift pressures) and reduce TDG.

- Based on numerical and physical model results, end bay deflectors are recommended to reduce or perhaps eliminate the circulation cell on the apron. However, even with deflectors on the outside bays, it seems likely that once debris is in the stilling basin, some movement will occur.

Even so, the severity of damage to the stilling basin will likely be significantly reduced. Frequent apron inspections should be conducted to gage the progress of apron scour, once deflectors have been installed. If damage continues at a significant rate, an engineering alternative should be developed that would exclude rock debris from being transported from the tailrace into the stilling basin.

- Stilling basin splitter walls can significantly reduce the horizontal circulation cell on the stilling basin floor. Splitter walls are recommended, but only as a last resort. Regardless of which gates are in operation or the discharge, it seems likely that once debris is transported into the stilling basin, some level of ball-mill grinding will occur. Thus, an engineering alternative should be developed that would exclude rock debris from being transported from the tailrace into the stilling basin.

- Three alternatives were investigated to reduce transport of debris into the stilling basin:

  a. Grouting or armoring the tailrace channel. Grouting or riprap protection would have to extend more than 120 ft downstream of the end sill. The minimum mean diameter for riprap protection in the tailrace is about 1.4 ft. Any design for riprap protection should be experimentally assessed in the general model.

  b. Installation of a trench downstream of the end sill to act as a rock trap. A 25.0-ft wide by 10.0-ft-deep trap located near the end sill that would run the entire width of the stilling basin is recommended as an initial design for Lower Monumental. The trap design should be investigated in the Lower Monumental general model.

  c. Higher end sill elevation. A higher end sill would only increase the length of time before debris was transported over the end sill into the stilling basin. This alternative is not recommended.

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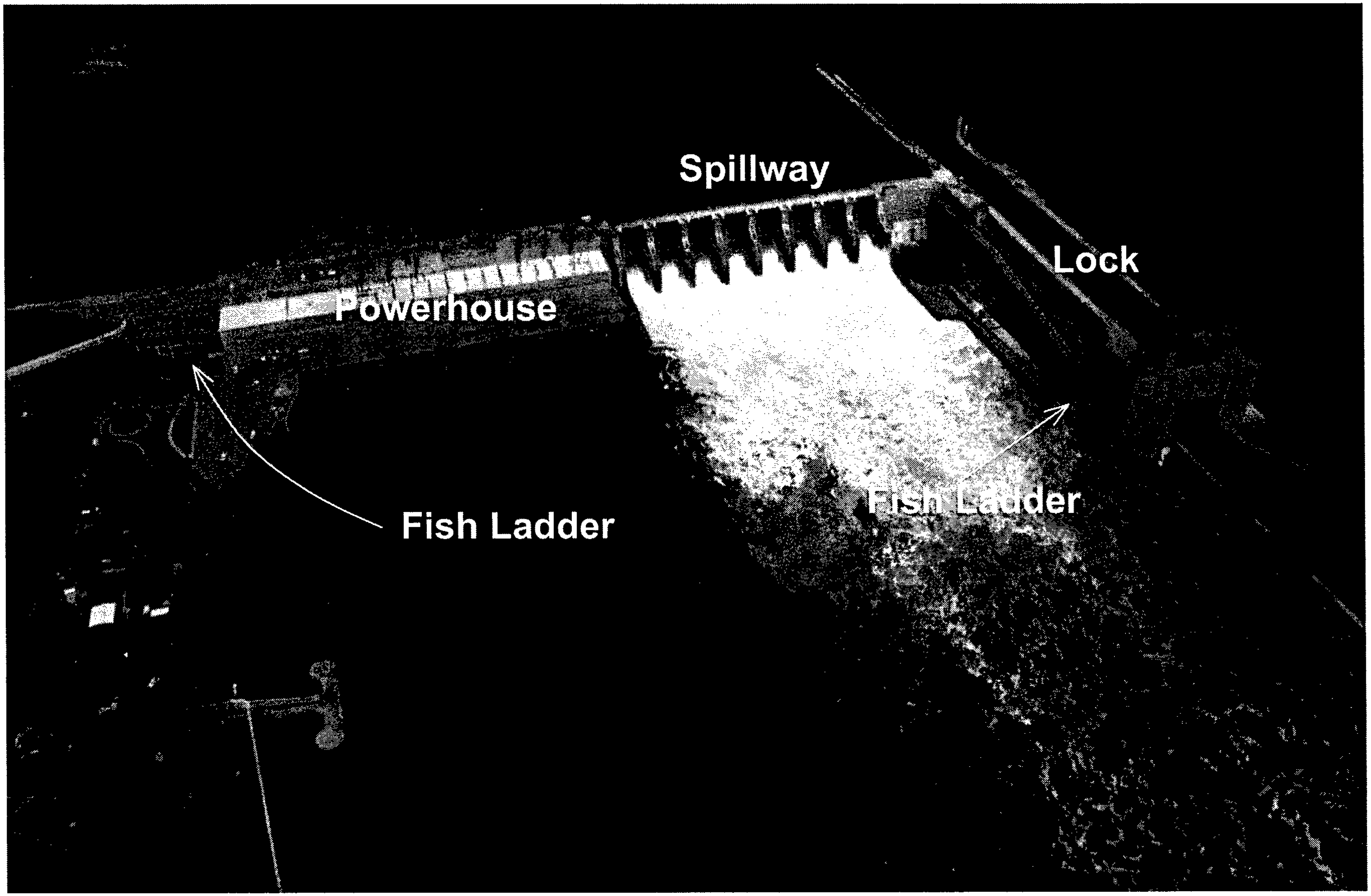

Figure 1. Aerial photograph of Lower Monumental Dam

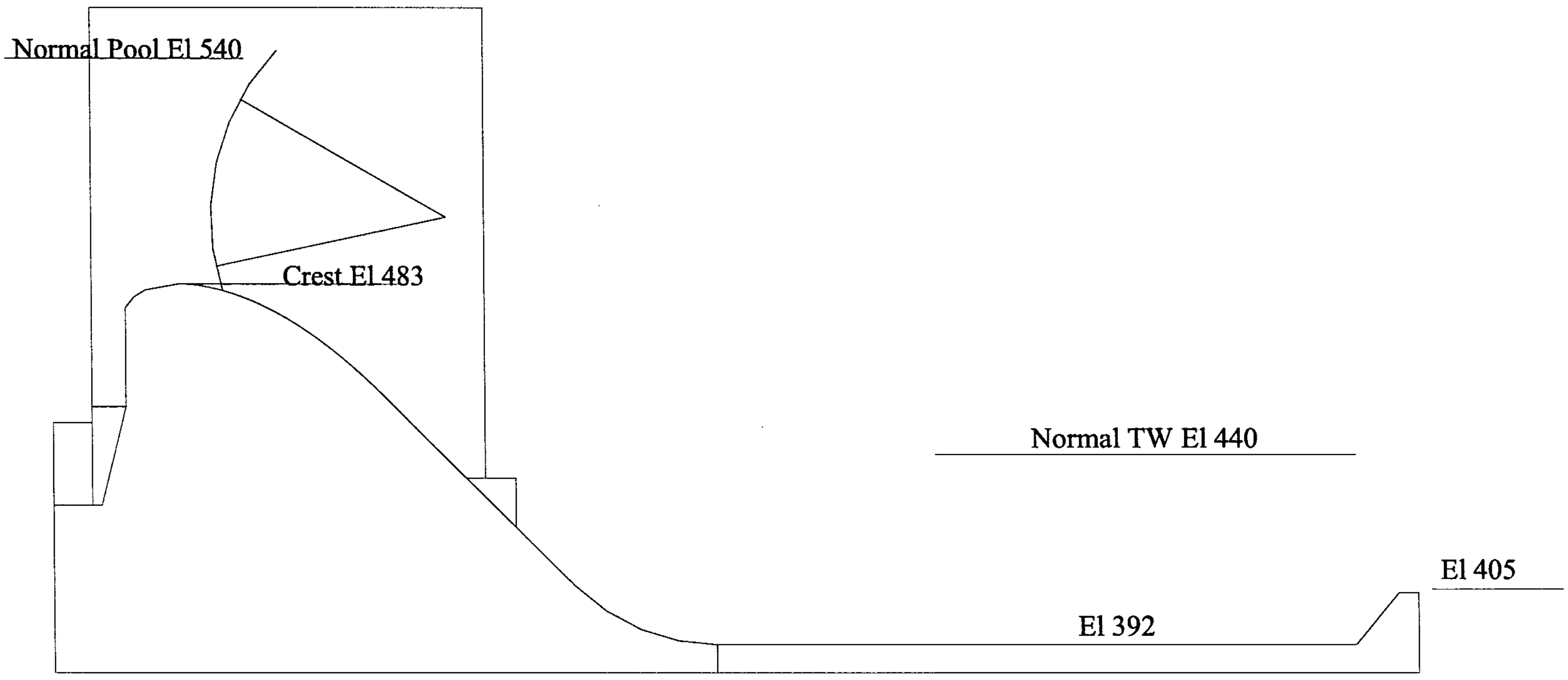

Figure 2. Lower Monumental section model, with Type I flow deflector, elevation view

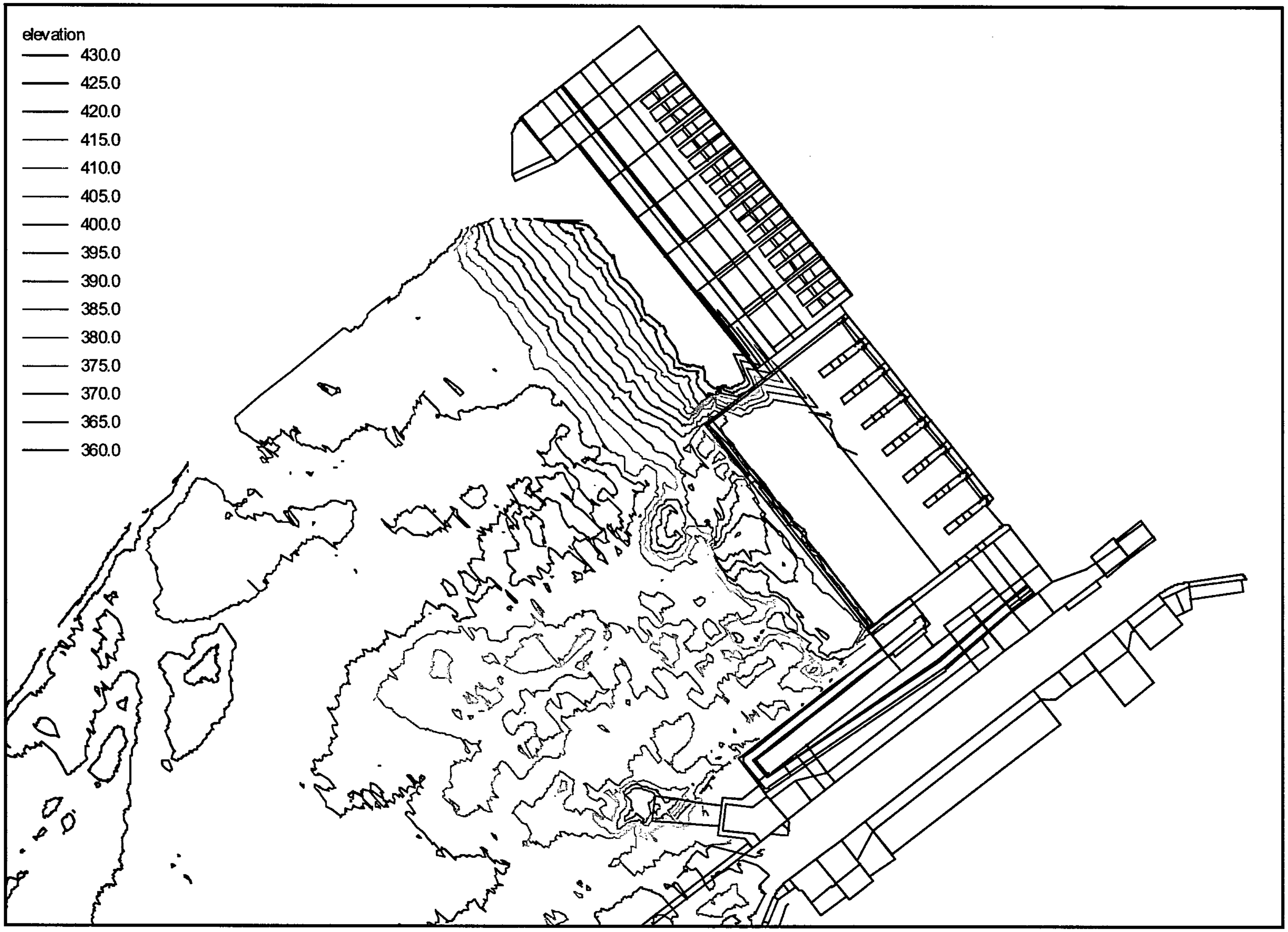

Figure 3. Tailwater channel bathymetry downstream of the Lower Monumental Spillway

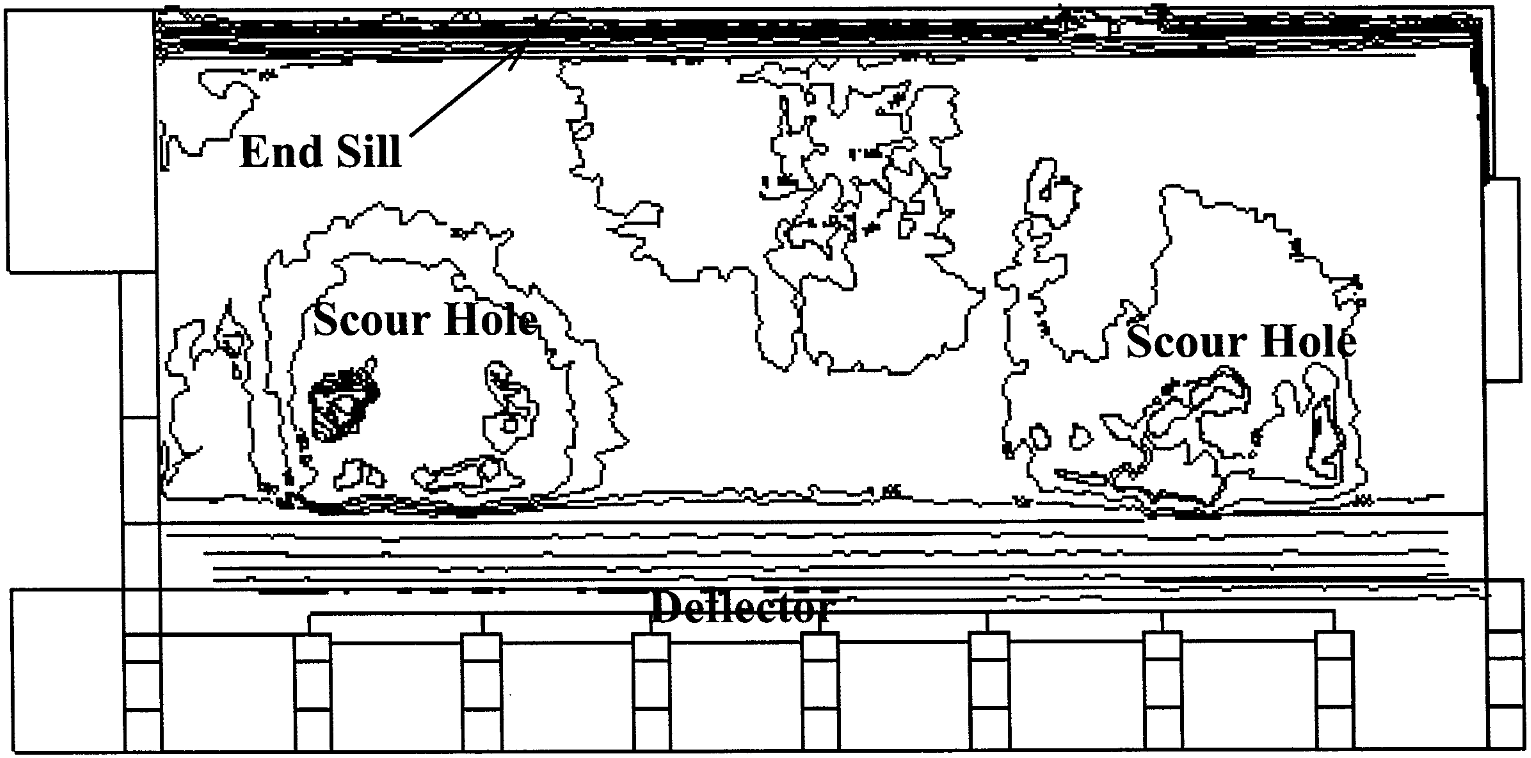

Figure 4. District supplied scour hole drawing

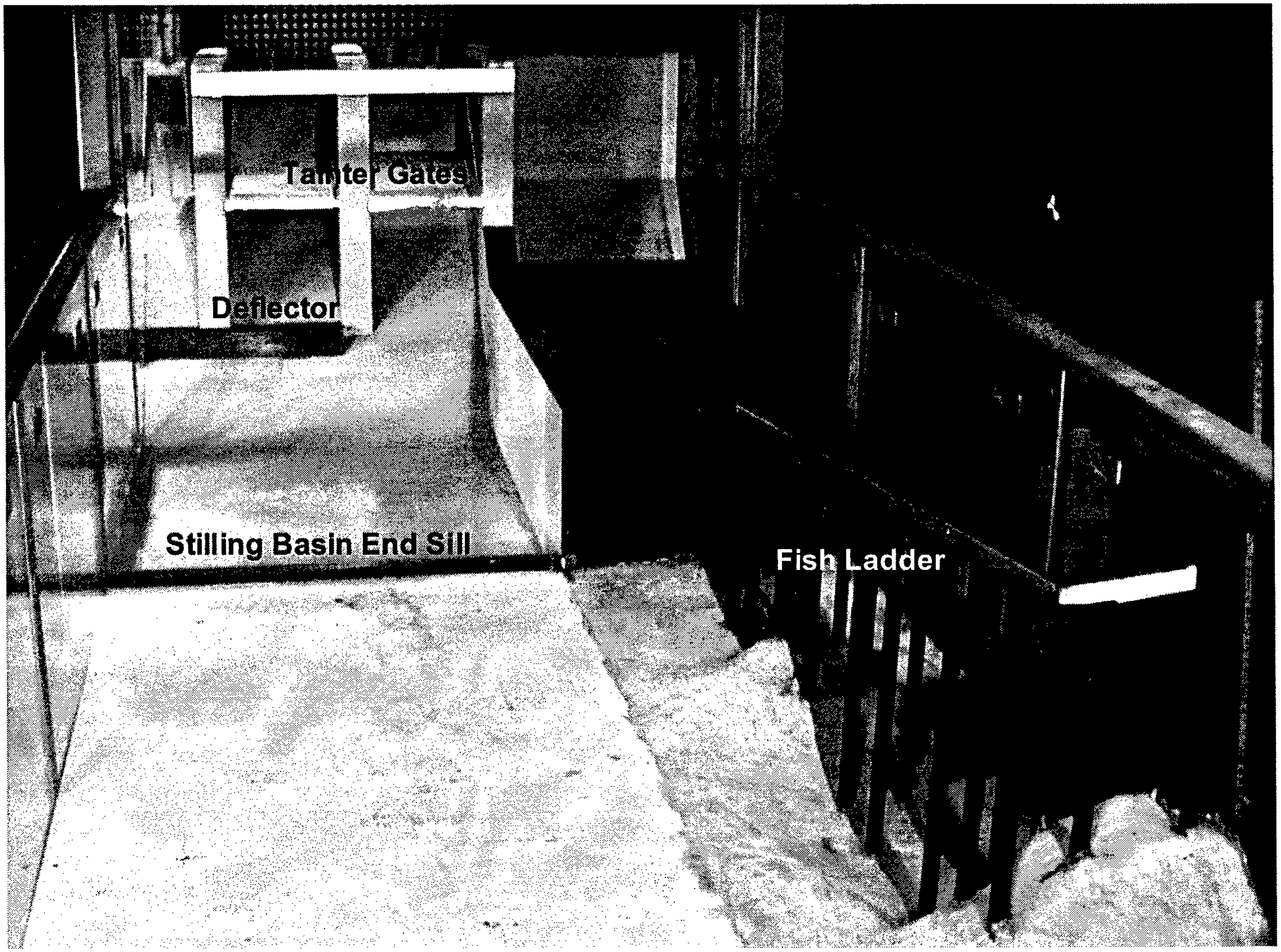

Figure 5. Lower Monumental section model with Type I flow deflector

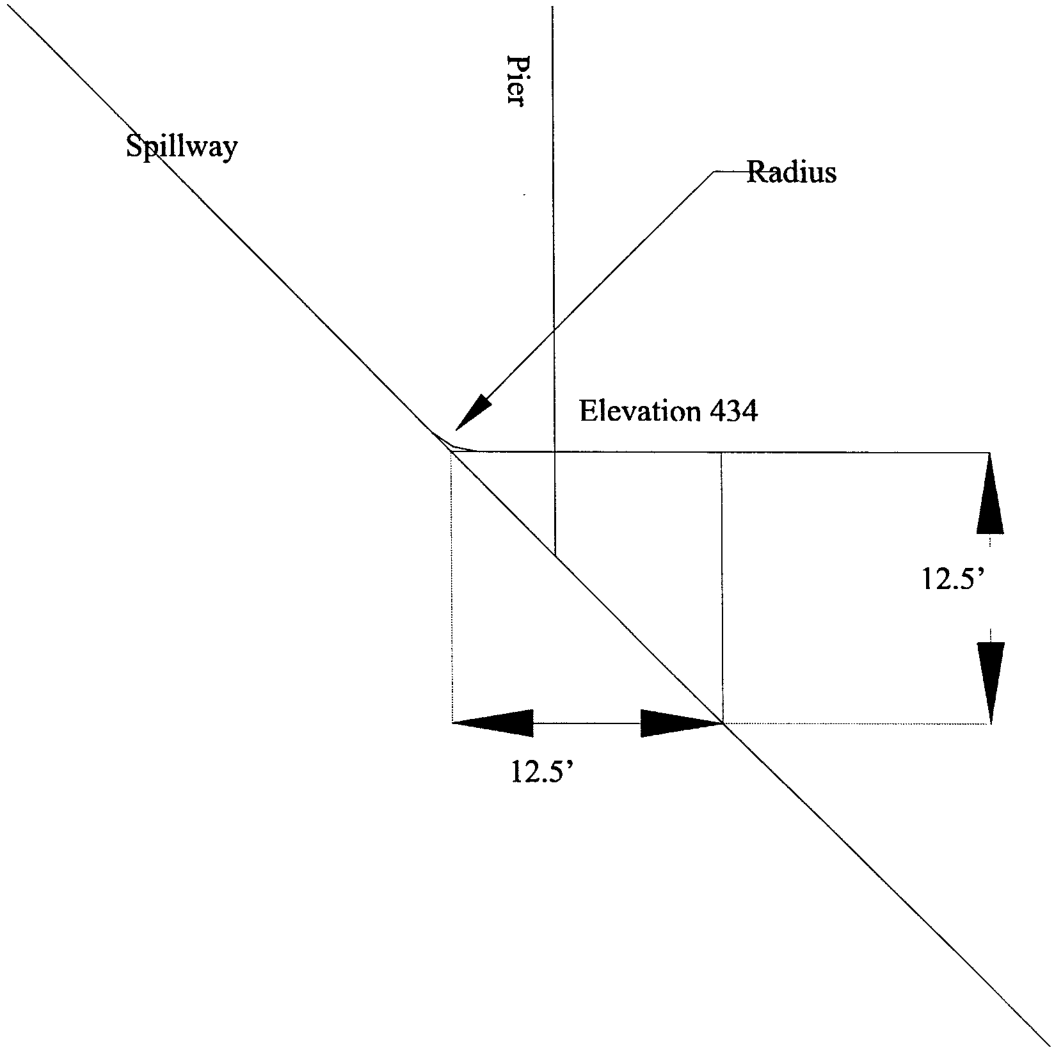

Figure 6. Lower Monumental Type I spillway deflector (existing design)

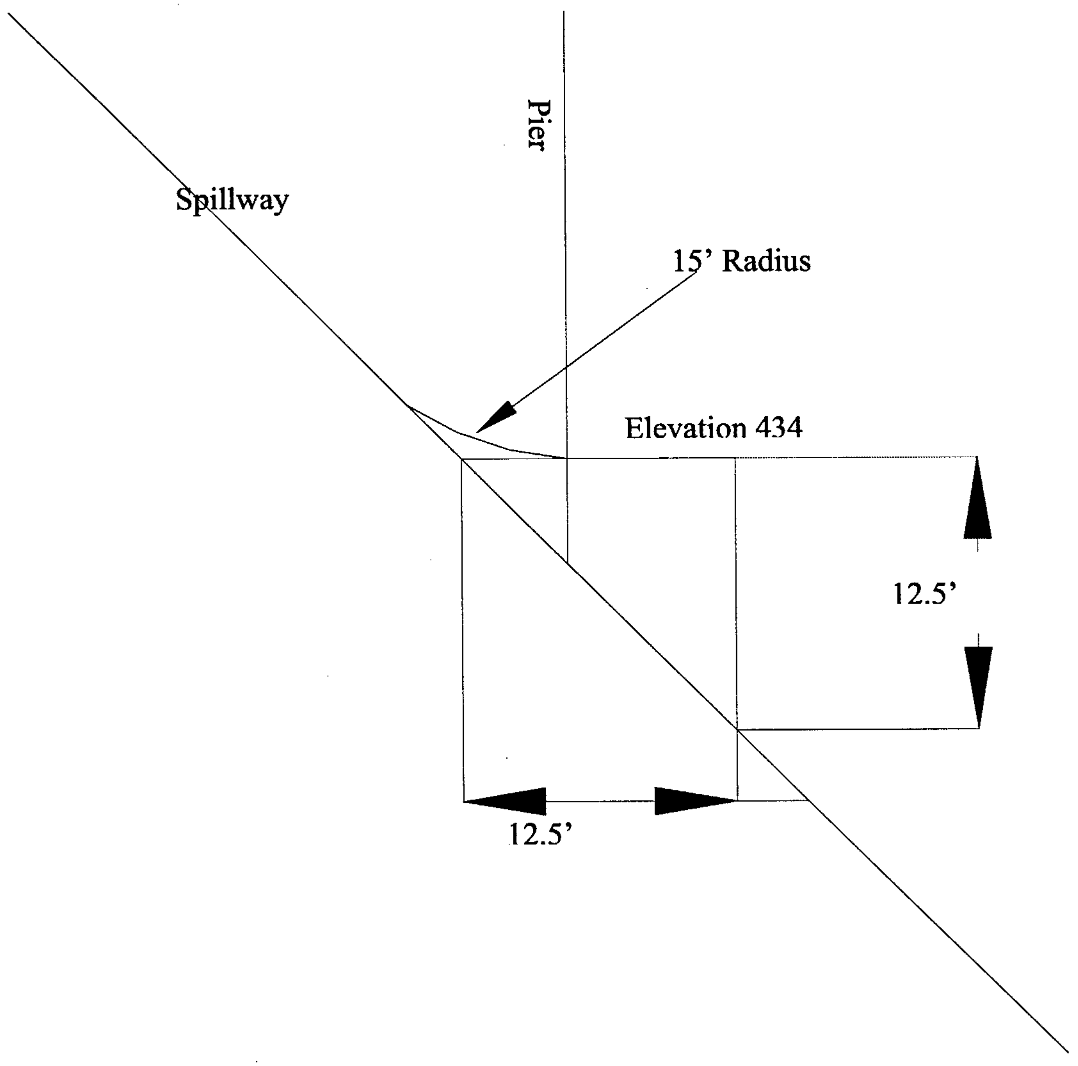

Figure 7. Lower Monumental section model Type II spillway deflector

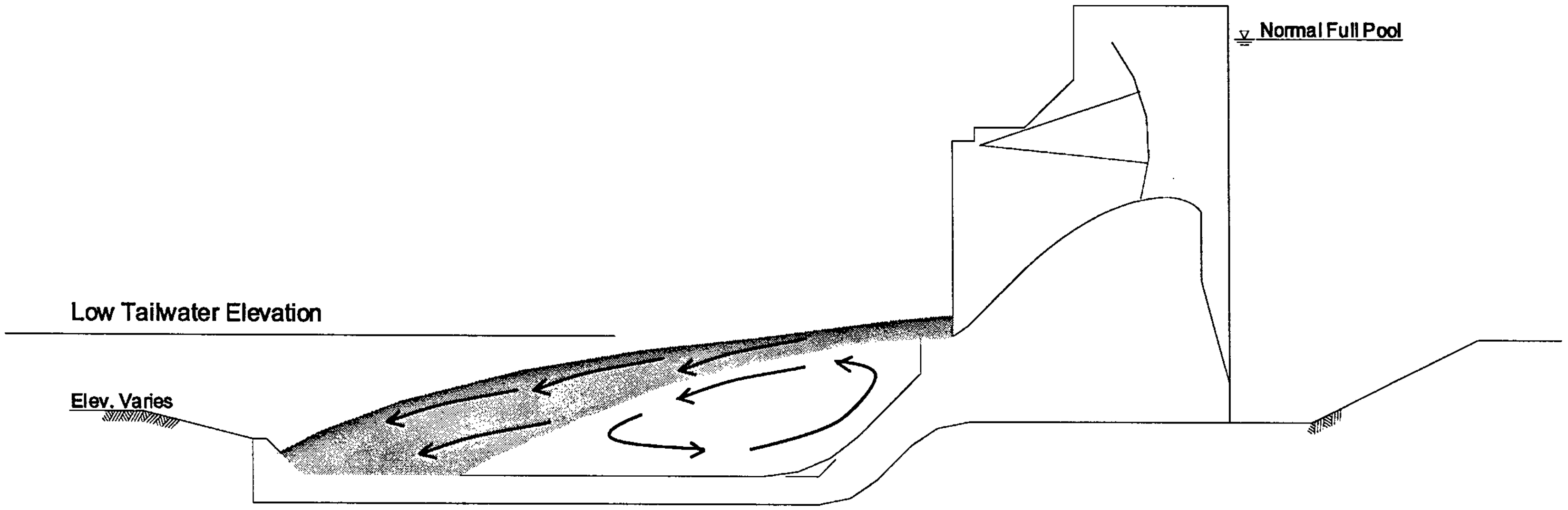

Figure 8. Plunging flow

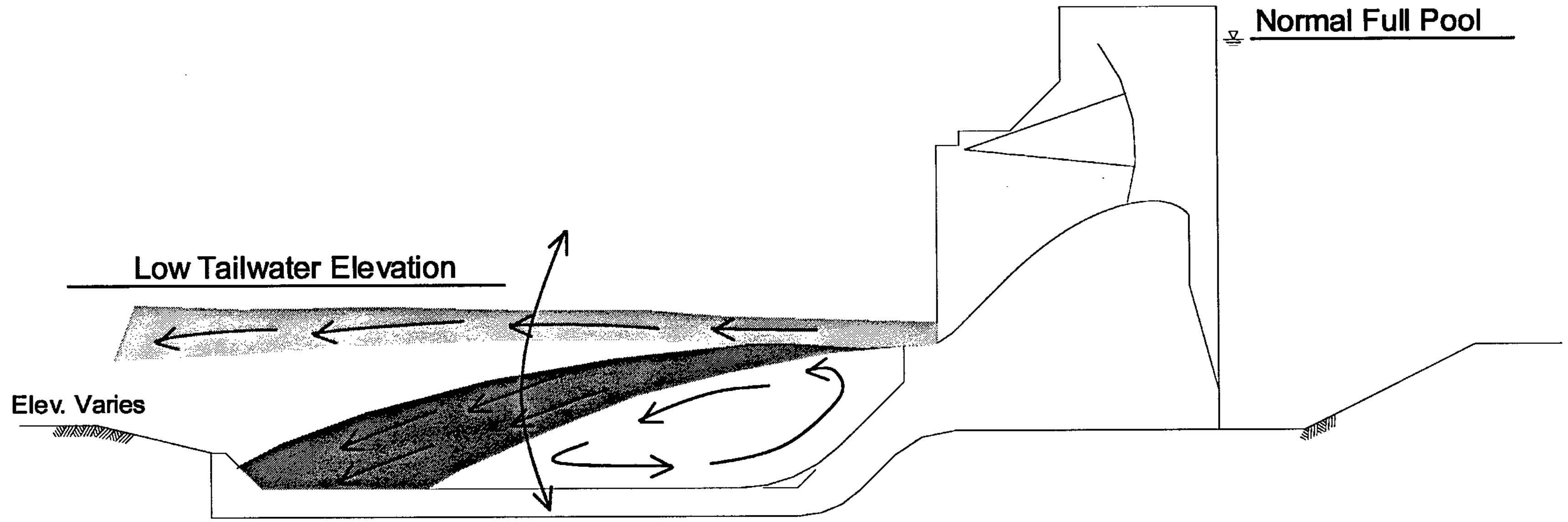

Figure 9. Unstable plunging jet

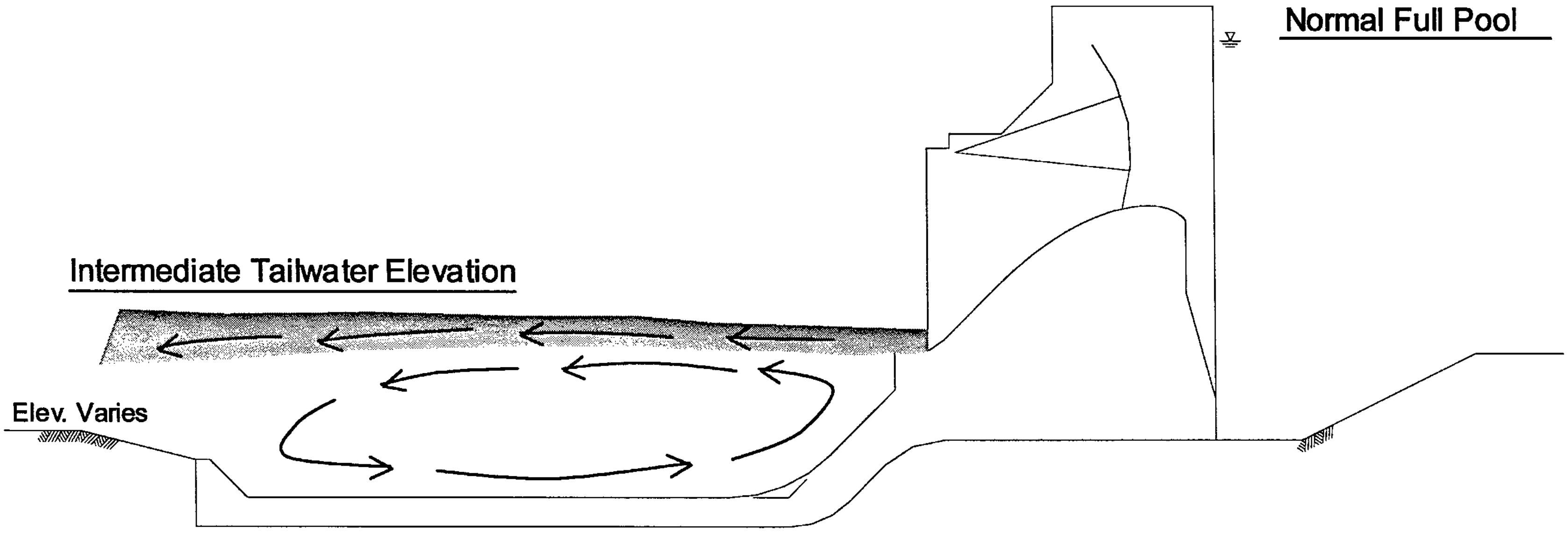

Figure 10. Skimming surface jet

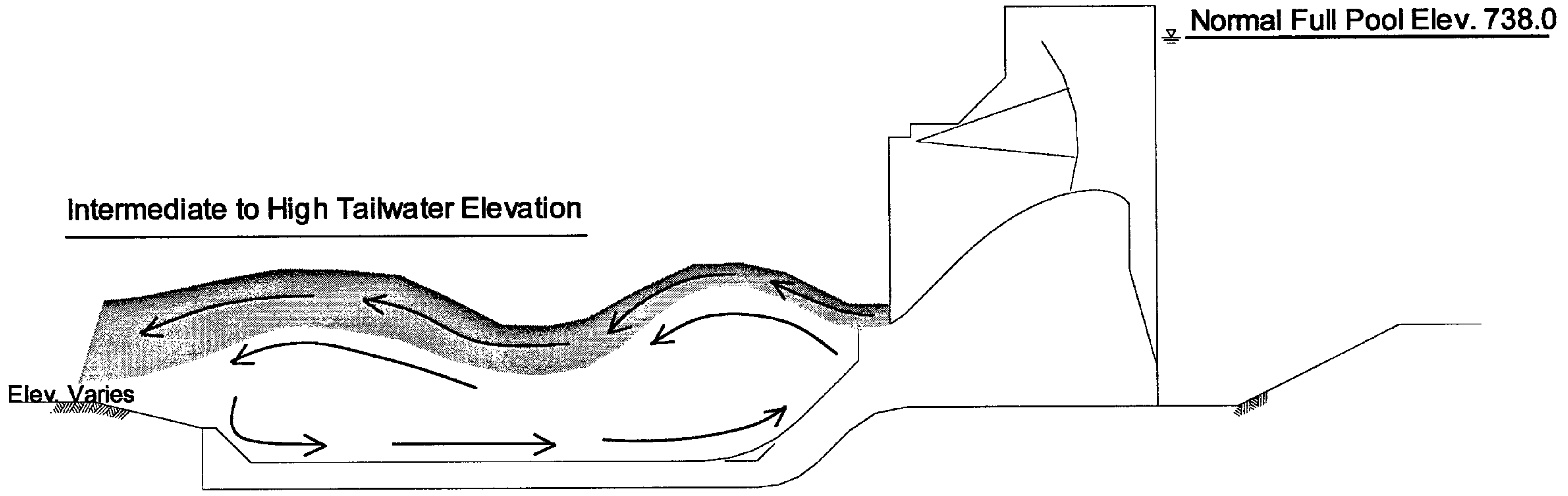

Figure 11. Undulating surface jet

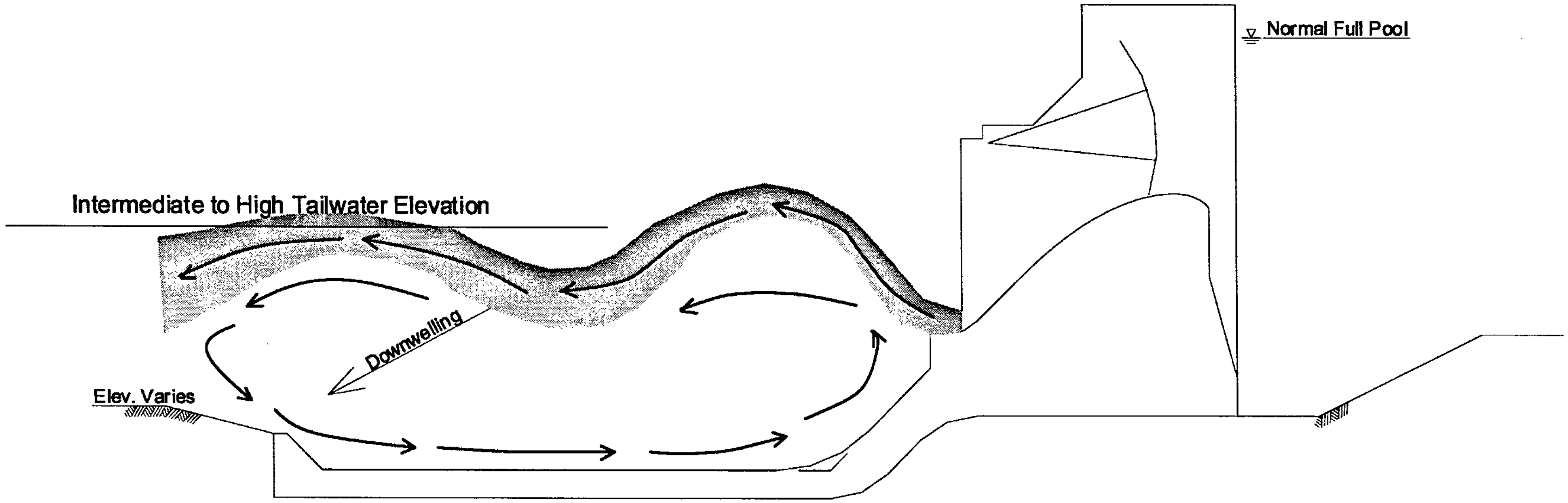

Figure 12. Ramped surface jet

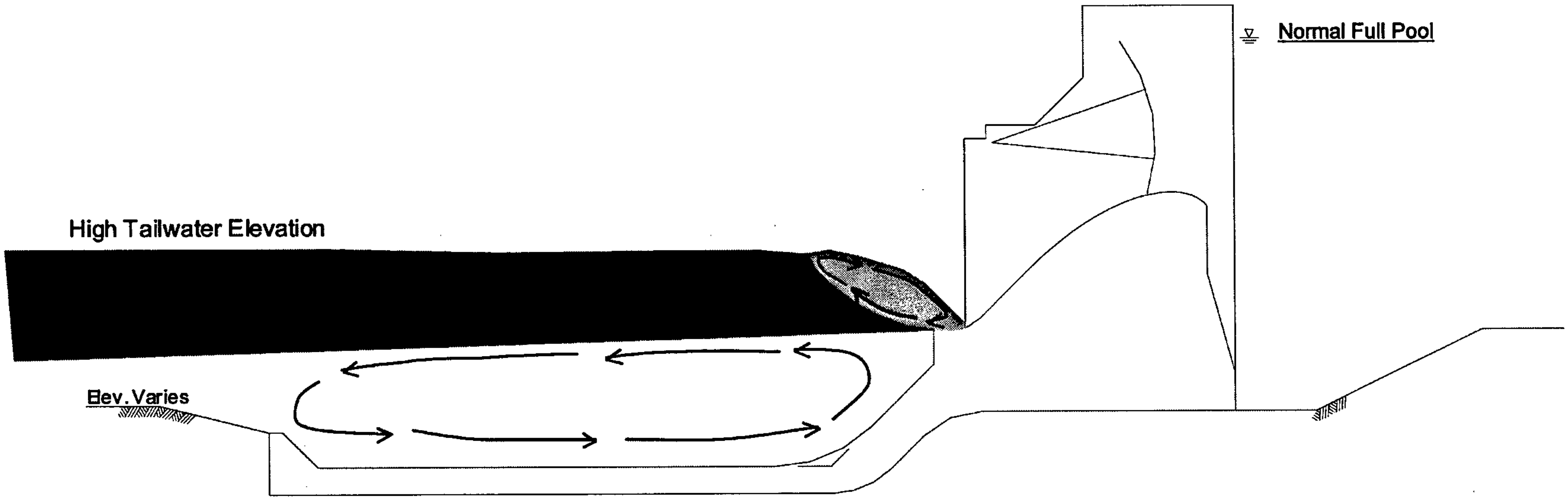

Figure 13. Surface jump

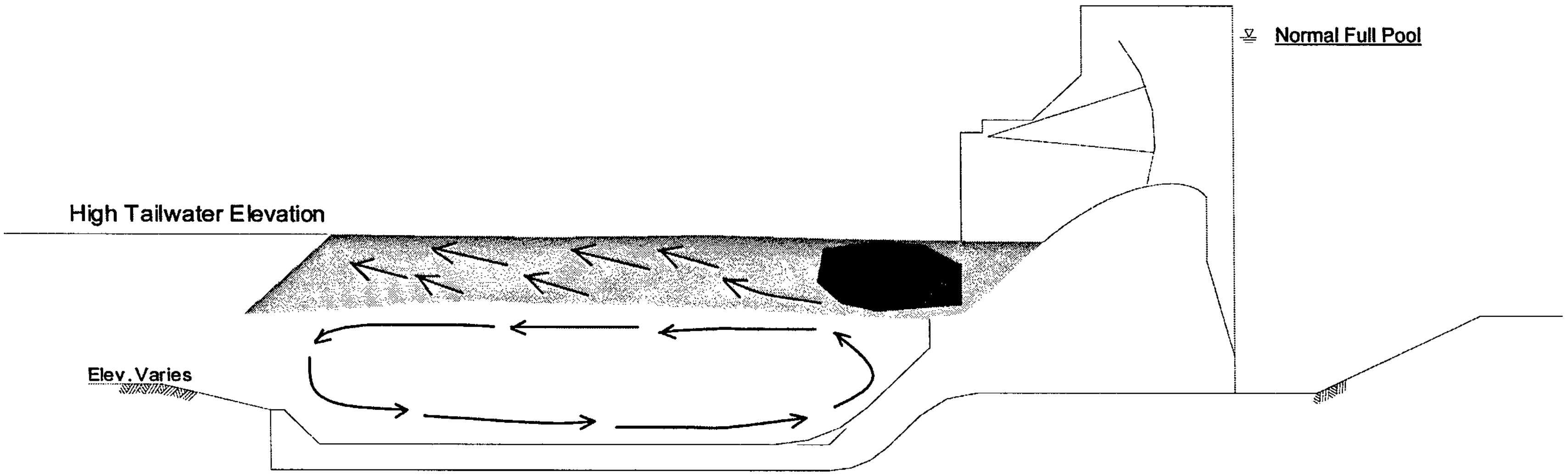

Figure 14. Submerged surface jump

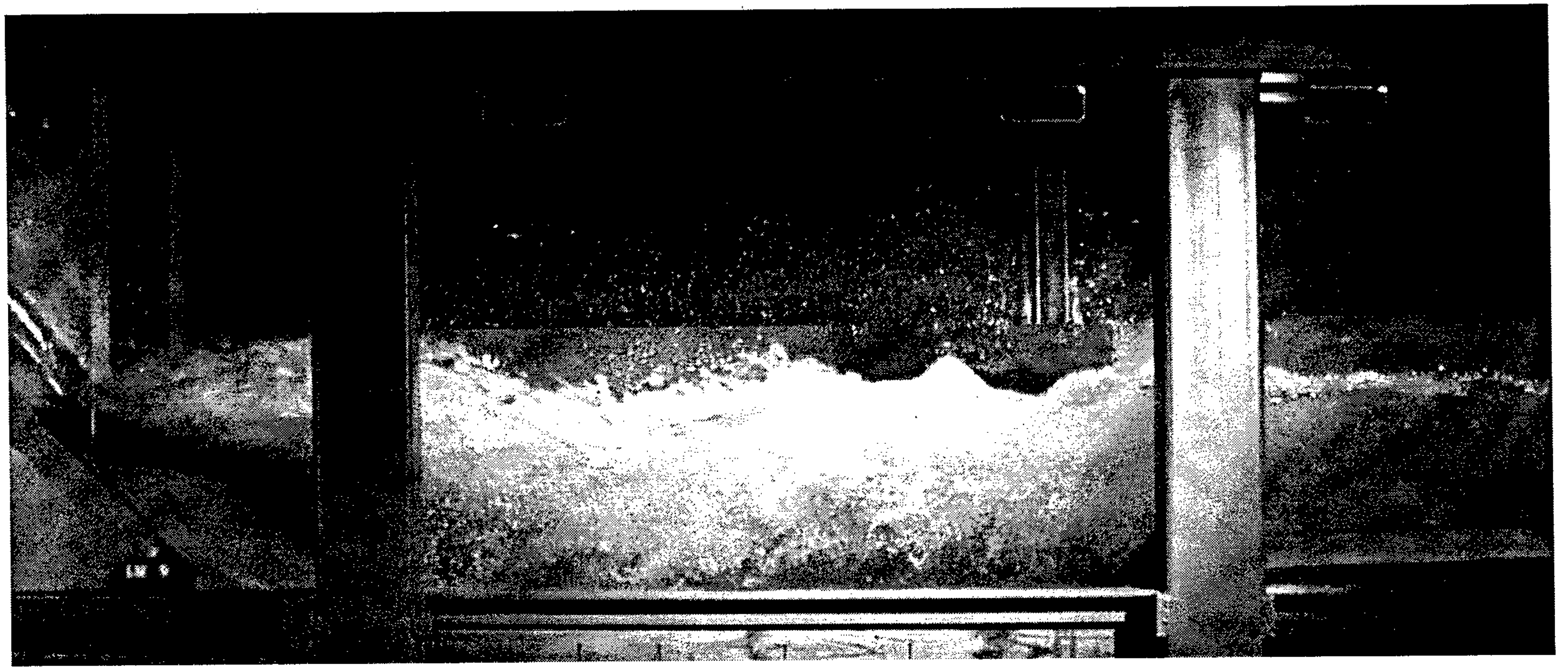

Figure 15. Plunging flow. Gate opening - 4 ft, discharge – 6.7 kcfs/bay, pool elevation - 537.0, tailwater elevation - 438.0

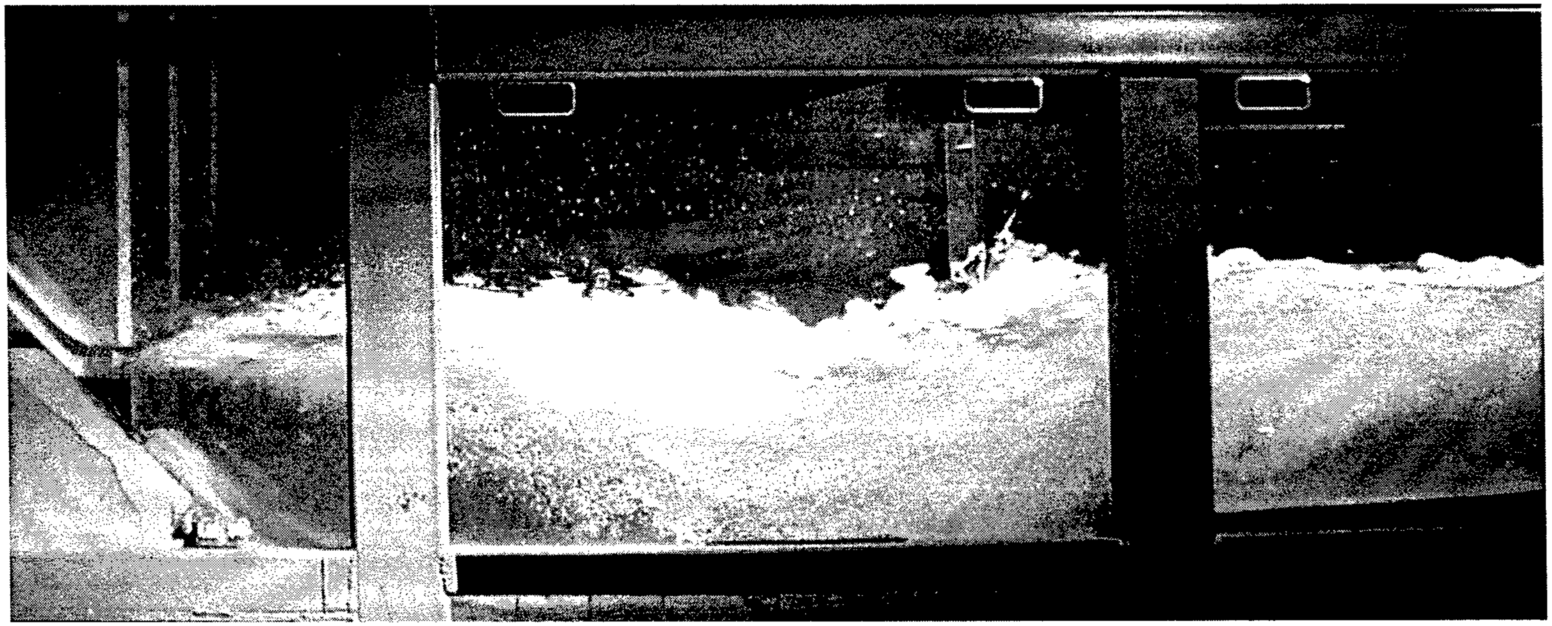

Figure 16. Plunging flow. Gate opening - 10 ft, discharge – 18.2 kcfs/bay, pool elevation - 537.0, tailwater elevation - 453.0

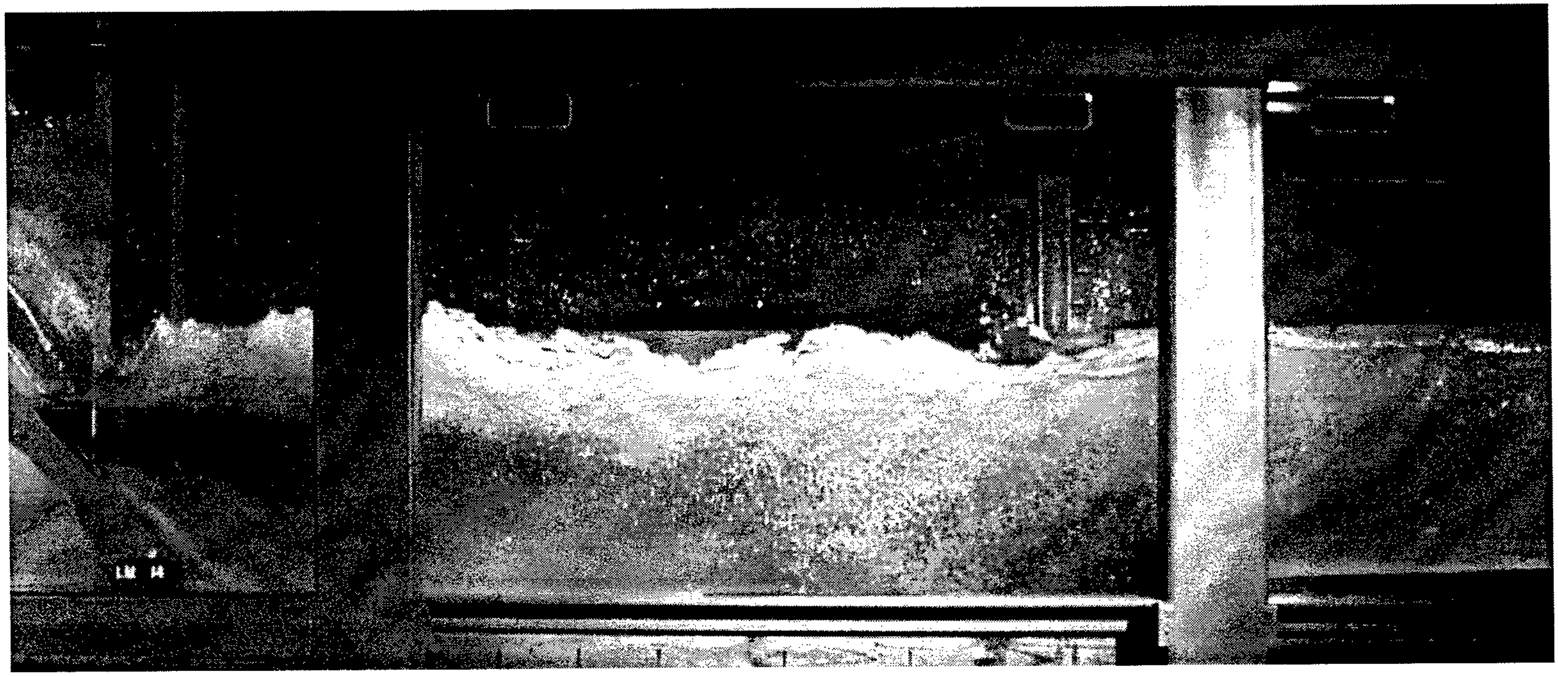

Figure 17. Undulating surface jet. Gate opening - 4 ft, discharge – 6.7 kcfs/bay, pool elevation - 537.0, tailwater elevation - 448.0

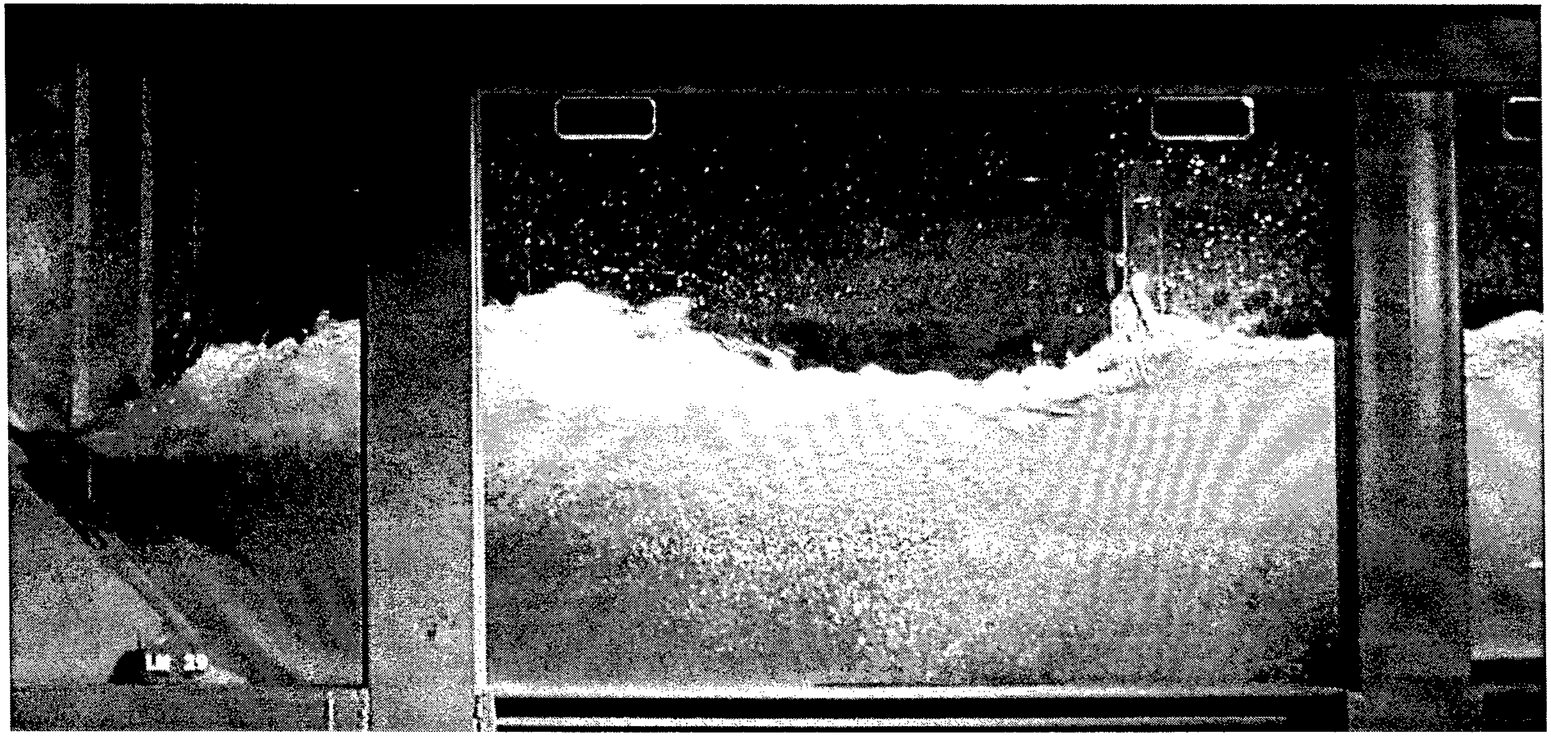

Figure 18. Ramped surface jet. Gate opening - 8 ft, discharge – 13.8 kcfs/bay, pool elevation - 537.0, tailwater elevation - 456.0

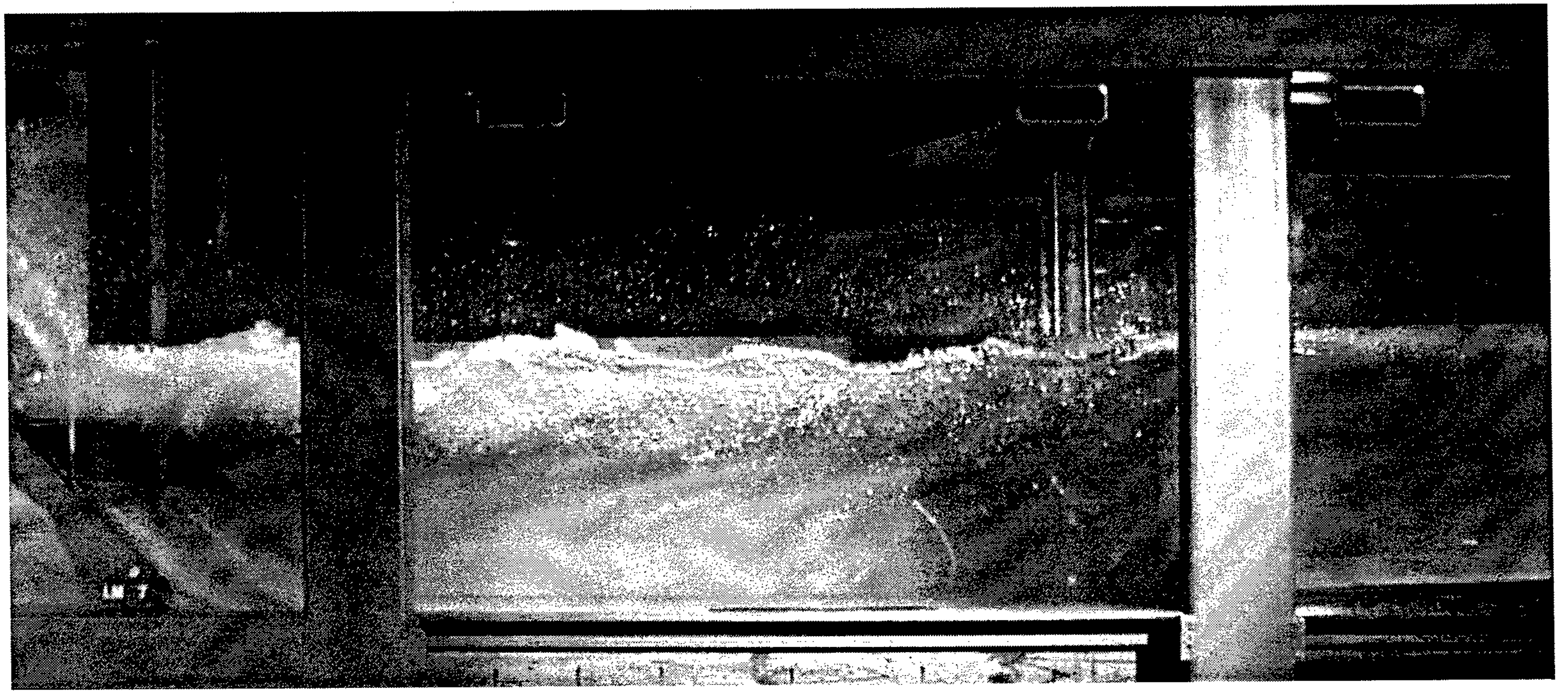

Figure 19. Surface jump. Gate opening - 2 ft, discharge - 4.2 kcfs/bay, pool elevation - 537.0, tailwater elevation - 447.0

Figure 20. Submerged surface jump. Gate opening - 2 ft, discharge - 4.2 kcfs/bay, pool elevation - 537.0, tailwater elevation - 449.0

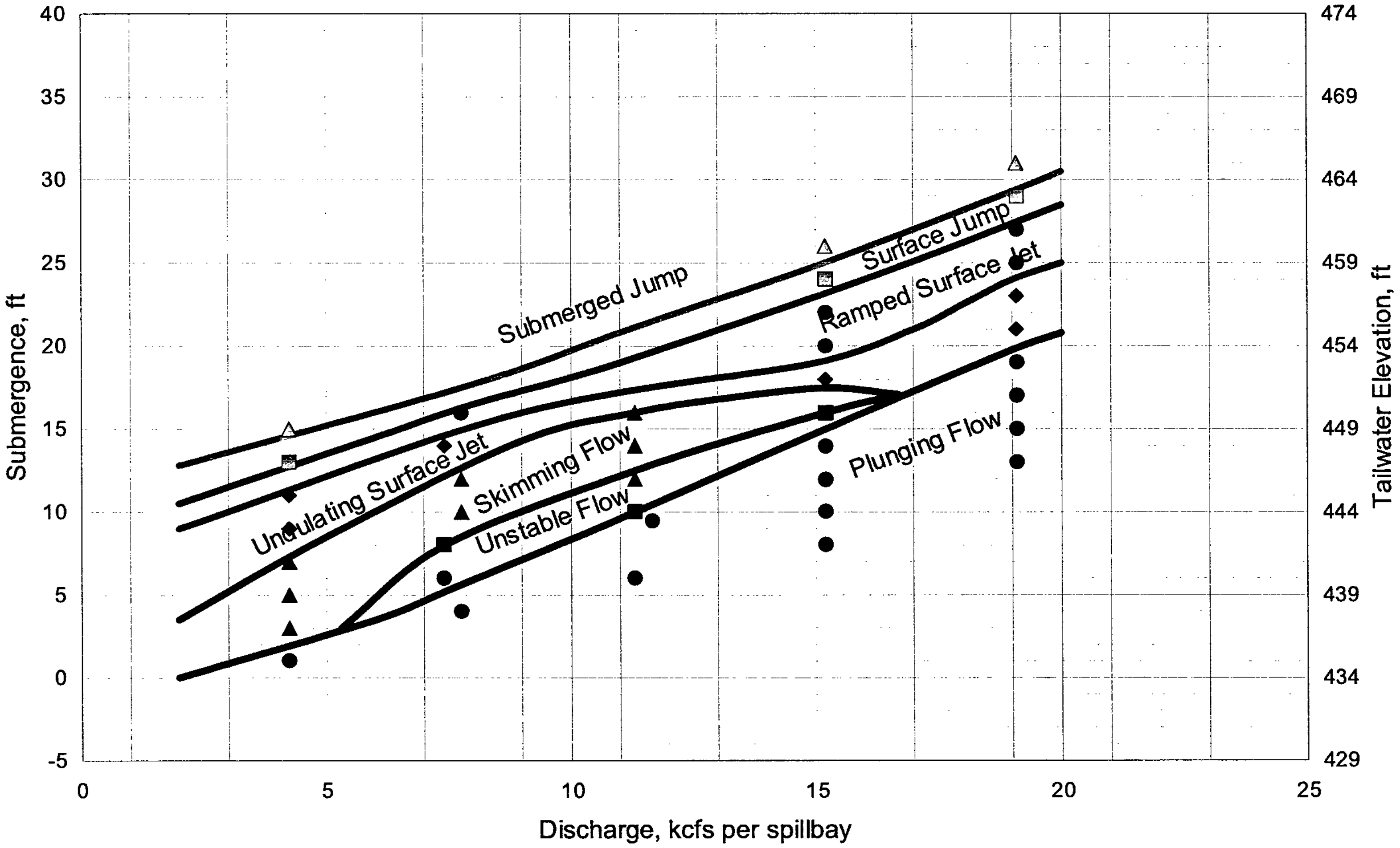

Figure 21. Performance characteristics of the Lower Monumental stilling basin with Type I deflector

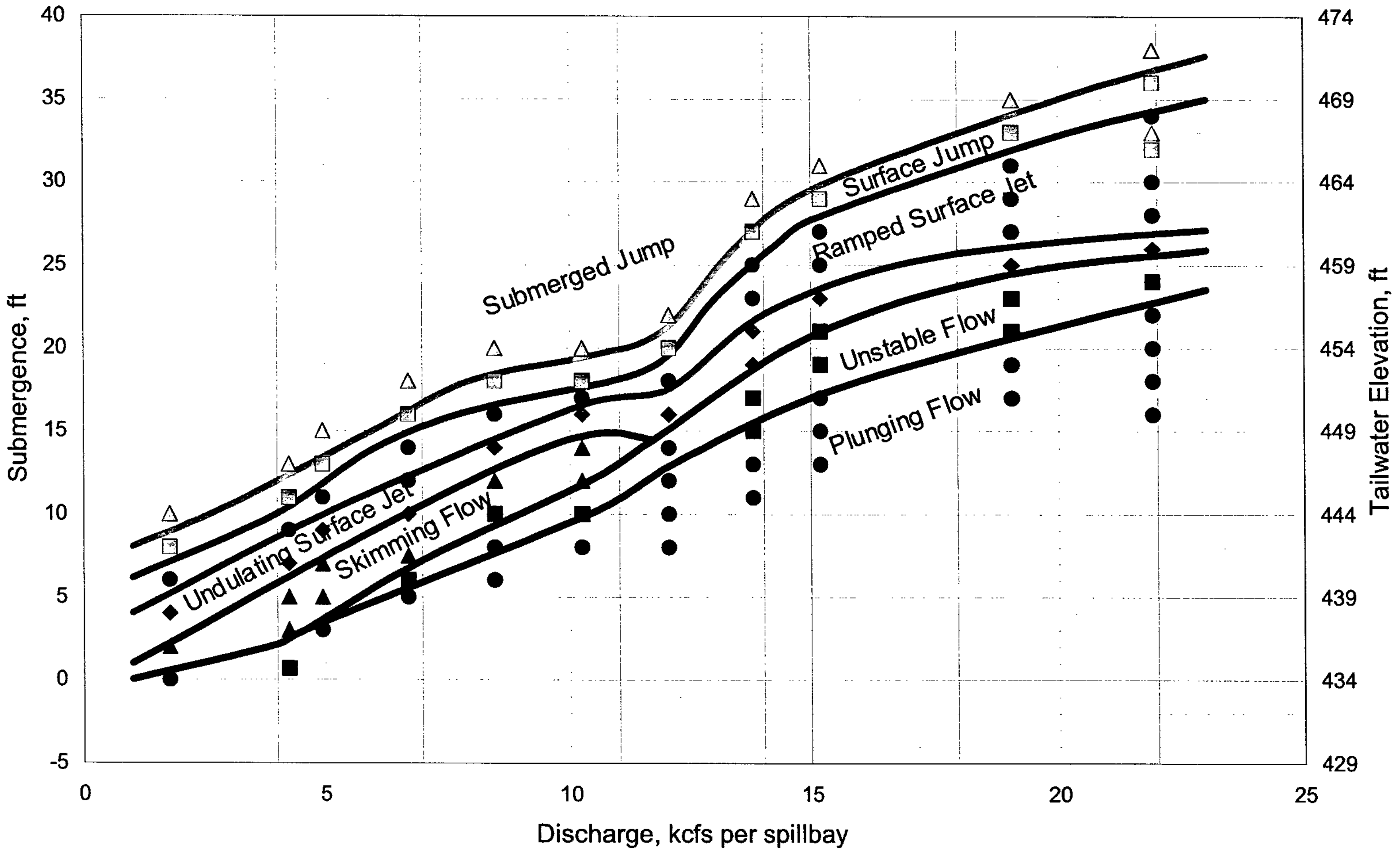

Figure 22. Performance characteristics of the Lower Monumental stilling basin with Type II deflector

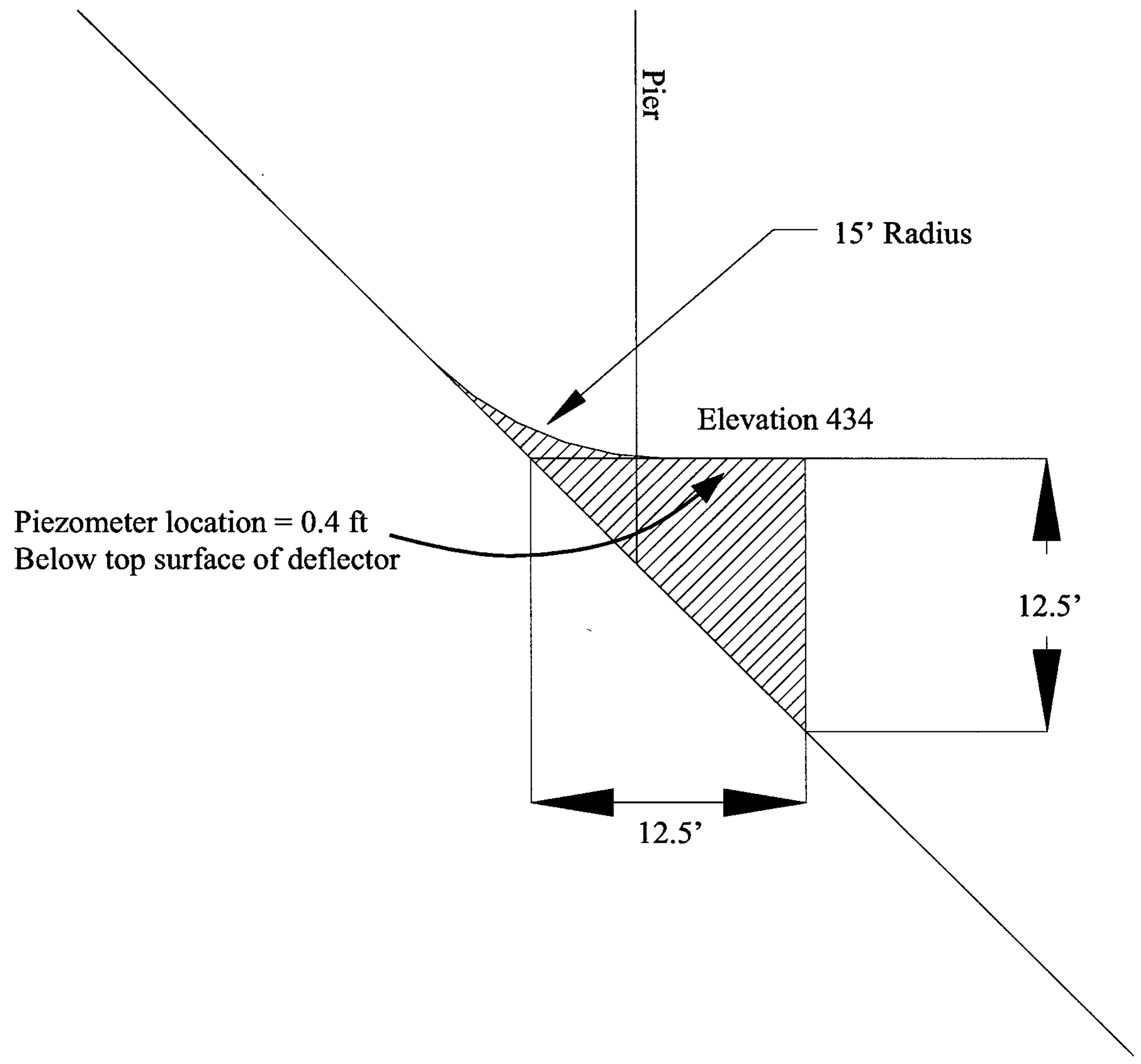

Figure 23. Piezometer located on the vertical face of the deflector

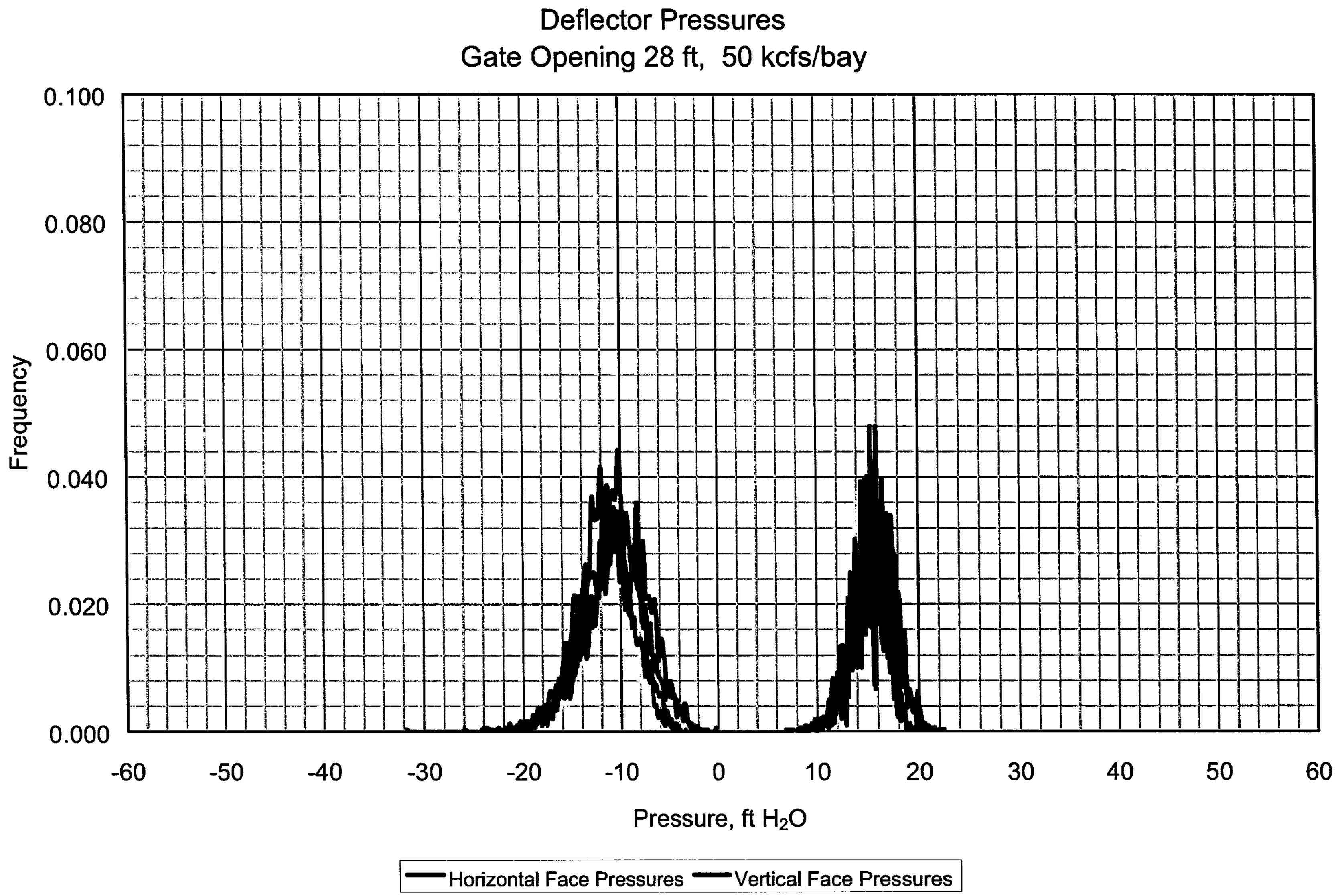

Figure 24. Frequency curves, gate opening – 28 ft, discharge – 50 kcfs/bay

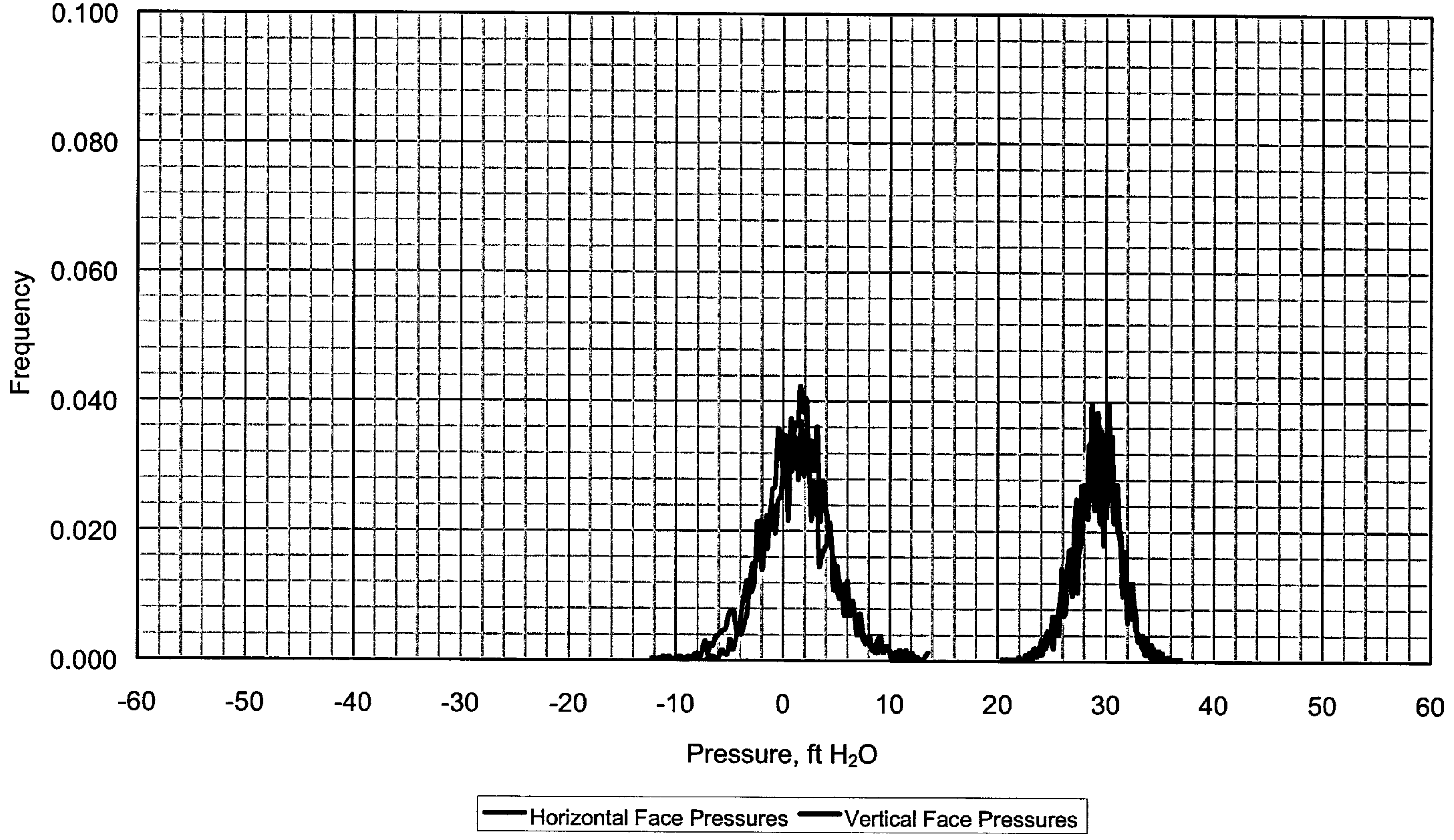

Figure 25. Frequency curves, full gate opening, discharge – 106 kcfs/bay

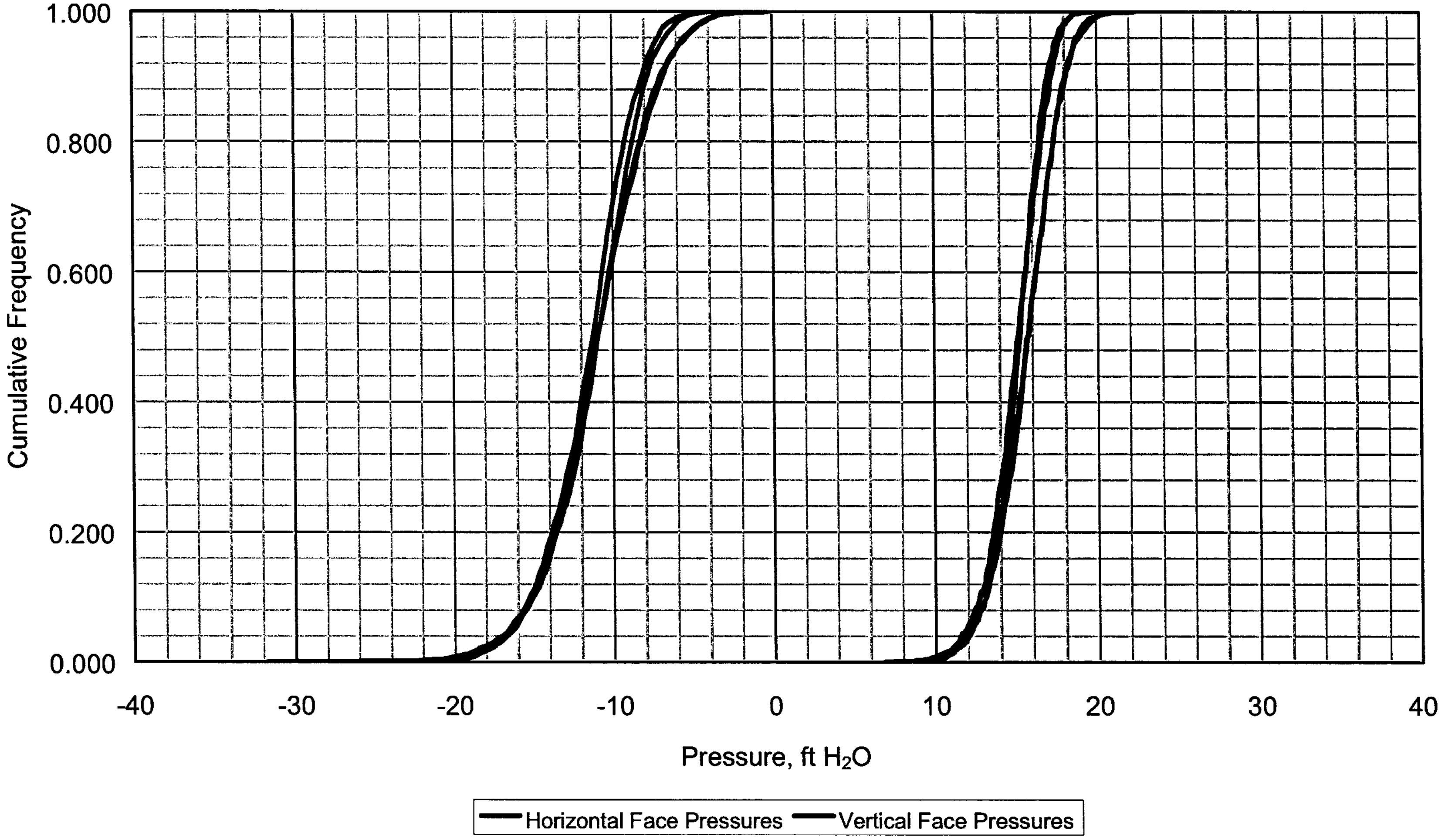

Figure 26. Cumulative frequency distribution, gate opening – 28 ft, discharge – 50 kcfs/bay

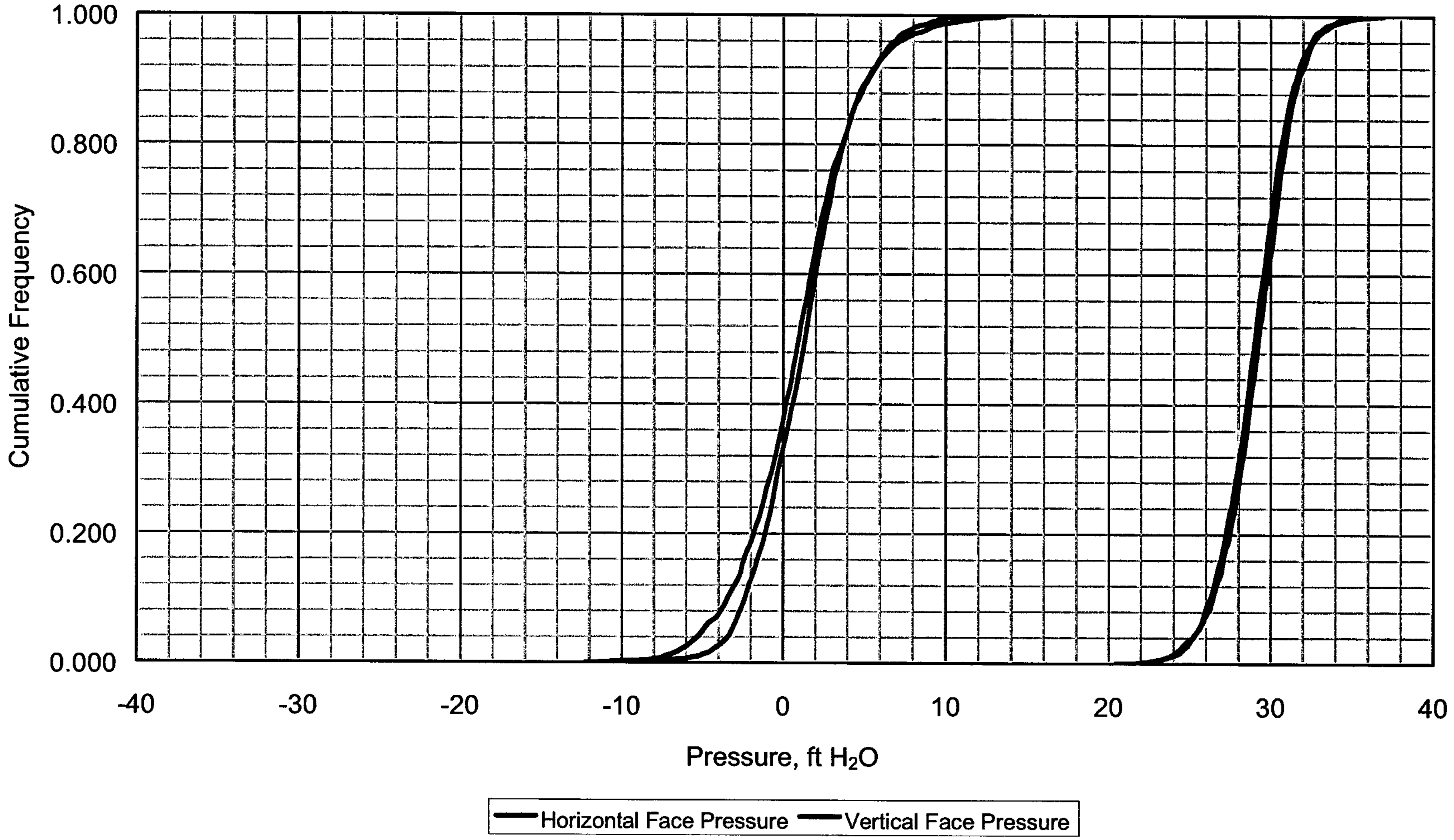

Figure 27. Cumulative frequency distribution, full gate opening, discharge – 106 kcfs/bay

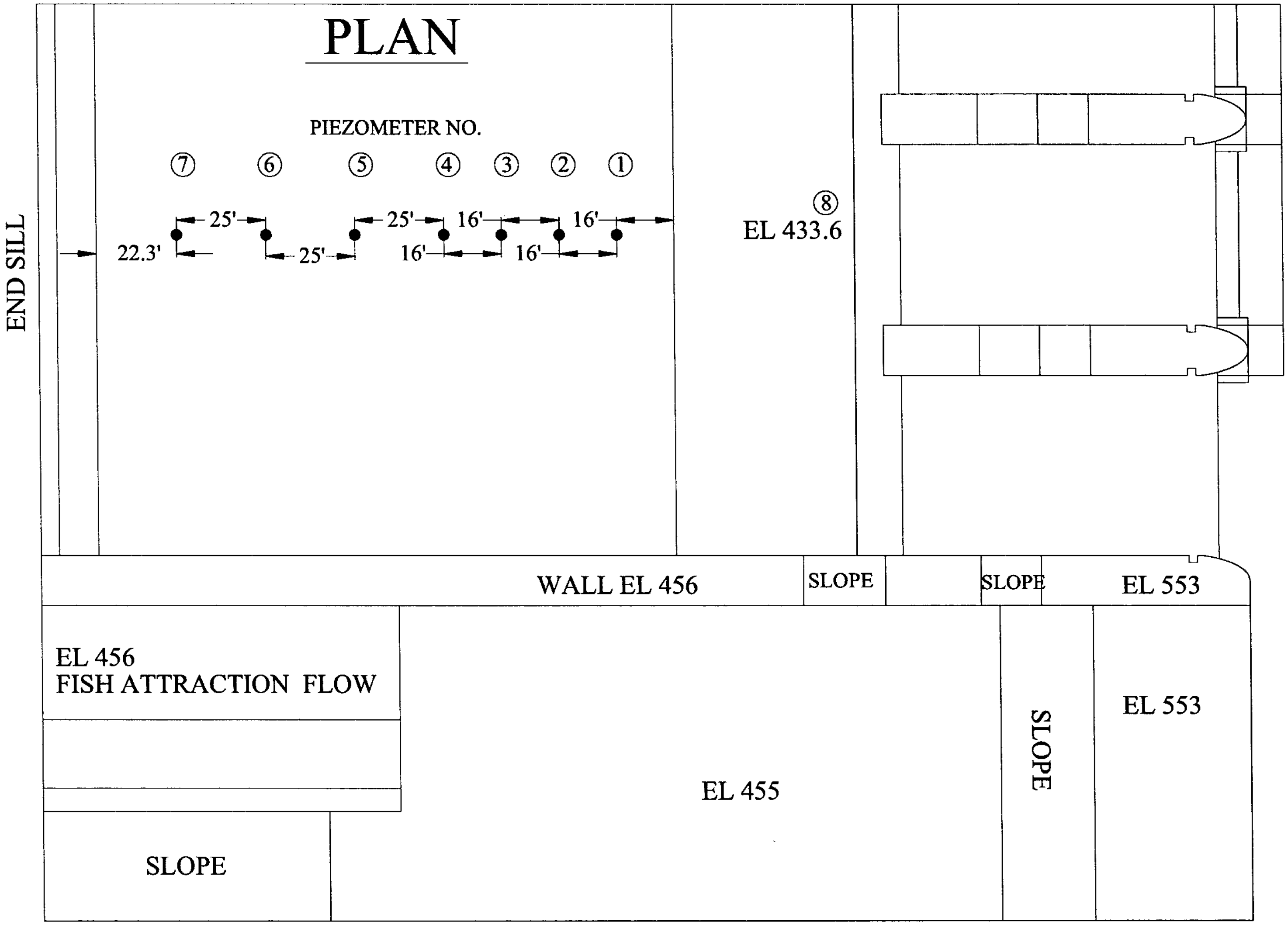

Figure 28. Piezometers located on the stilling basin floor

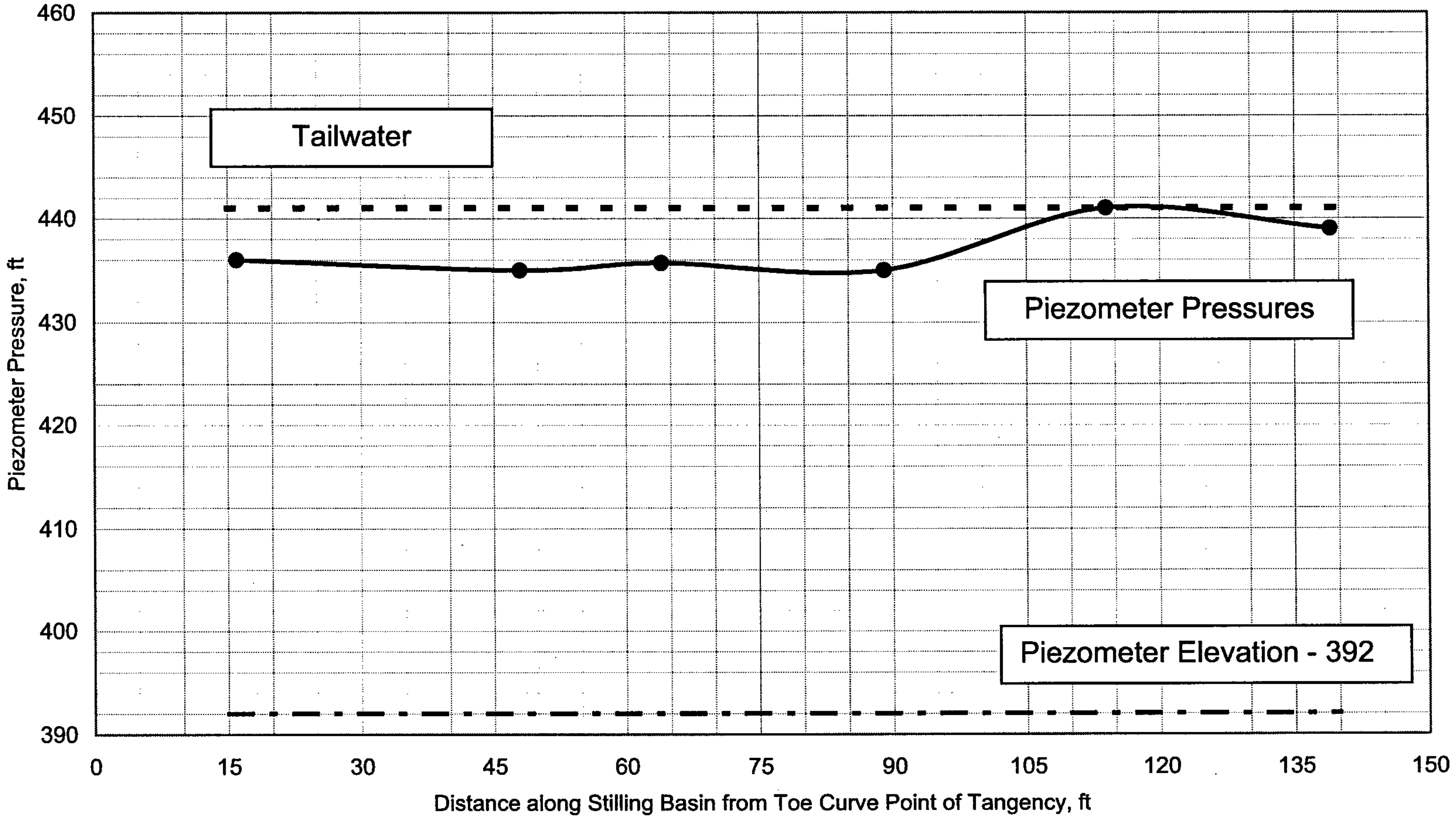

Figure 29. Pressure measurements along stilling basin floor, gate opening - 2 ft, discharge - 4.2 kcfs/bay, tailwater elevation – 441.0

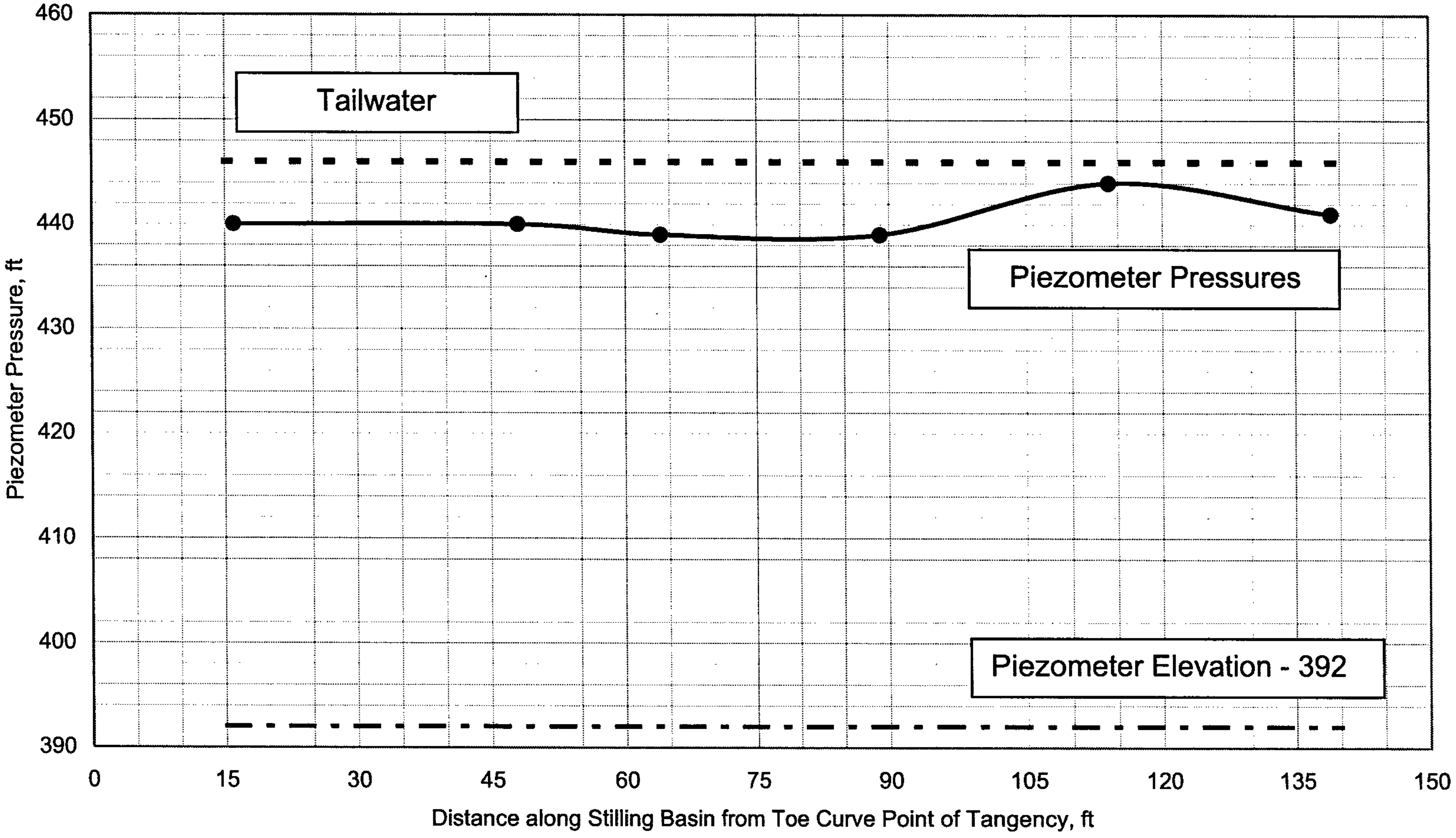

Figure 30. Pressure measurements along stilling basin floor, gate opening - 4 ft, discharge – 6.7 kcfs/bay, tailwater elevation - 446.0

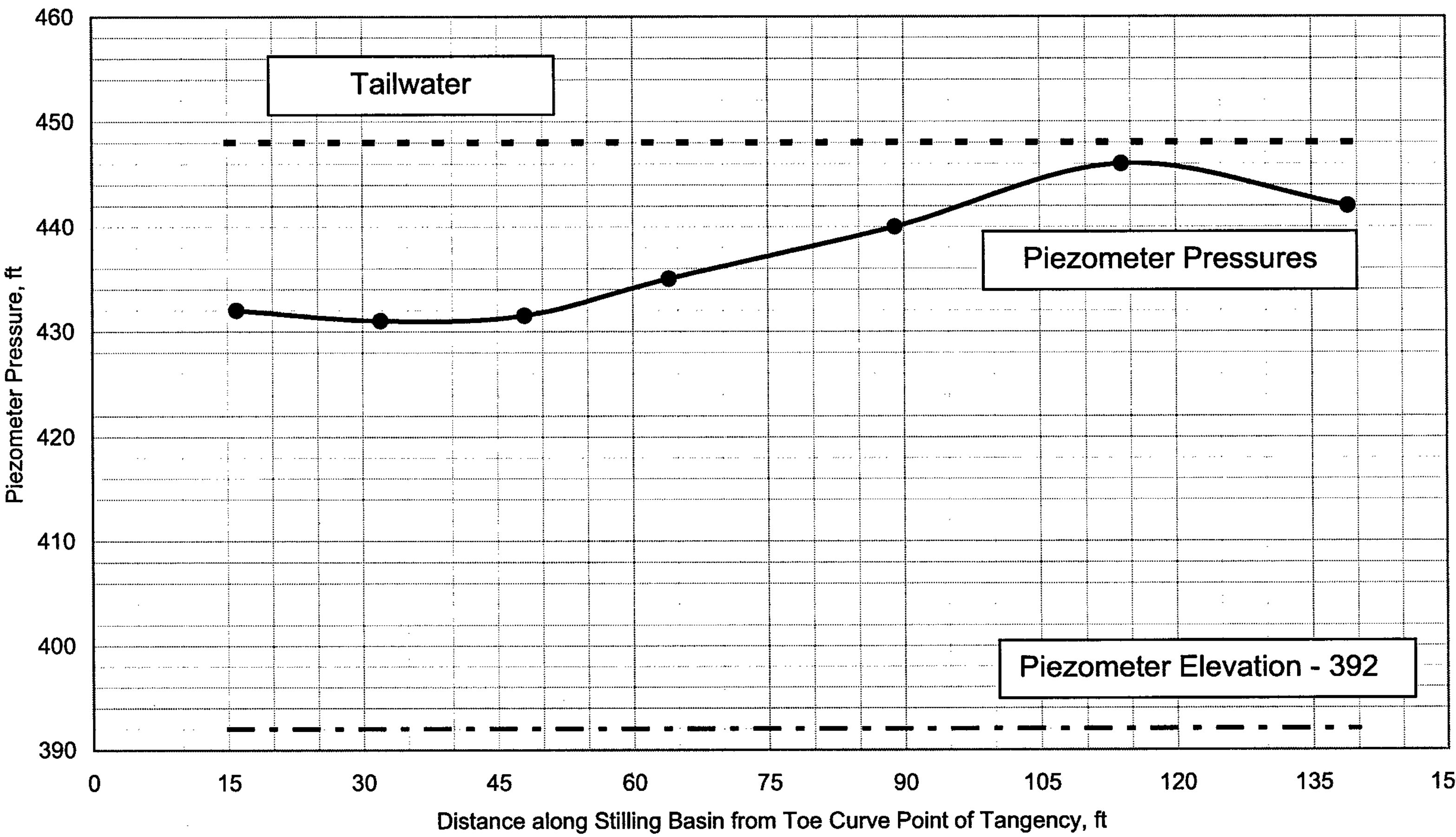

Figure 31. Pressure measurements along stilling basin floor, gate opening - 6 ft, discharge – 10.2 kcfs/bay, tailwater elevation – 448.0

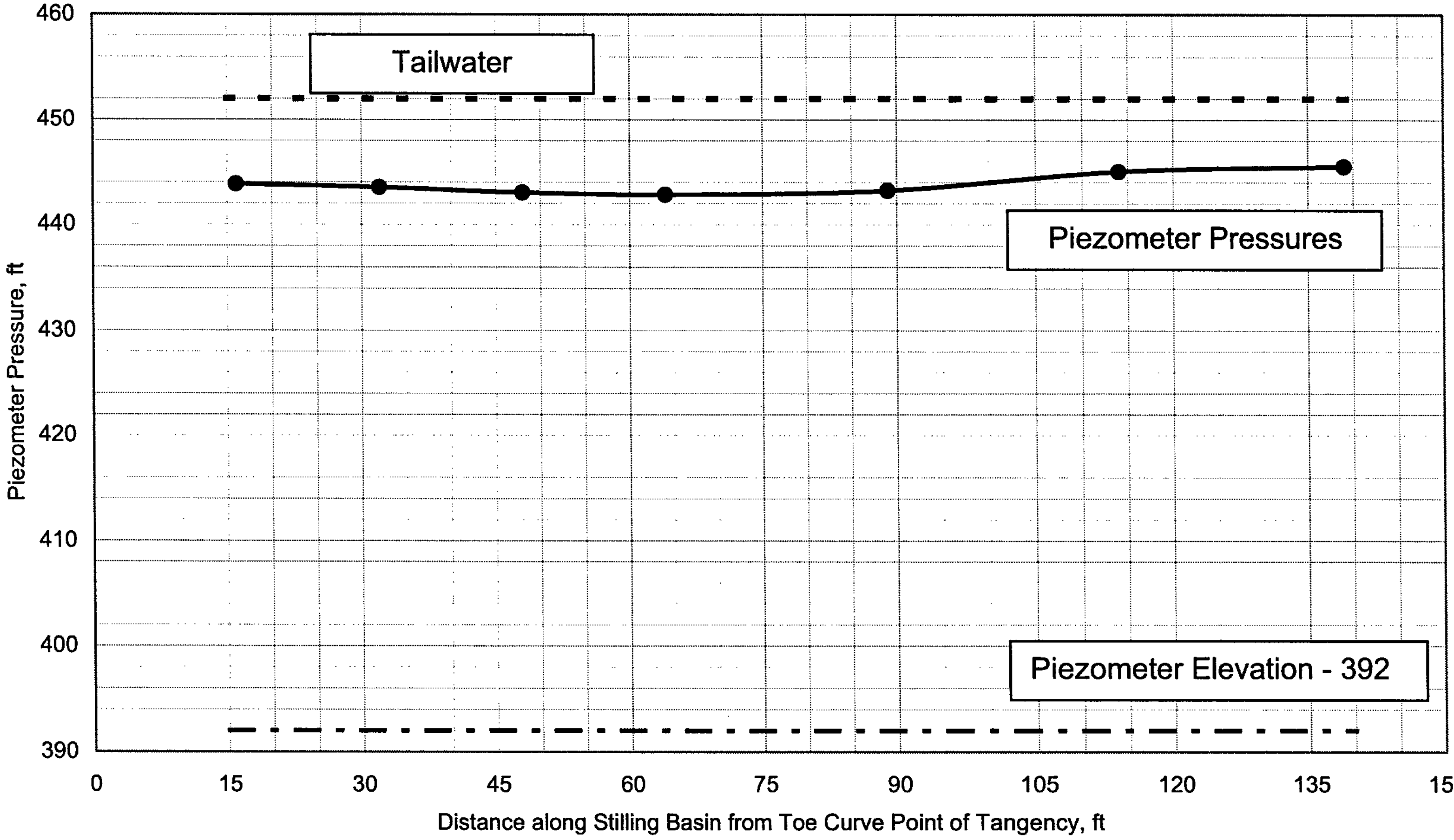

Figure 32. Pressure measurements along stilling basin floor, gate opening - 8 ft, discharge –13.8 kcfs/bay, tailwater elevation – 452.0

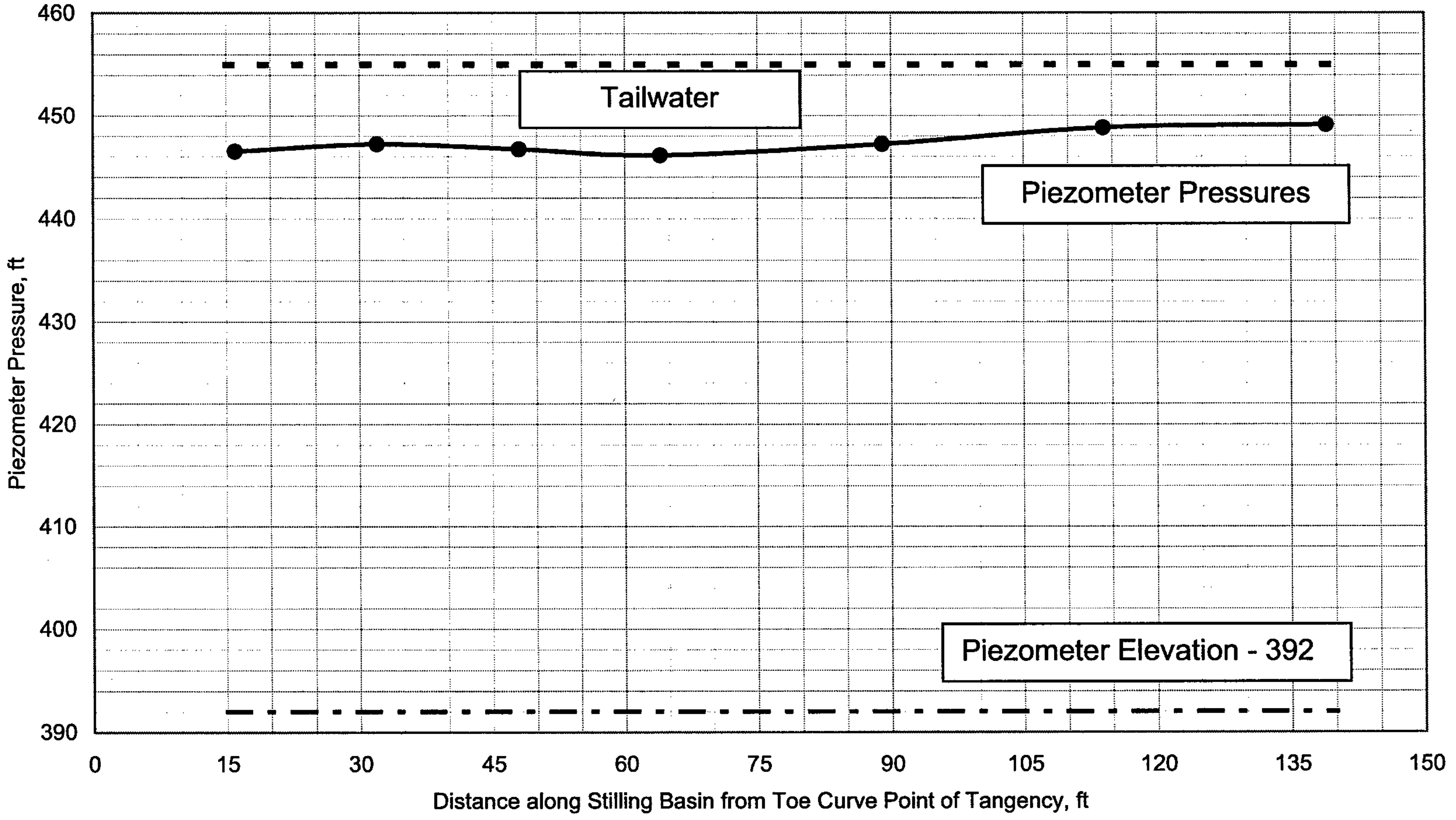

Figure 33. Pressure measurements along stilling basin floor, gate opening -10 ft, discharge – 18.2 kcfs/bay, tailwater elevation – 455.0

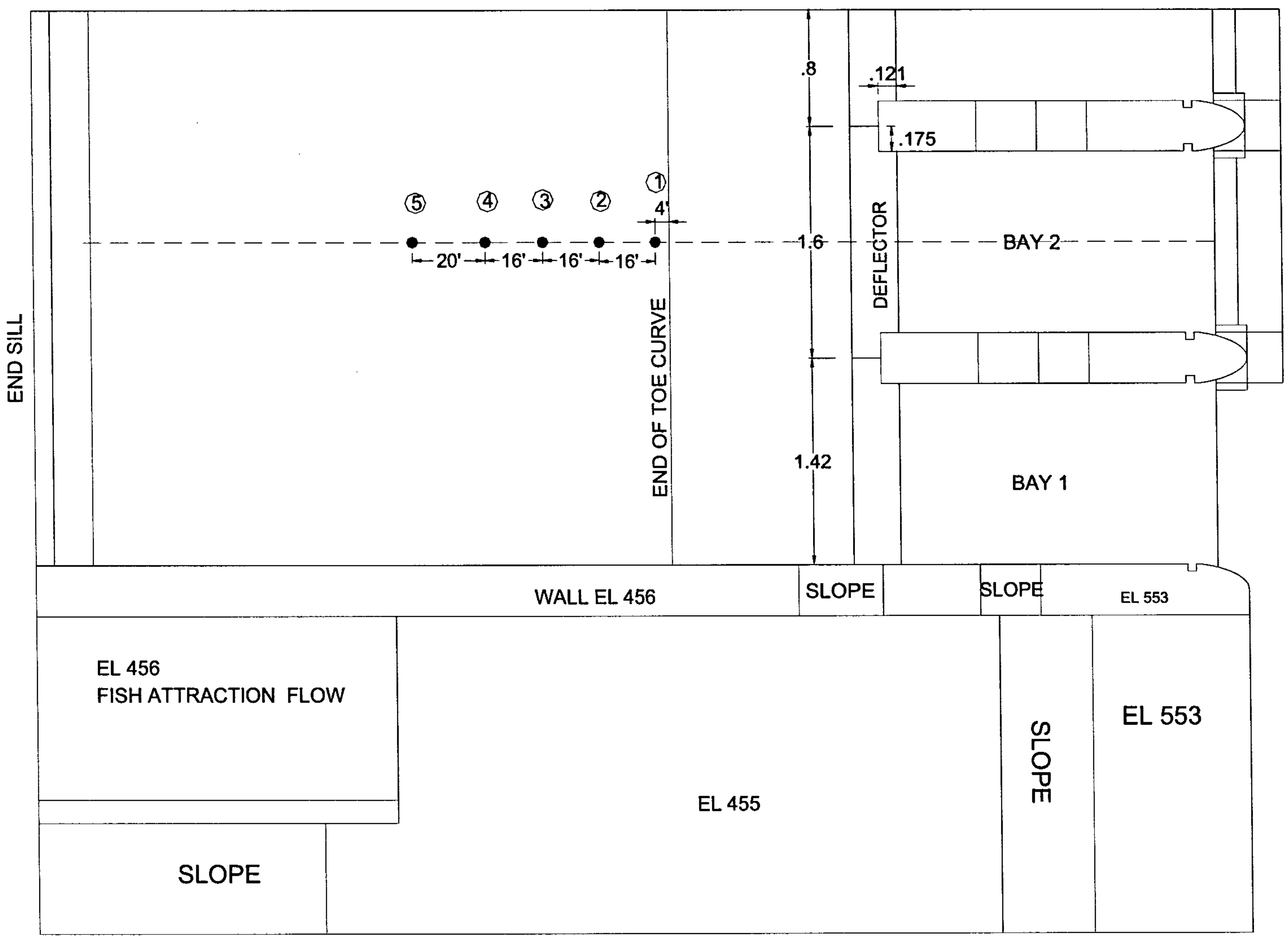

Figure 34. Transducer location along the center line of bay 2 at the original stilling basin elevation of 392

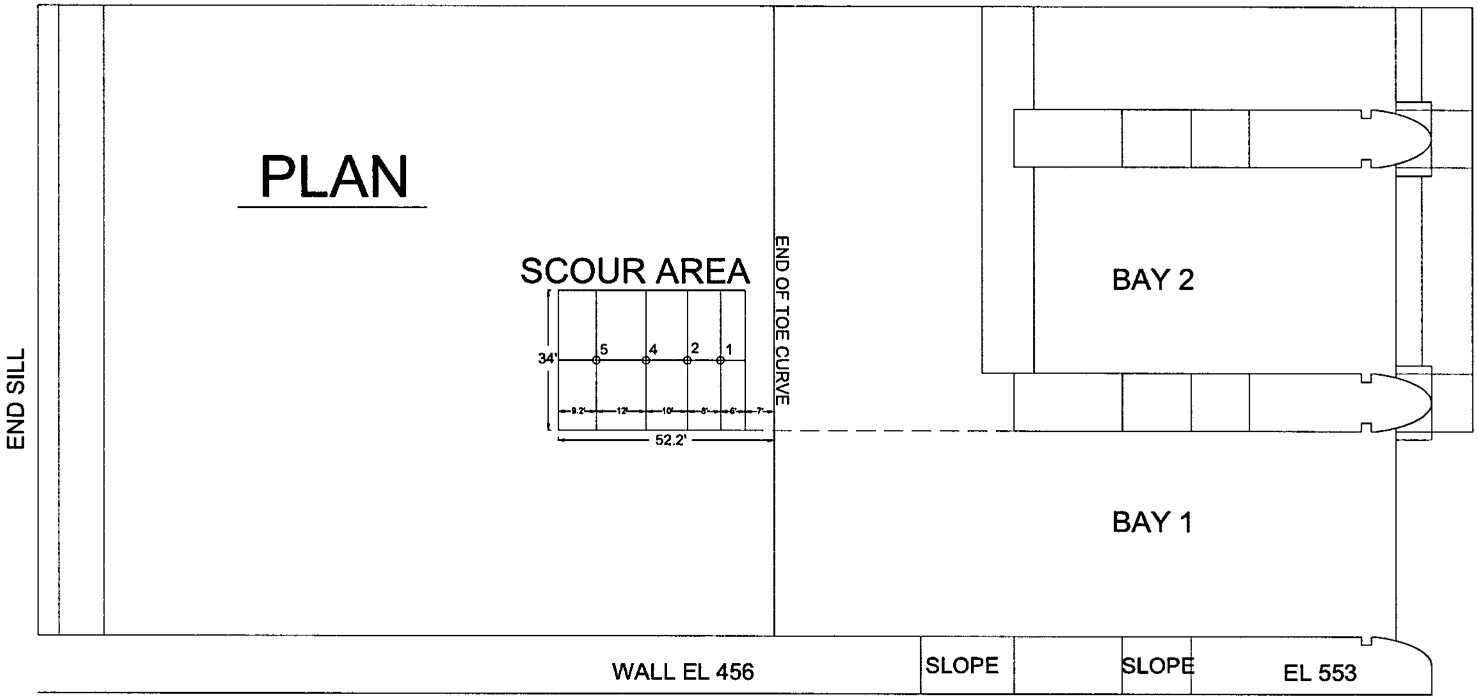

Figure 35. Pressure transducer locations for the Year 2000 scour hole

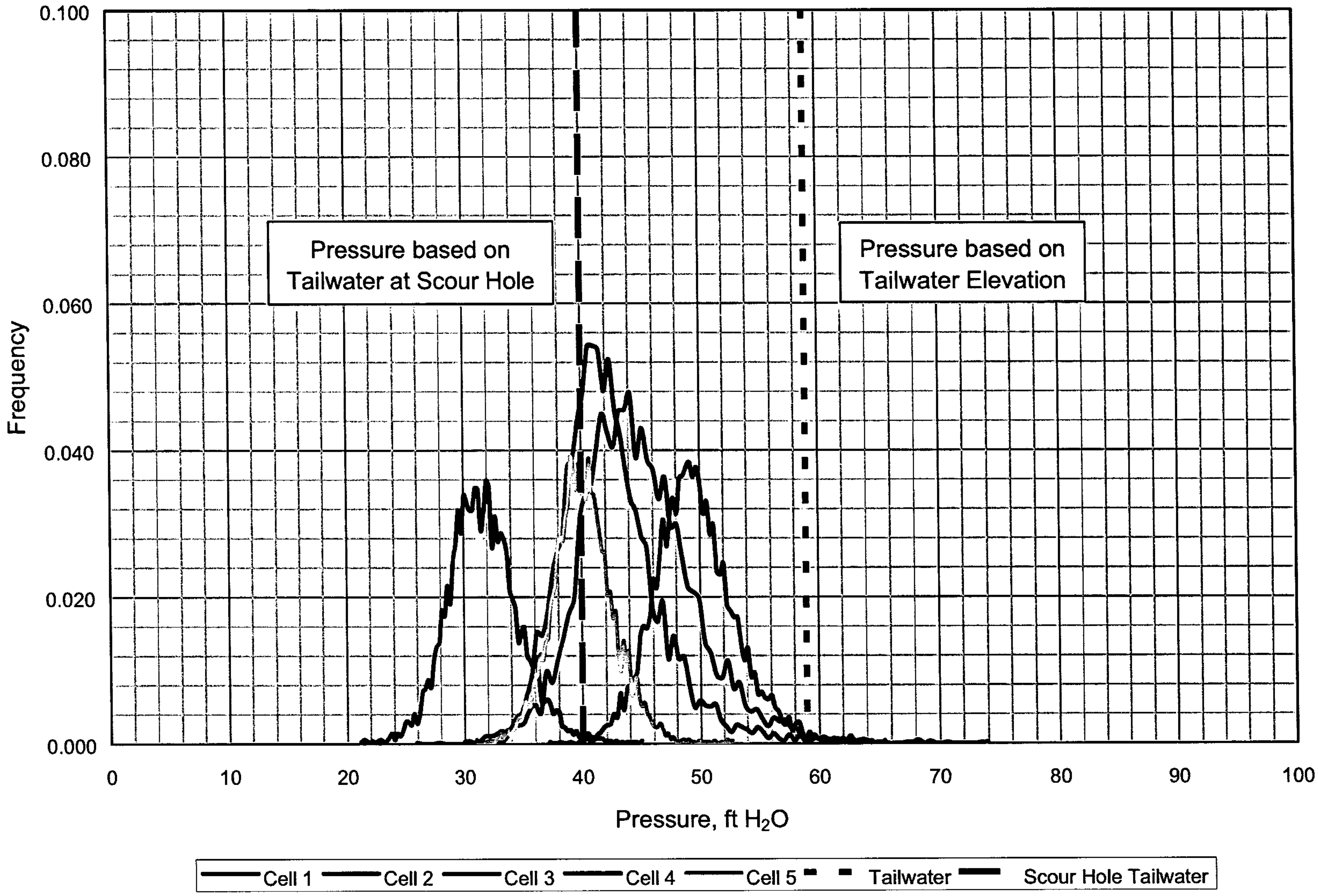

Figure 36. Frequency curves from five pressure cells along center line of bay 2. Discharge – 29 kcfs/bay, gate opening – 16.5 ft, pool elevation – 537.0, tailwater elevation – 451.0, no deflector on end bay

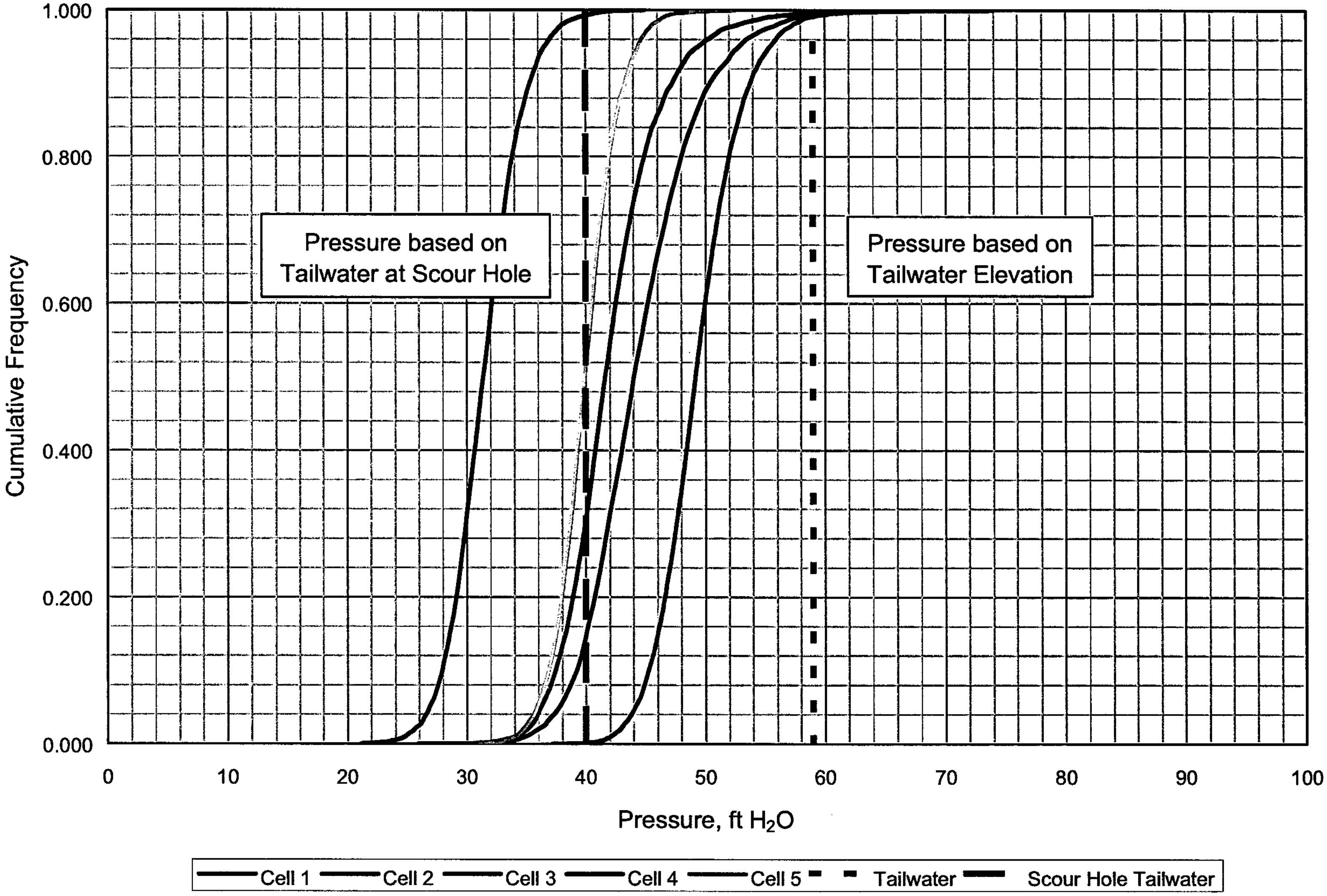

Figure 37. Cumulative frequency distribution for pressures along center line of bay 2. Discharge – 29 kcfs/bay, gate opening – 16.5 ft, pool elevation – 537.0, tailwater elevation – 451.0, no deflector on end bay

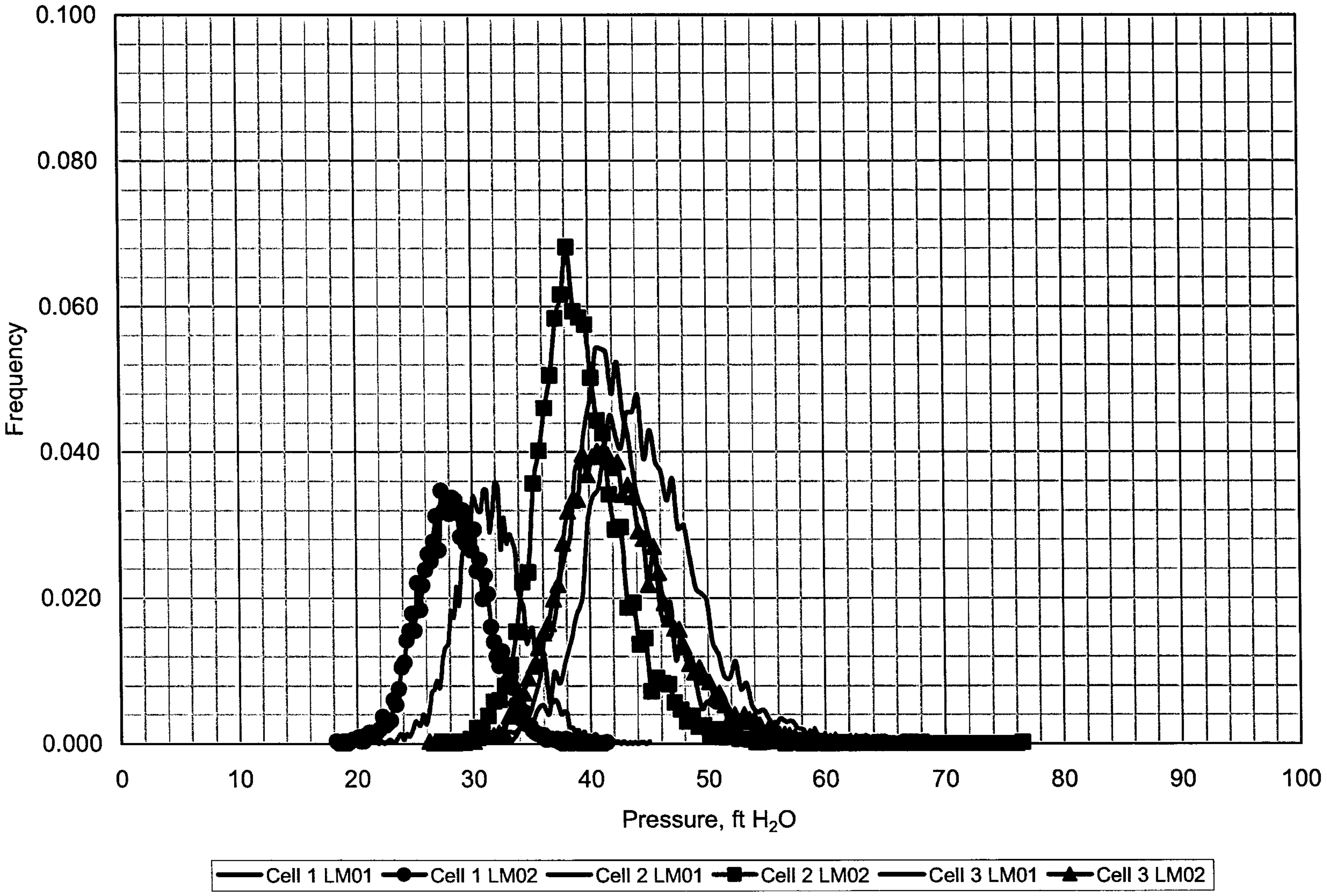

Figure 38. Lower Monumental stilling basin pressure investigation. Replicate frequency curves from three pressure cells. 29 kcfs/bay, gate opening 16.5 ft, pool elevation - 537.0, tailwater elevation - 451.0, center line of bay 2, no deflector on end bay

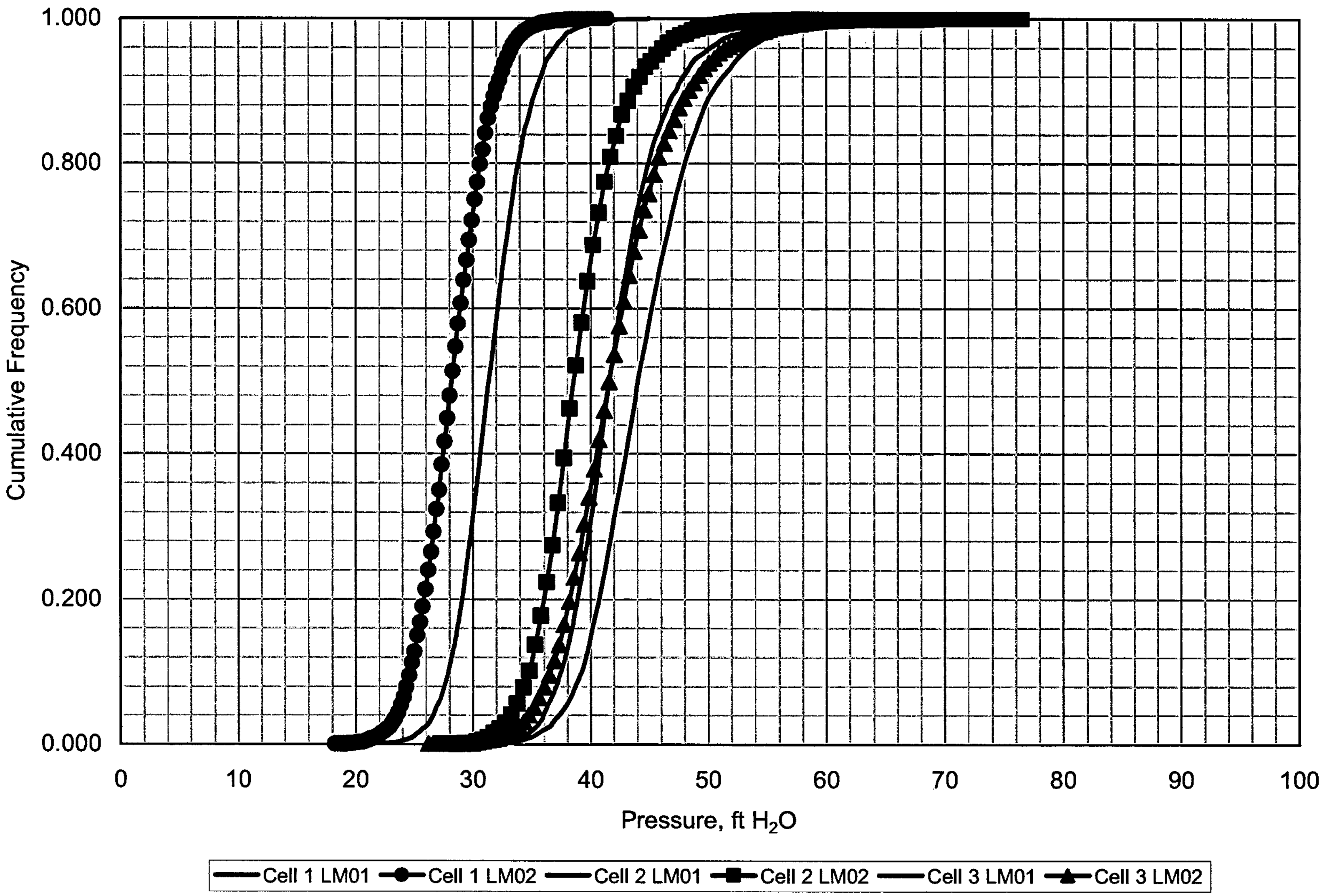

Figure 39. Lower Monumental stilling basin pressure investigation. Replicate cumulative frequency from three pressure cells. 29 kcfs/bay, gate opening 16.5 ft, pool elevation - 537.0, tailwater elevation - 451.0, center line of bay 2, no deflector on end bay

Figure 40. 84 kcfs/bay, full gate opening, pool elevation – 540.0, tailwater elevation – 461.0, tailwater at scour hole – 429.0, end gate open, no deflector on end bay, 2000 scour hole

Figure 41. Roughened tailrace

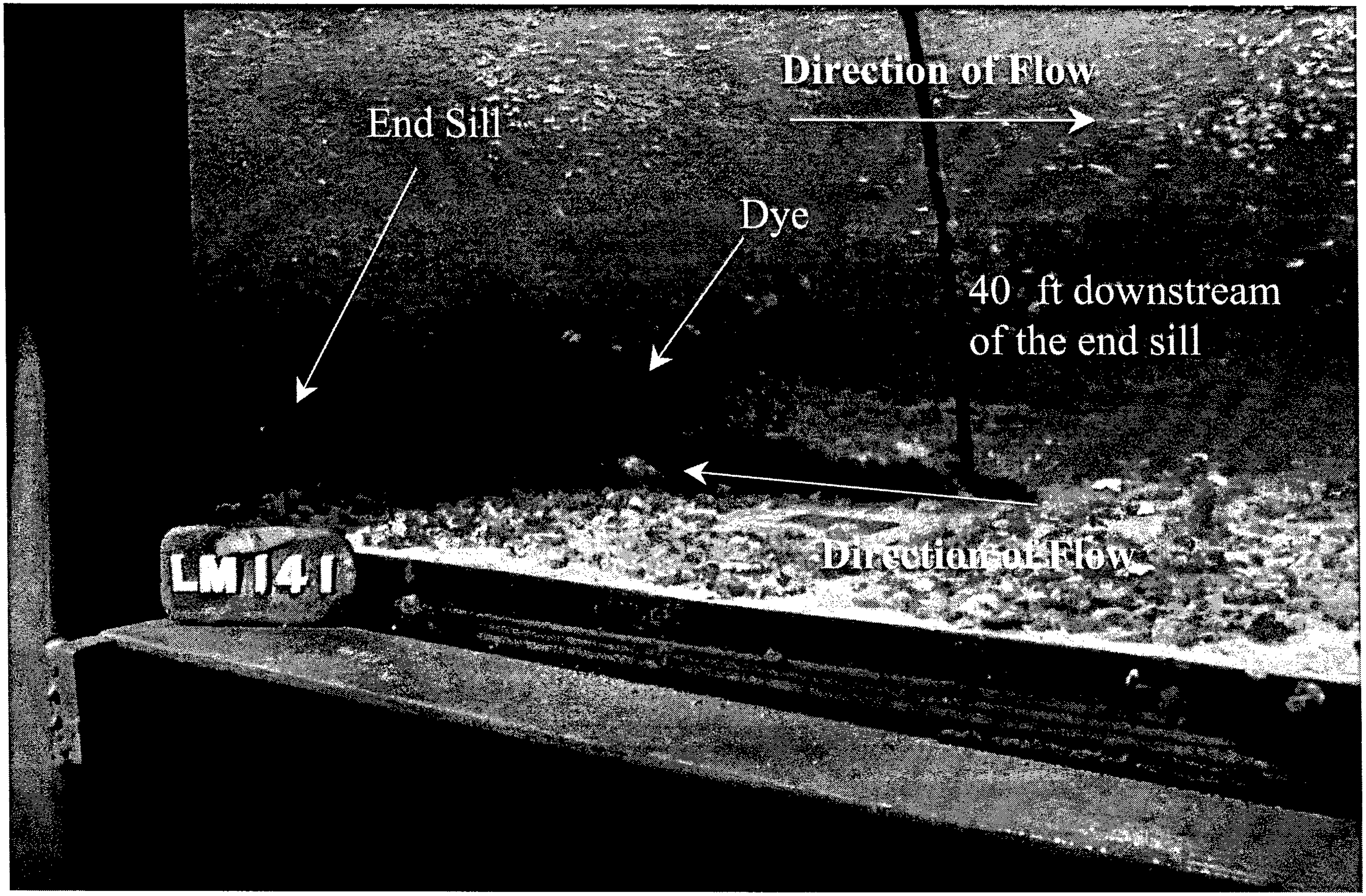

Figure 42. Upstream current along tailrace bottom for a surface skimming jet

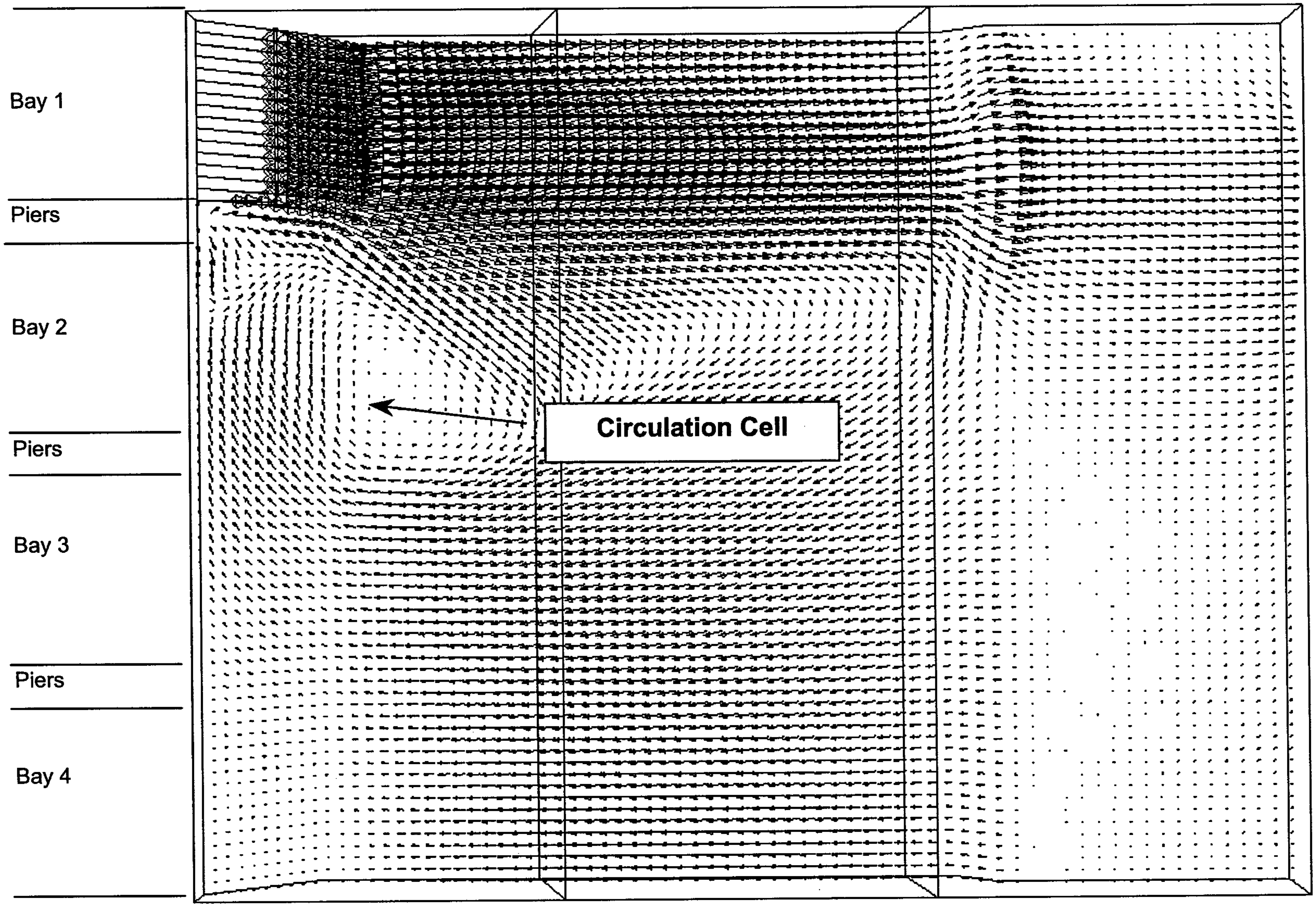

Figure 43. Velocity vectors along the stilling basin floor with plunging flow on the outside bay (no deflector), deflected flow on interior bays

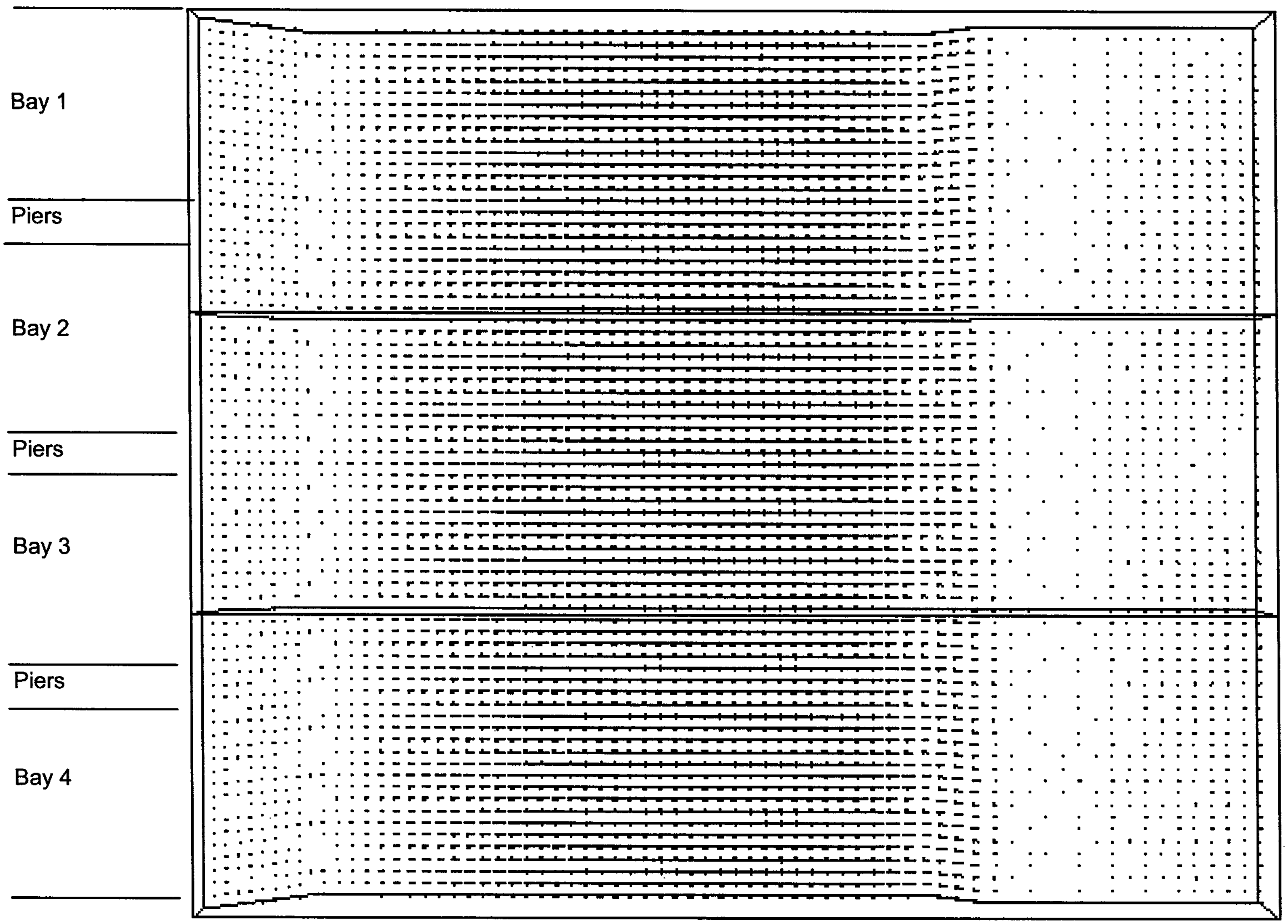

Figure 44. Velocity vectors along the stilling basin floor with deflected flow on all bays

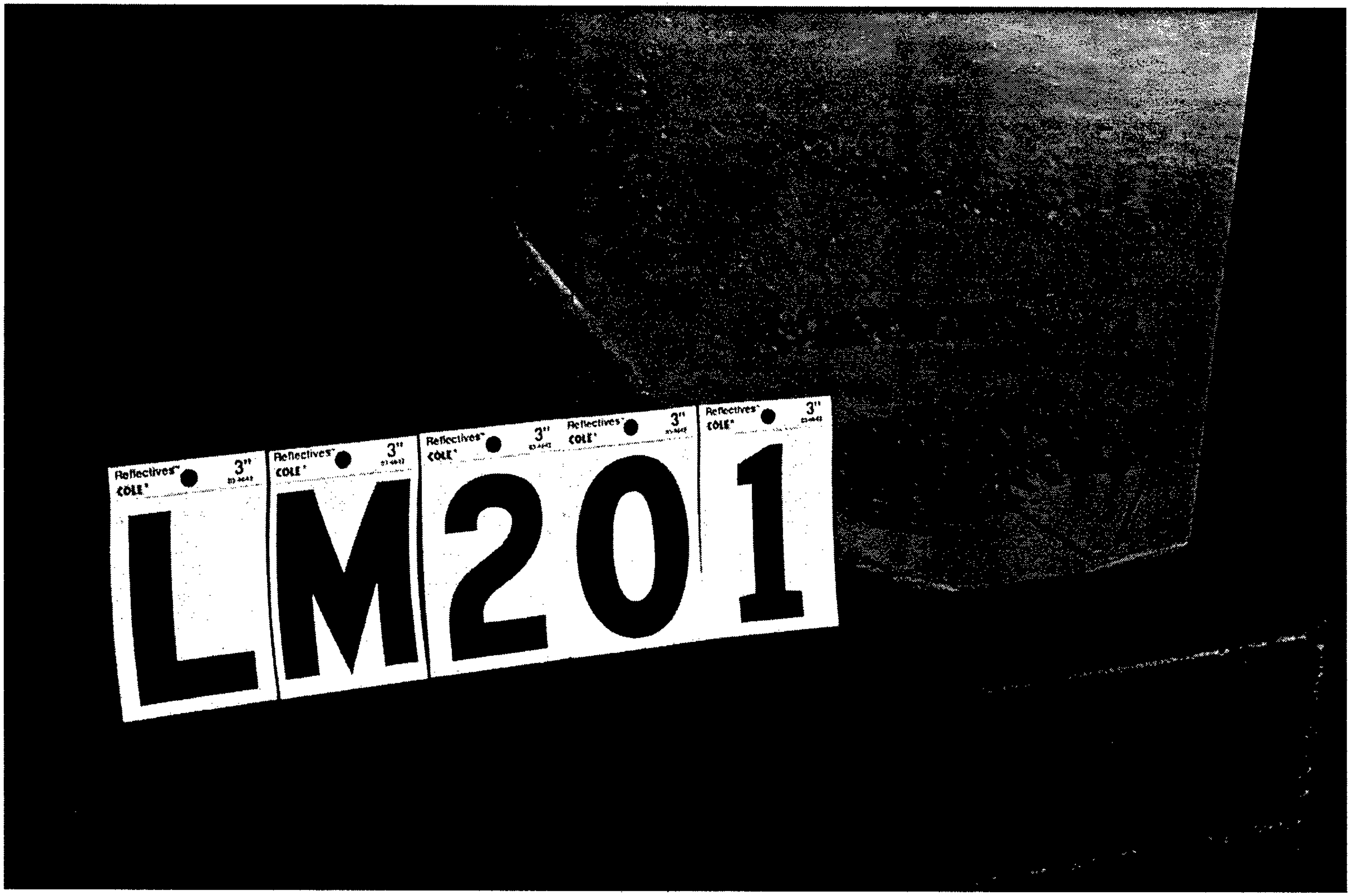

Figure 45. Lower Monumental stilling basin scour hole

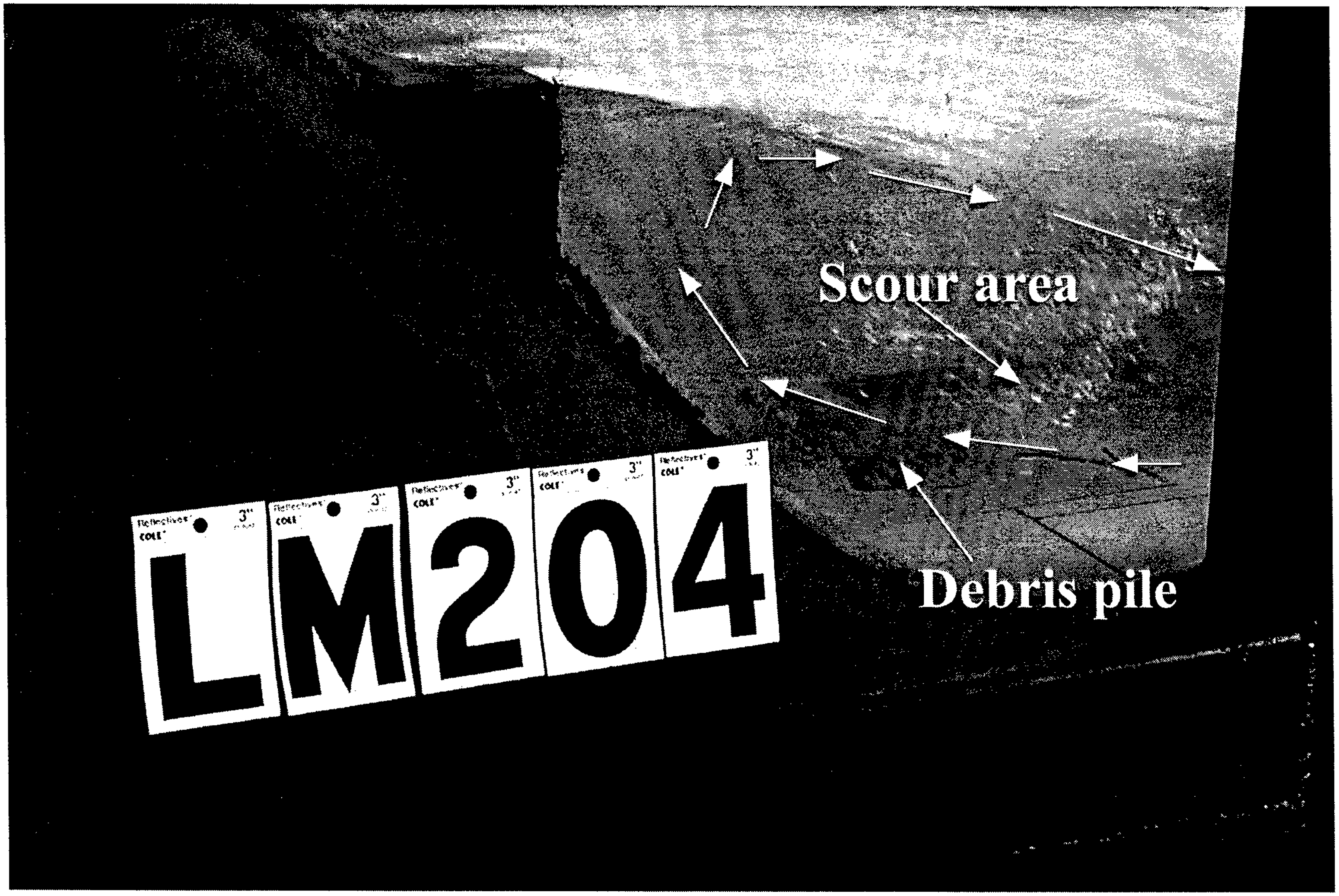

Figure 46. Lower Monumental debris study – view from center bay. Gate opening - 4.0 ft, discharge – 6.7 kcfs/bay, pool elevation - 537.0, tailwater elevation - 436.0, end bay operating with no deflector

To view the video, click the center of the photograph

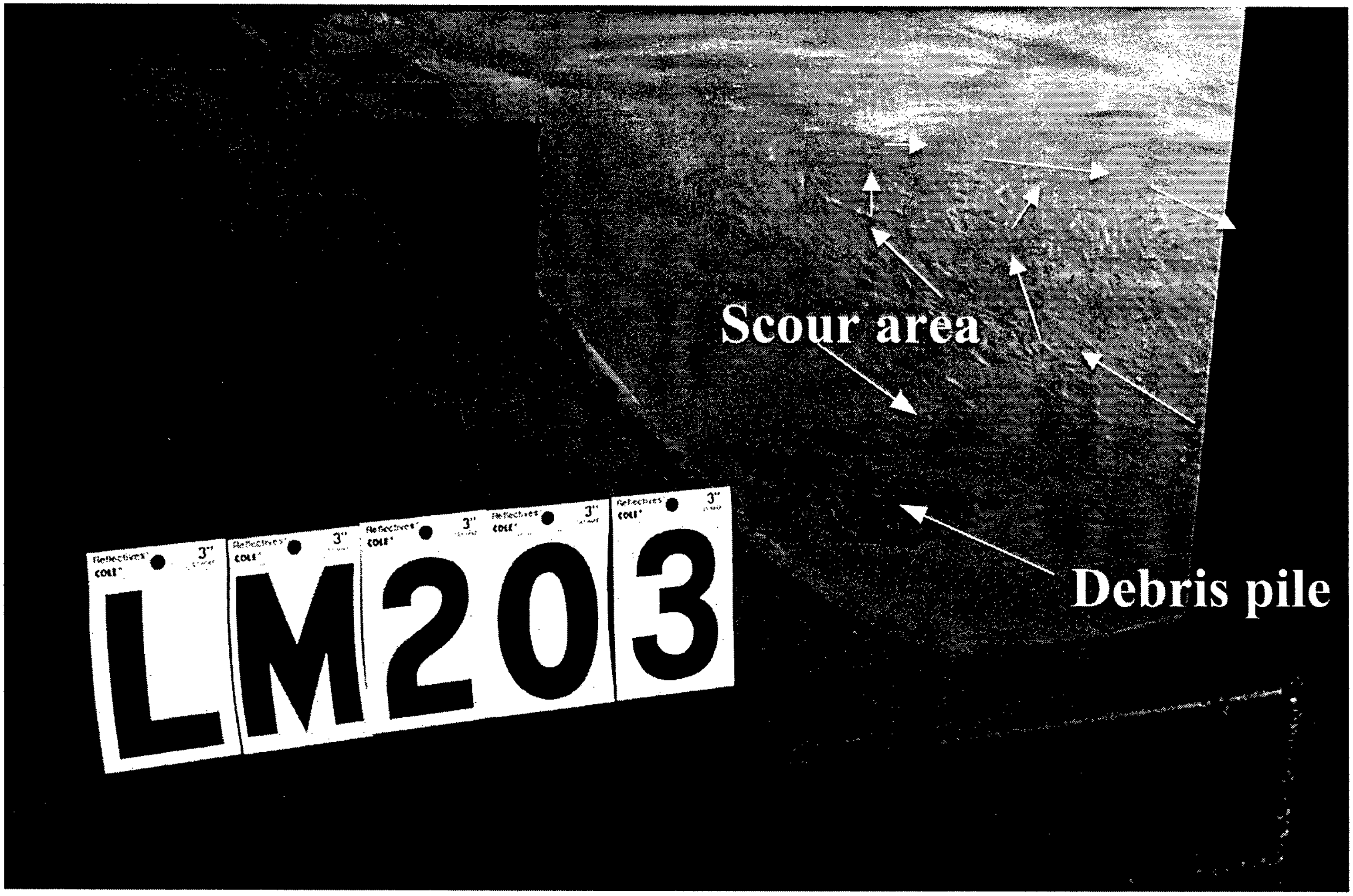

Figure 47. Lower Monumental debris study – view from center bay. Gate opening - 8.0 ft, discharge 13.8 kcfs/bay, pool elevation – 537.0, tailwater elevation - 444.0, end bay operating with no deflector

To view the video, click the center of the photograph

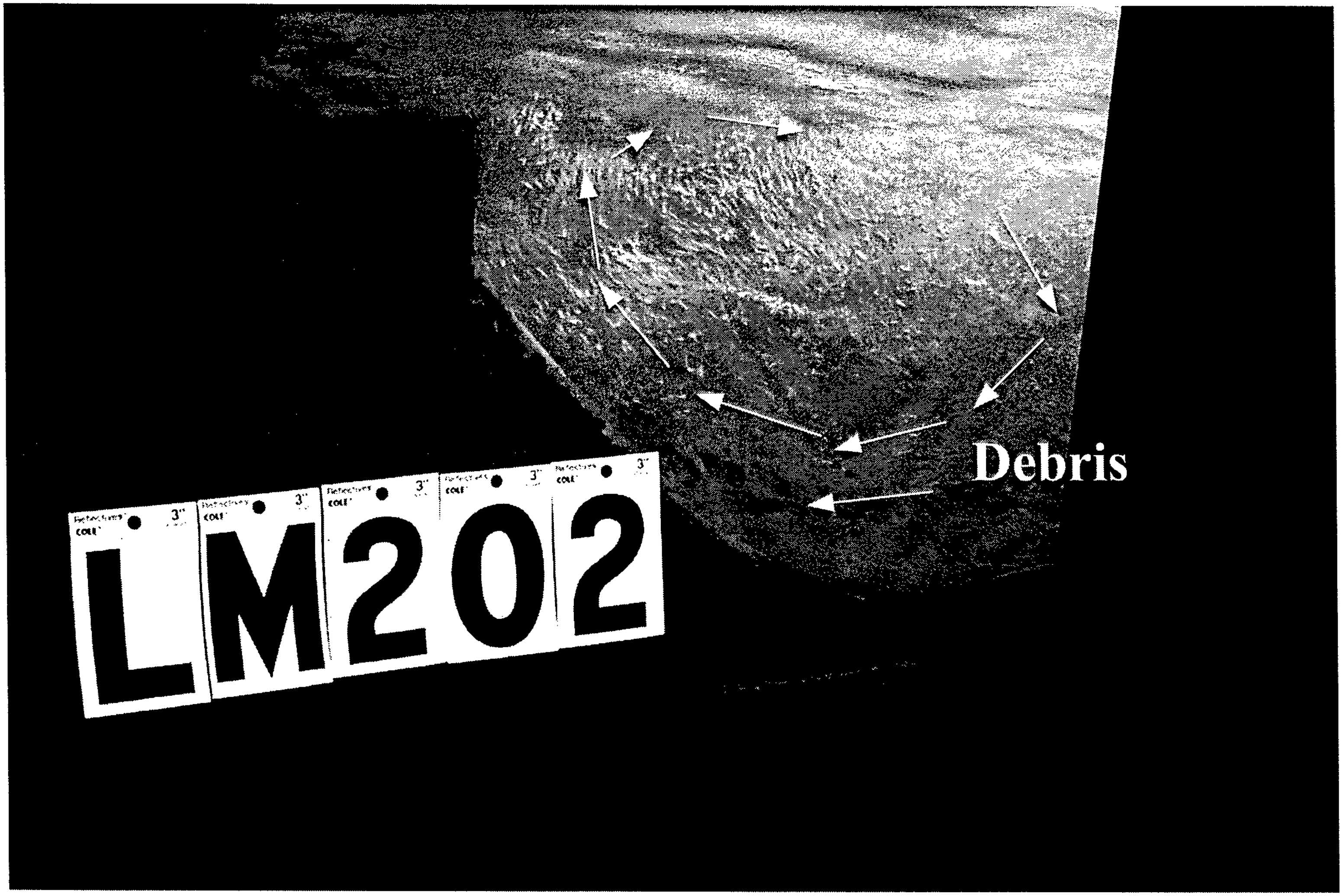

Figure 48. Lower Monumental debris study - view from center bay. Gate opening - 12.0 ft, discharge – 21.9 kcfs/bay, end bay operating with no deflector, pool elevation – 537.0, tailwater elevation - 449.0

To view the video, click the center of the photograph

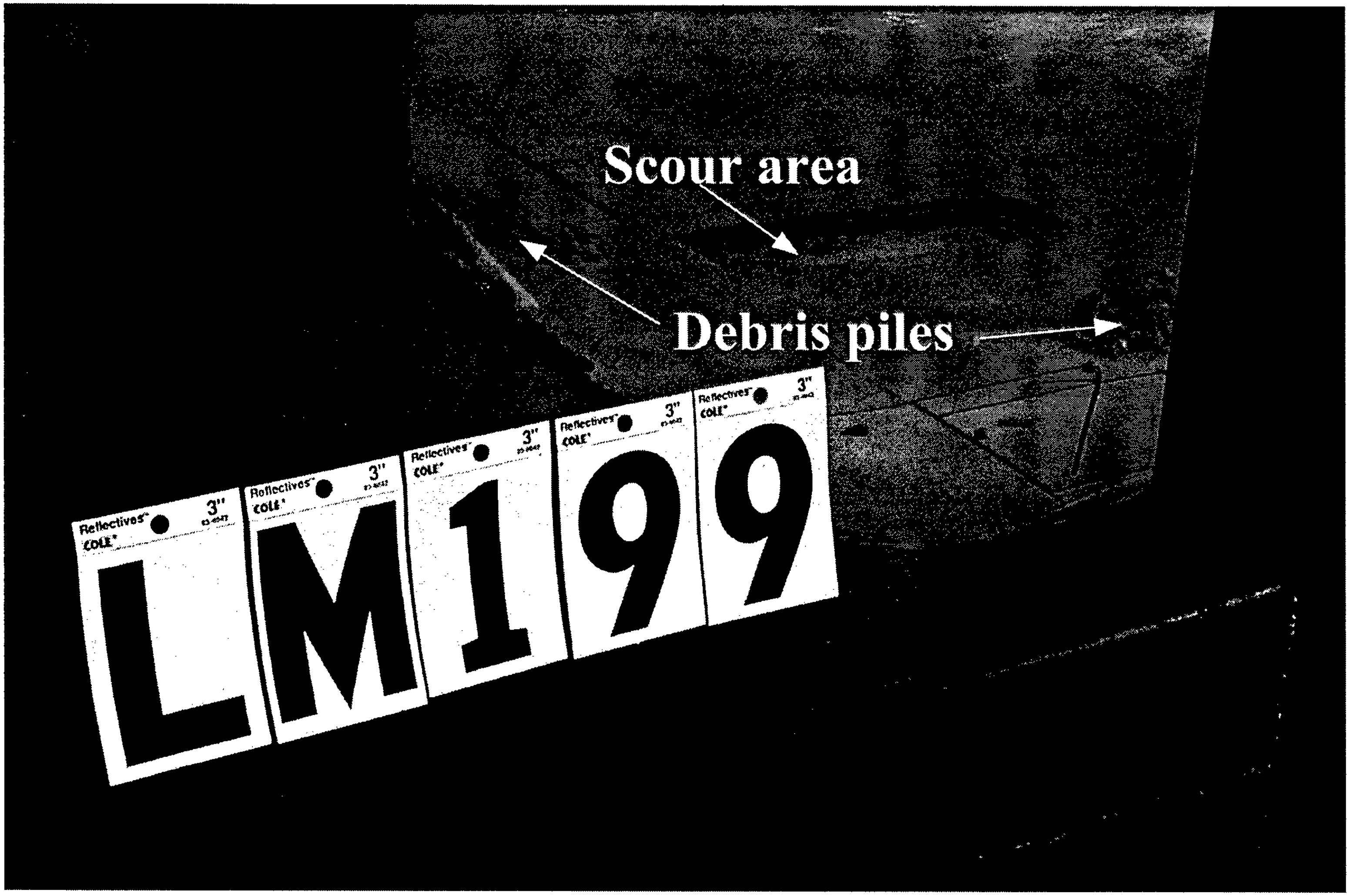

Figure 49. Lower Monumental debris study – view from center bay. Gate opening - 4.0 ft, discharge – 6.7 kcfs/bay, end bay closed, pool elevation - 537.0, tailwater elevation - 436.0

To view the video, click the center of the photograph

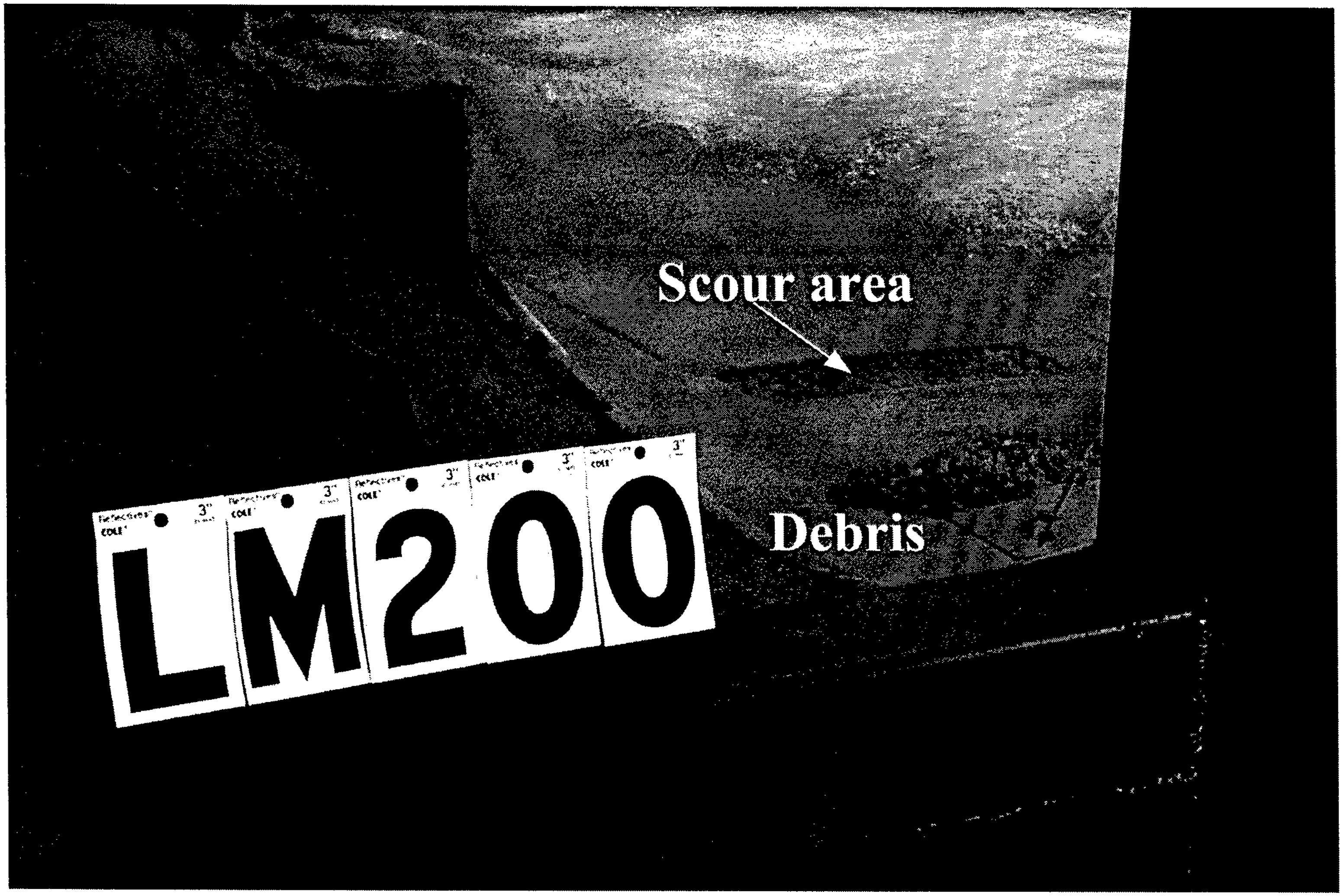

Figure 50. Lower Monumental debris study - view from center bay. Gate opening - 8.0 ft, discharge - 13.8 kcfs/bay, end bay closed, pool elevation - 537.0, tailwater elevation - 441.0

To view the video, click the center of the photograph

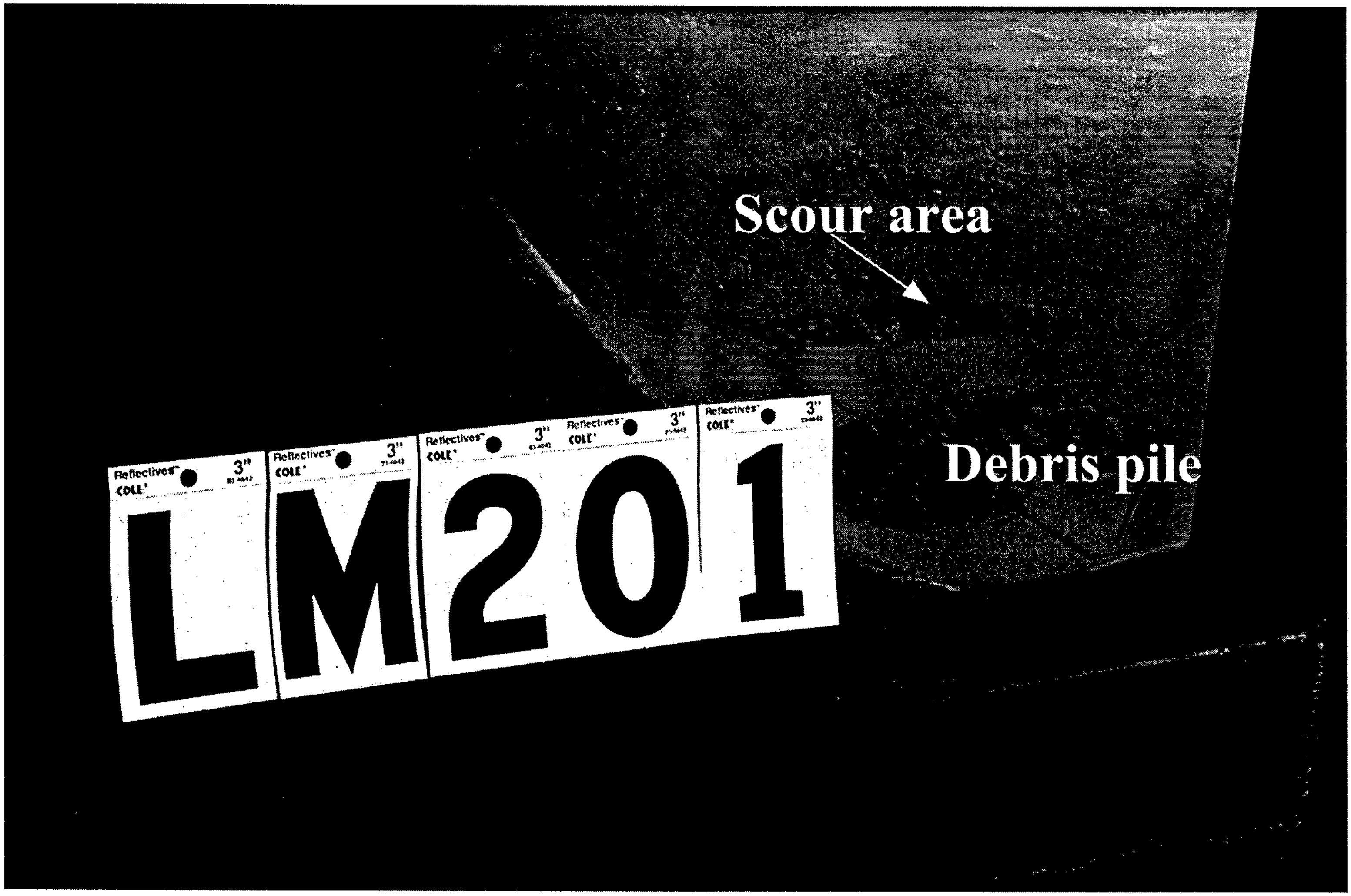

Figure 51. Lower Monumental debris study - view from center bay. Gate opening - 12.0 ft, discharge - 21.9 kcfs/bay, end bay closed, pool elevation – 537, tailwater elevation - 445.0

To view the video, click the center of the photograph

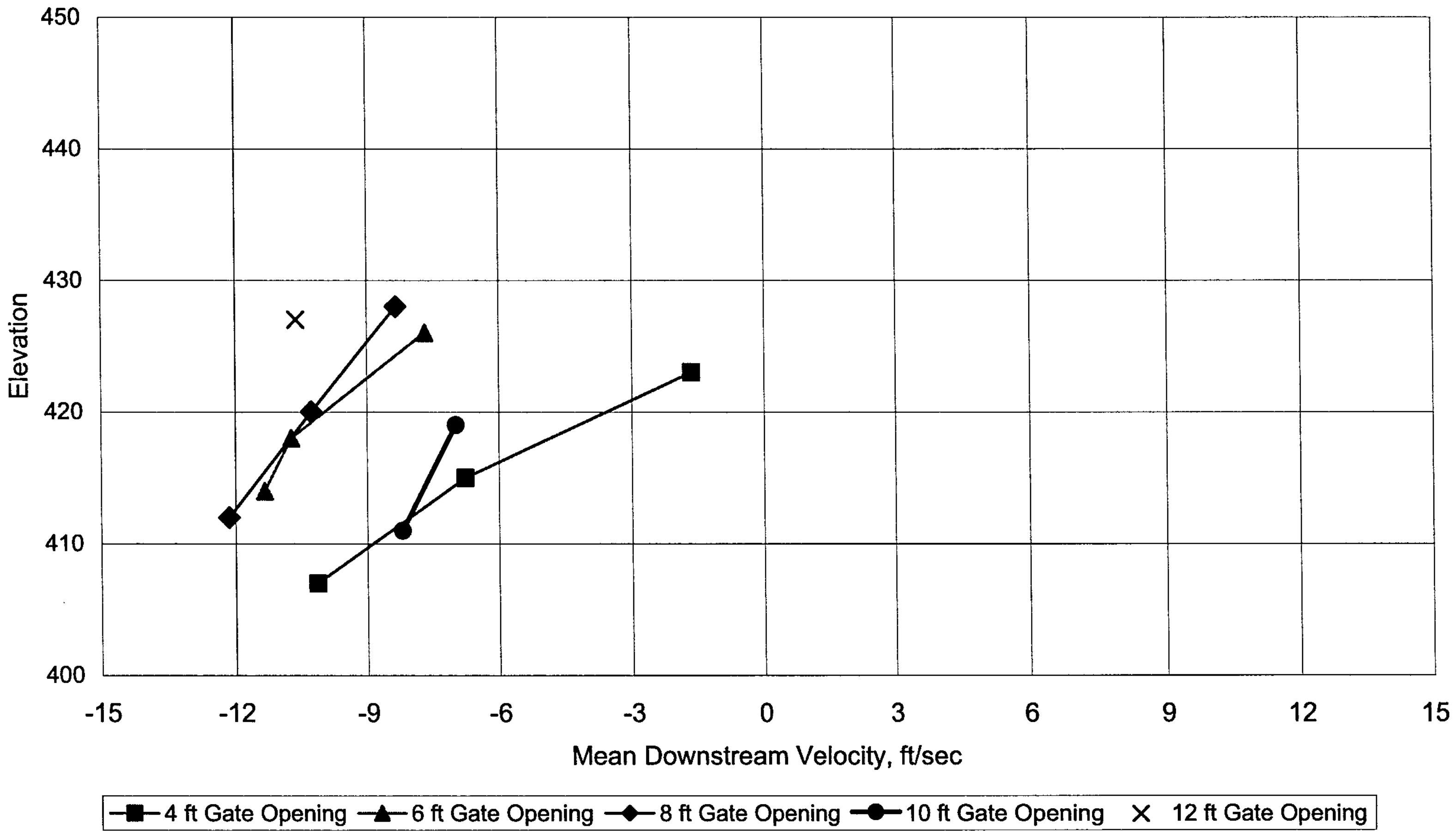

Figure 52. Mean velocities above end sill

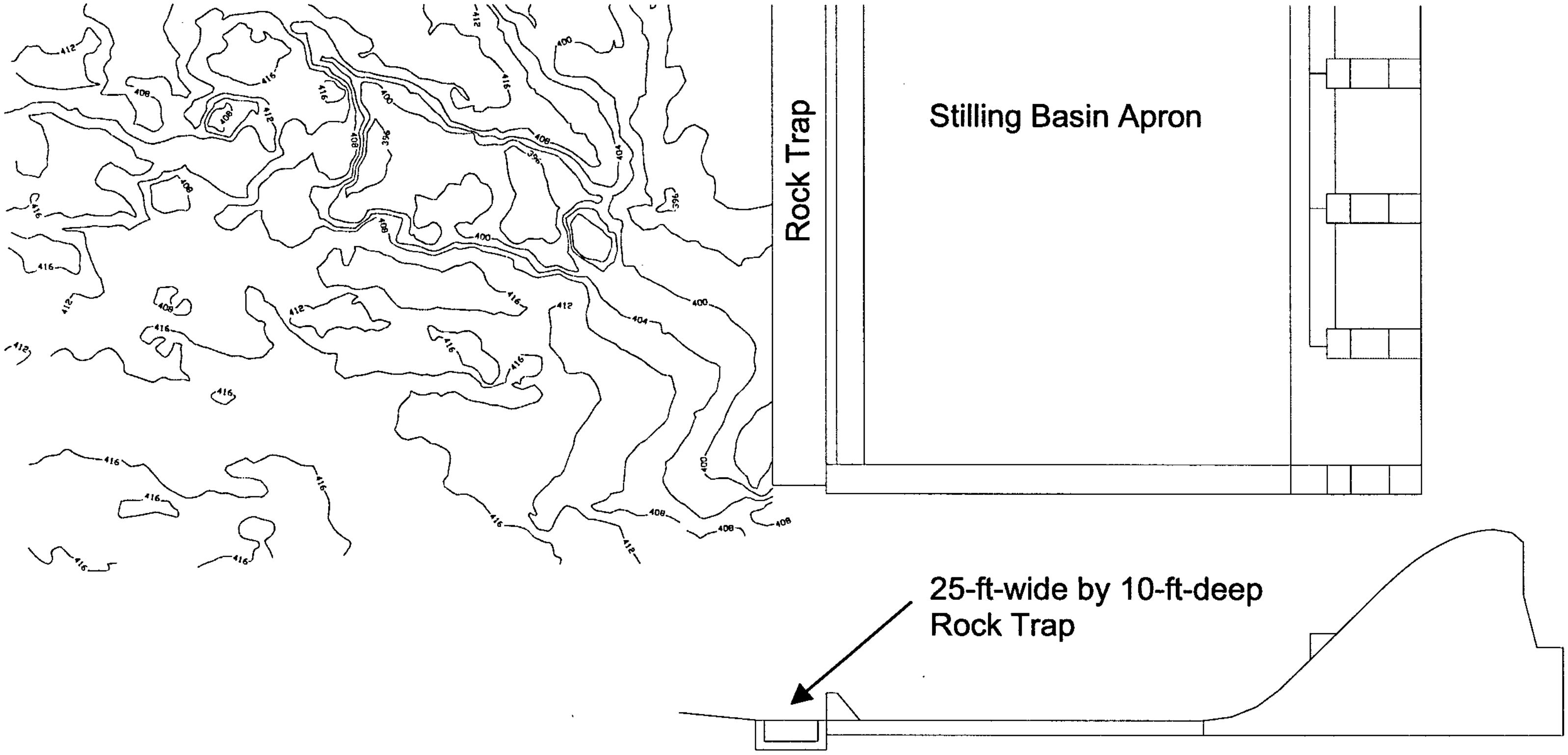

Figure 53. Rock trap downstream of stilling basin

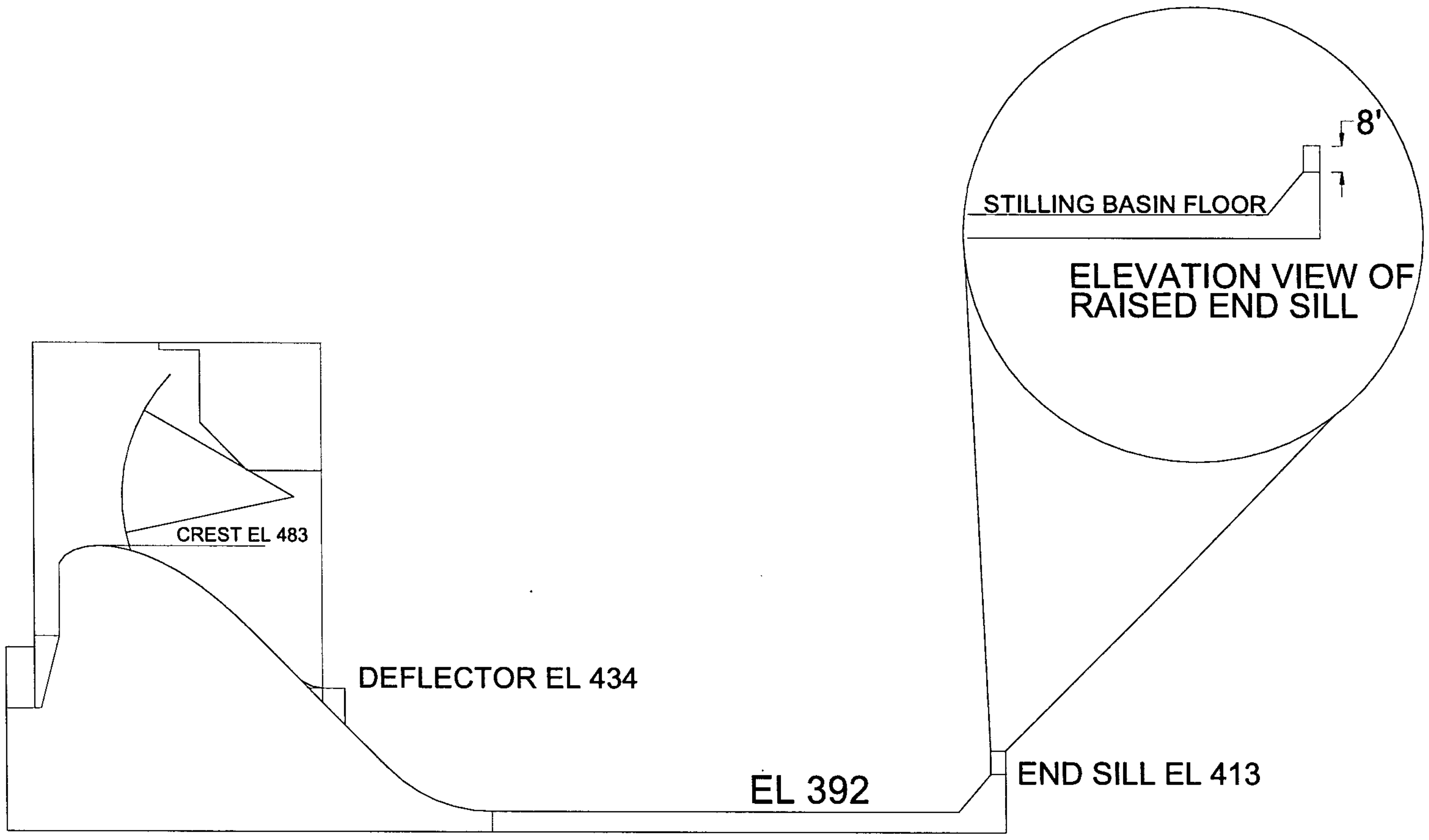

Figure 54. Stilling basin cross section with added end sill height

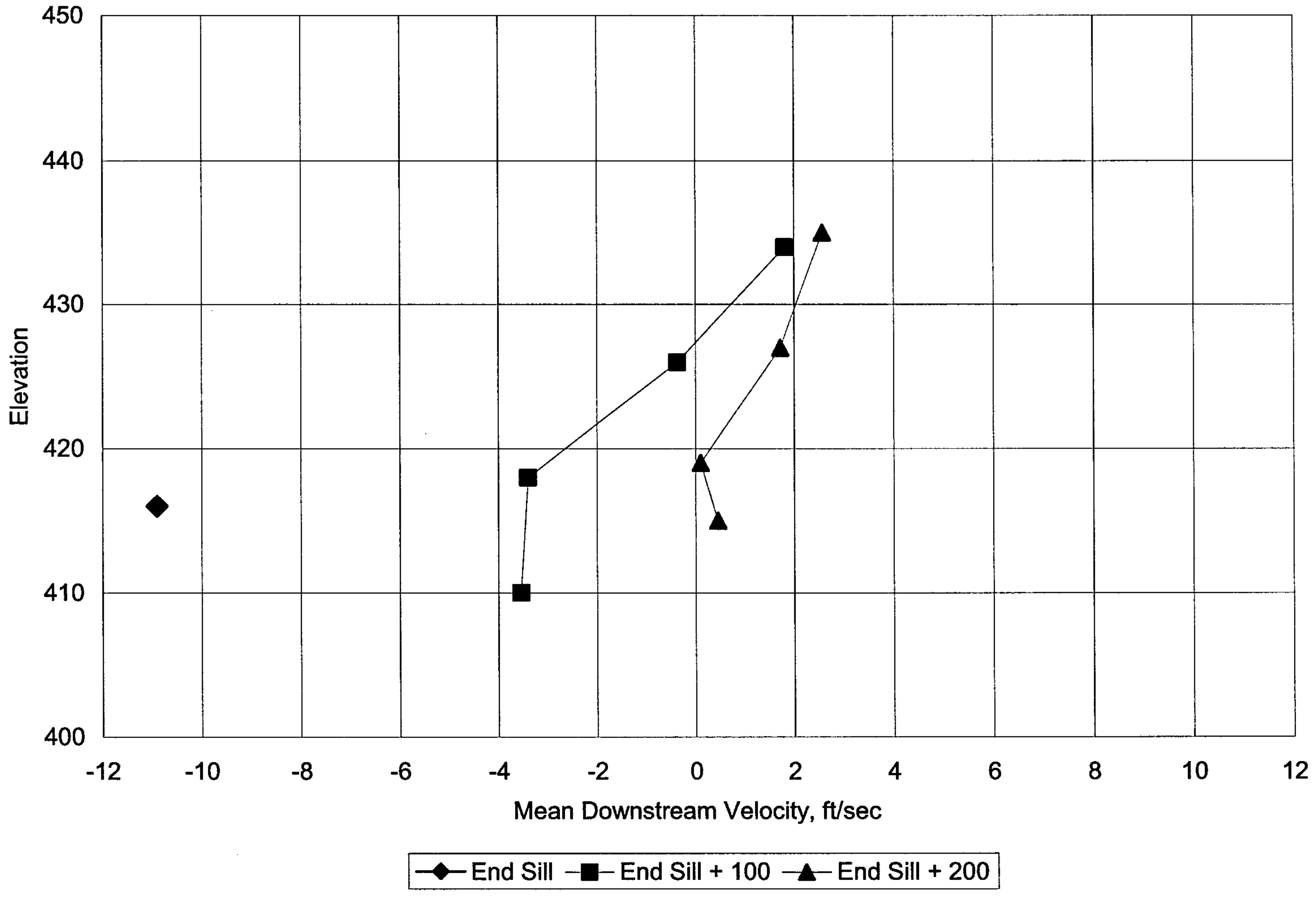

Figure 55. Velocity measurements with elevated end sill. Gate opening – 4 ft, discharge – 6.7 kcfs/bay, pool elevation – 537.0, tailwater elevation – 443.0

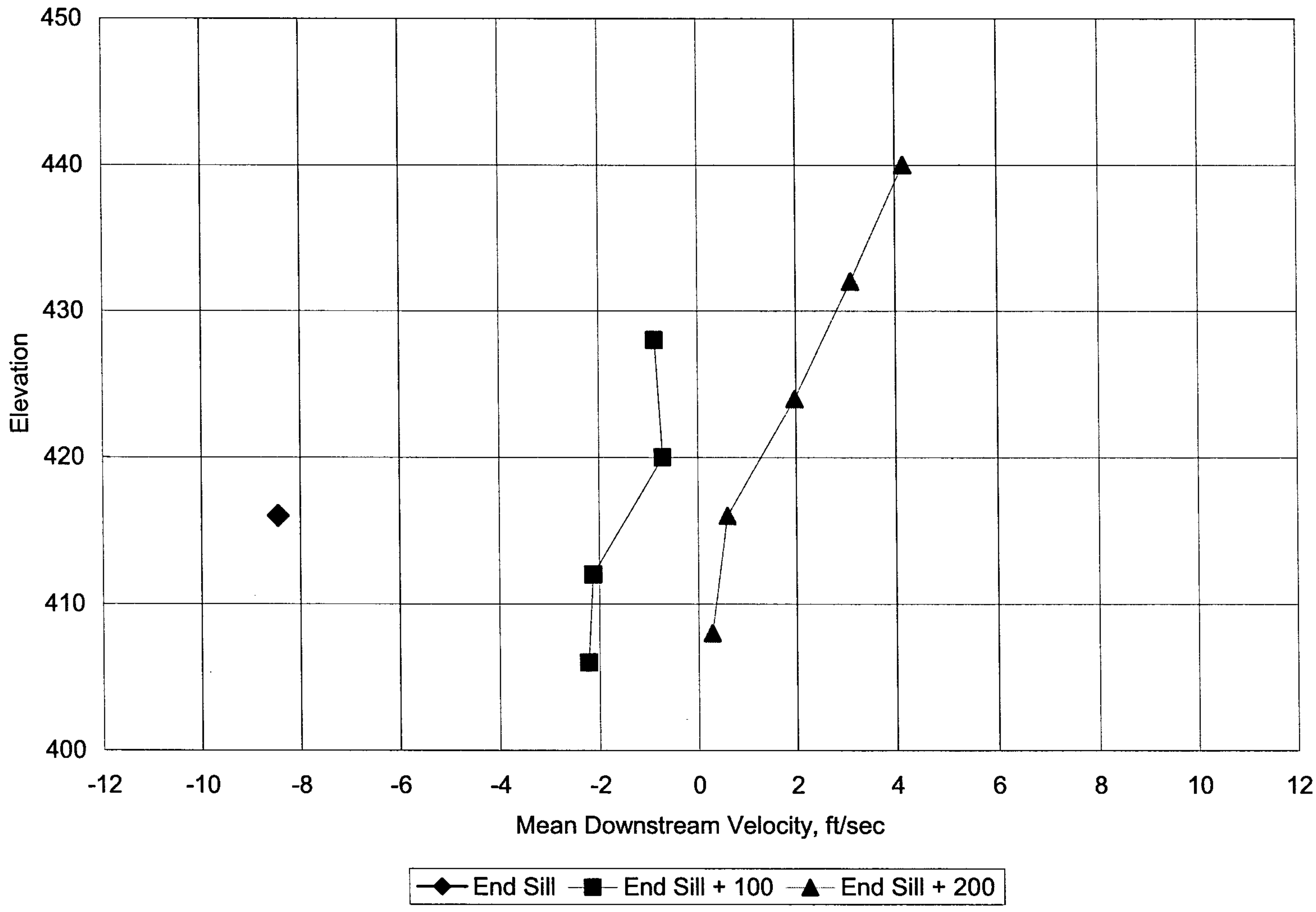

Figure 56. Velocity measurements with elevated end sill. Gate opening – 8 ft, discharge – 13.8 kcfs/bay, pool elevation - 537.0, tailwater elevation – 449.0

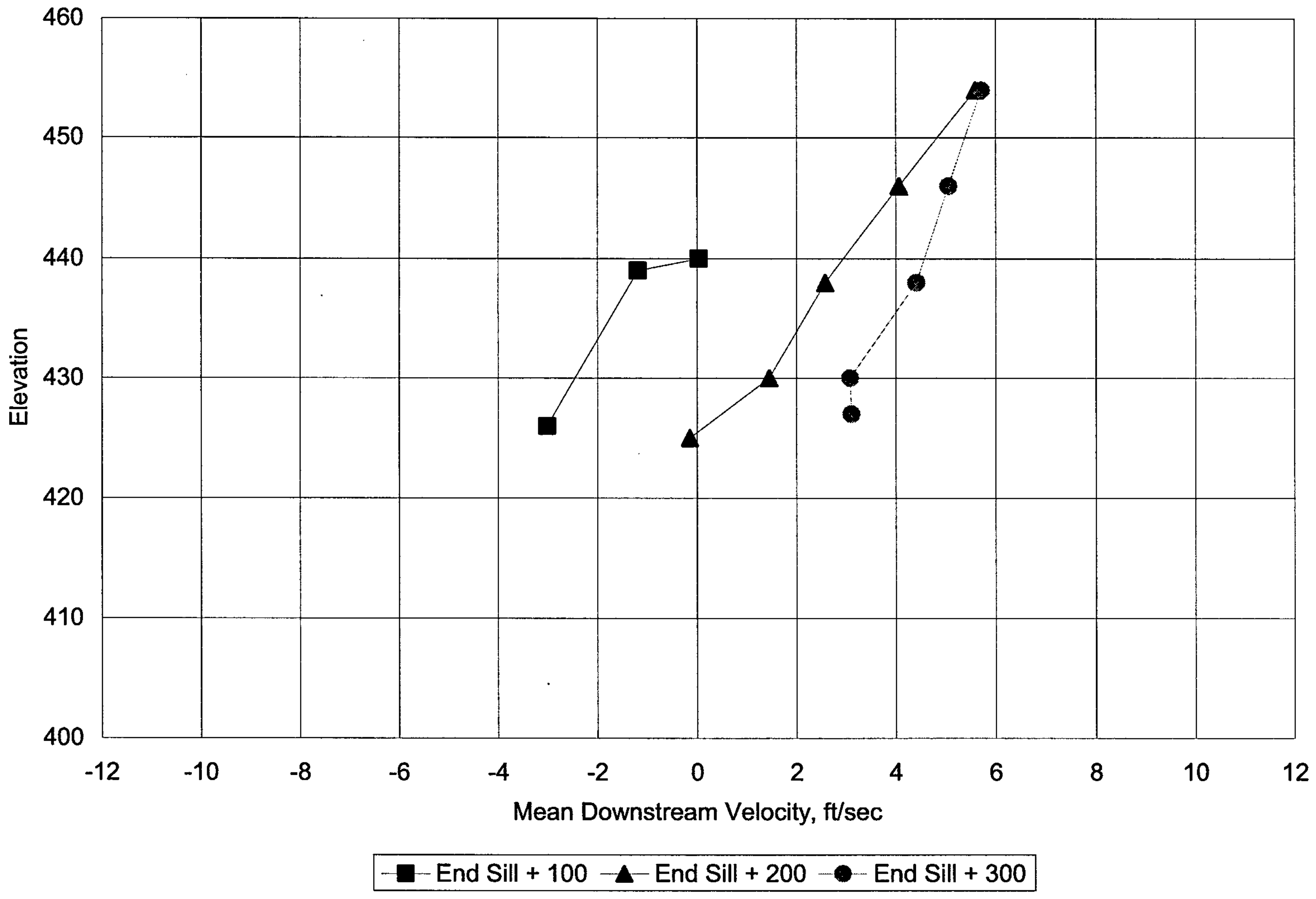

Figure 57. Velocity measurements with elevated end sill. Gate opening – 12 ft, discharge – 21.9 kcfs/bay, pool elevation - 537.0, tailwater elevation - 454

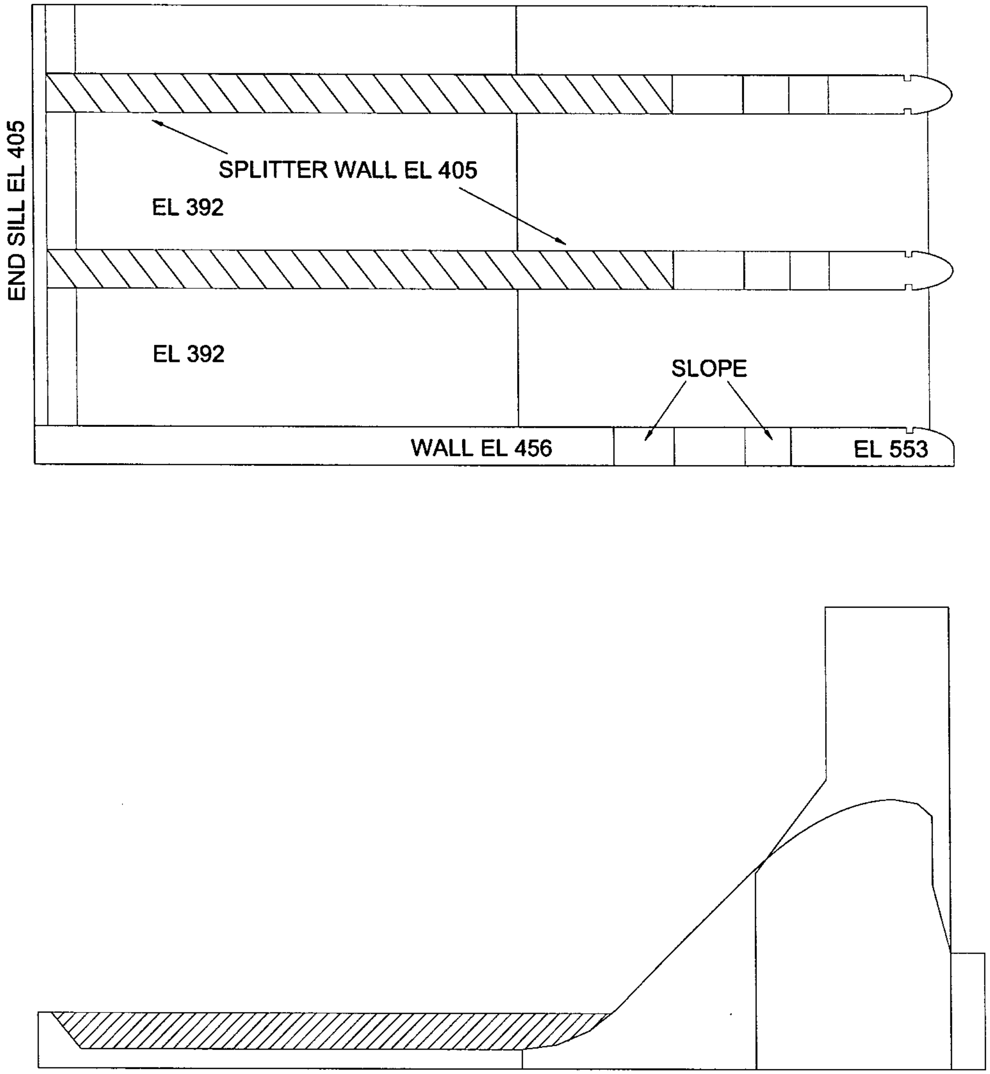

Figure 58. Lower Monumental Section Model stilling basin with splitter walls in place

Appendix A
Scopes of Work

The U.S. Army Engineer District, Walla Walla and the U.S. Army Engineer Research and Development Center (ERDC) personnel developed an initial scope of work (SOW) for the sectional model study that included design and construction of the model and an initial testing plan. Items in this SOW (Appendix A-1) included: (a) spillway tests with existing geometry; (b) tests with changes to the spillway; and (c) stilling basin erosion tests. The initial tests conducted in the model were deflector performance curves with the existing deflector and then with the modified deflector.

Based on model results from tests outlined in Appendix A-1, a revised SOW (Appendix A-2) was developed that included changes for the stilling basin erosion tests and Dissolved Gas Abatement Study (DGAS) experimentation with a uniform spill over all three bays with the modified deflector.

A third SOW (Appendix A-3) was developed to expand the stilling basin erosion testing by minimizing erosive currents within the spillway stilling basin, the prevention of debris movement into the stilling basin, and if necessary, modified configurations in the model that would include experiments with the modified spillway deflectors, riprap downstream of the end sill, baffle blocks, and training walls.

DISSOLVED GAS ABATEMENT
FAST – TRACK PROGRAM
Lower Monumental Dam Spillway
Physical Hydraulic Sectional Model Study
Scope of Work

I. PURPOSE. The purpose of the sectional model study of the Lower Monumental spillway, stilling basin, and adjacent features is to identify operational and structural changes that may reduce stilling basin erosion and downstream dissolved gas concentrations, while minimizing impacts on other river uses.

II. PROCESS. ERDC and the Walla Walla District develop and finalize the model study SOW, budget and schedule as follows.

- **A.** The Walla Walla District prepares a draft scope of work.
- **B.** The scope is e-mailed or faxed to the ERDC principal investigator (PI).
- **C.** The District hydraulic lead and the ERDC PI agree on a scope and schedule.
- **D.** Changes to schedule or budget during the study are documented by e-mail or hard copy.
- **E.** MIPRs are faxed or emailed directly to the PI with copies furnished to Walla Walla District Section Chief and John George.
- **F.** ERDC financial POC fax acceptance of MIPR to District lead for acceptance by CEFMS.
- **G.** The ERDC PI prepares a monthly update of actual or estimated expenditures and emails it to the Walla Walla District hydraulic lead.

III. BACKGROUND.

A. A recent National Marine Fisheries Service (NMFS) proposal calls for investigating the potential installation of additional spillway deflectors and/or providing modifications to existing deflectors on the spillways of the Lower Snake and Columbia River dams. The purpose of the additional deflectors and/or modifications is to allow higher spill levels for passing juvenile salmonids while staying below the 120 percent total dissolved gas (TDG) supersaturation level as recorded by the tailrace fixed monitoring stations. Spillway deflectors are in place on all Lower Snake and Columbia River dams except The Dalles. However, not all spillway bays at all projects have deflectors, and in some cases, the performance of the existing deflectors can be improved.

B. Stilling basin inspections over the last 20 years show a gradual deepening and broadening of holes in the concrete stilling basin floor. It is very likely that reverse flow patterns within the stilling basin eroded the holes by entraining debris from downstream. Spillway deflectors are a known cause of such reverse patterns, although no definitive studies have yet been accomplished in the Lower Monumental stilling basin. This sectional model study will be used to identify the cause of the present erosion, to develop short-term and permanent operational and structural solutions, and to optimize them for gas levels and other river uses.

C. Modifications to the spillway may include new deflectors in non-deflected bays, adding a transition curve from the slope of the spillway to the horizontal deflector surface, extending the downstream spillway pier to the downstream face of the deflectors, and changing deflector length and elevation to optimize for current operating conditions. Stilling basin modifications may include patching existing holes, adding training walls between the spillway endbays and their adjacent bays, and changing the configuration of the end sill to prevent rock from migrating into the basin. Each of these modifications may provide a smoother, more stable discharge jet, possibly minimizing future stilling basin erosion while reducing downstream dissolved gas levels. .

IV. TASKS.

TASK A. Model Design.

1) Facility. ERDC will develop the model facility, including the pump system, head tank, inflow baffle, 1:40 section model, tailwater elevation control, and return flow drain.
2) Model width. The model design will simulate a total of 2-1/2 bays of the existing spillway and stilling basin at Lower Monumental Dam. The model will incorporate the area between the south training wall of the stilling basin and the north wall of the navigation lock. The total model width will be about 6.25 ft at 1:40 model scale.
3) Flexibility.
   a. The model design will permit the stilling basin to be readily changed from the original design to the present eroded condition, and to the proposed temporary and permanent repaired conditions.
   b. The model design will include a removable transparent wall on the left training wall of the stilling basin. This will permit the study of 2-D flow (e.g., for development of performance curves), and 3-D flow (e.g., to determine causes and solutions to stilling basin erosion).
4) Maximum discharge. Total discharge capacity of the model will be 265,625 cfs (106,250 cfs per bay).[1]
5) Forebay range. Normal operating forebay elevations range from el 537.0 to 540.0.[2] However, the reservoir will surcharge to about el 548.3 during the spillway design flood (106,250 cfs per bay).
6) Tailwater elevation. Normal operating tailwater elevations range from about el 437 to 446.5 (0 to 200 kcfs total spill). Tailwater elevations as low as el 430 may be examined during deflector performance tests (with spillway discharges less than 10,000 cfs per bay). The maximum tailwater elevation, el 471.0 fmsl, occurs in the spillway design flood (850 kcfs total spill).
7) Water-surface measurement. The forebay and tailwater elevations will be measured using stilling wells. The forebay elevation will be measured at least 150 ft upstream of the spillway crest. The tailwater elevation will be measured in about three locations, including one just downstream of the end sill, another close to the downstream end of the model, and one location halfway between these.

TASK B. Model Construction. Model construction is currently underway. The following items may require particular attention during construction.

1) Channel bathymetry and roughness. The channel bathymetry downstream of the stilling basin will be developed from the survey data provided by Walla Walla District. The model tailrace downstream of the end sill will be a composite of tailrace bathymetry. It may not exactly match the bathymetry downstream of bays 1 to 3, since the model should be representative of all bays. The model will be constructed with a fixed bed channel, but provisions will be made so that debris movement can be simulated and observed in the tailrace.
2) Viewing and access.
   a. Transparency. A portion of both of the flume's sidewalls will be constructed using a clear, transparent material to facilitate viewing and photographing hydraulic conditions during model testing. The transparent portion on both sides of the model will extend about 160 ft upstream of the spillway crest to 500 ft downstream of the stilling basin end sill. The wall

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[1] All discharges and dimensions specified in this Scope-of-Work (SOW) are prototype discharges and dimensions, unless noted.
[2] All elevations (el) cited are in feet, referenced to the mean sea level datum. (To convert feet to meters, multiply by 0.3048).

that is used for photographing the model during testing will have adequate clear space for good photographing and videotaping.

b. Platforms will be constructed if necessary for viewing both the top and side of the spillway and stilling basin.

c. The area beneath the spillway ogee will be accessible for installation of pressure taps and instrumentation.

3) Deflectors. Existing deflectors, modified deflectors, and pier extensions will be constructed for easy addition to or removal from the model. A final deflector design may also be located at a different elevation than the current existing deflectors. New designs will be constructed so their length can be adjusted from 12.5 to 20 ft, and placed at any elevation (on 1-ft increments) between el 425 and 440. More than one additional design may be required to maintain the smooth radius transition from the spillway slope to the horizontal surface of the deflector.

4) Hydraulic capacity. The model pumps will be able to discharge at least 265,625 cfs (prototype scale), and the baffles, approach channel, spillway, downstream channel, return flume and sump will be capable of passing the flow.

5) Inspection. After construction of the model and prior to full model testing, Walla Walla District personnel will inspect the model facility, view initial model operations and preliminary testing, and meet with ERDC to review and finalize the data collection and testing program.

6) Model construction drawings. As-built drawings of the Lower Monumental spillway and most recent channel bathymetry survey data will be provided by Walla Walla District to ERDC. ERDC will prepare shop drawings for model construction and send them to Walla Walla District for review.

TASK C. Test Plan. The following describes the general intent and goals of the model study, and includes a concept-level description of the model test plan. The outline is arranged in proposed chronological order of testing. ERDC and Walla Walla District will review and revise it before testing begins.

a. Spillway Test with Existing Geometry.

i. Erosion patterns. Explain hydraulics of existing erosion pattern in the stilling basin, through use of entire model width for three-dimensional (3-D) flow, or the truncated model width for two-dimensional (2-D) flow, as appropriate. Model width can be altered with the removable divider wall (subtask 3b., Task A). Operate the spillway to recreate the following conditions. (This task will require up to the maximum flow rate.)

- Current spill pattern.
- Interim spill pattern (refer to Lower Monumental FDM #10, Spillway Basis of Design, Addendum to Supplement 1, Appendix C, 1998).
- Past spill patterns and volumes will be tested, including flows evenly distributed in all bays, and deflectors in bays 2 and 3; even spill in all bays, with spillway deflector only in bay 2 (high flows in 1970s occurred when not all deflectors were yet in place. This operation may show whether unusual flow patterns occurred which might have damaged the basin).

ii. Deflector performance curves. Test existing deflectors to document their performance. With model divider wall in place (sub-task 3b., Task A) to achieve 2-D flow, develop a performance curve relating Q, tailwater, submergence, and nominal gate opening.

b. Tests with Changes to Spillway.

i. Deflector performance curves. Document the deflector performance for selected new designs over a range of spillway discharges and tailwater elevations.

- Discharges. Test deflectors with 1.5, 3, 4.5, 6, 8, 10, 12.5, and 15 kcfs (1,000 cfs) per bay.
- Tailwater elevation. For each spillway discharge, test a range of tailwater elevations to define the zones of the performance curves to be reported in Task F. 4 (Interim Data Reports).
- Deflector geometry tests. Tests will include the existing deflector with two different transition curves; up to 12 other deflectors having up to four different lengths (e.g. 12.5 ft, 15 ft, 17.5 ft and 20 ft) with pier extensions and up to three different transition curves.

ii. Stilling basin erosion. Tests conducted for this sub-task will be to identify the effects of new designs on erosion in the stilling basin. ERDC and Walla Walla District will choose the best two deflector designs and test them in the full width sectional model. Three high discharges, including 106 kcfs per bay, will be tested. The tests are to determine what changes in flow pattern might affect erosion within the stilling basin. The following three model configurations will be tested in this sub-task.

- Stilling basin with new deflectors and unrepaired holes.
- Repaired stilling basin.
- Repaired and improved stilling basin. Tests may include training wall between bays 1 and 2. Tests will determine optimum training wall length and height, and the effects of other features, including a repaired end sill, and possibly a modified end sill, functioning as a rock trap.

iii. For the selected final deflector design, pressure data will be collected at up to 12 locations on the deflector and piers, to provide structural engineers with design information. Data will be collected for up five different spillway operating conditions, including 106,250 cfs per bay.

iv. Color still photographs and video recordings will be taken to document various significant model conditions and observations.

TASK D. Documentation. ERDC will prepare the following documents.

1) Model test plan. The test plan developed in Task C. with letter of approval will be included in an appendix to the final model investigations report.

2) Modifications. Modifications and amendments to the scope of work and/or construction of the model will include a summary of associated costs and changes in schedule. This documentation will be included within an appendix to the final model investigation report.

3) Interim data reports. Interim data reports will be prepared at the conclusion of the following sub-tasks or group of sub-tasks: 3b, 3c and 3d, and 3e and 3f. The interim reports will include performance curves, photographs of significant model conditions, and any other information necessary to portray the work accomplished by ERDC. The interim reports will be written for incorporation into the final report.

4)Model investigations report outline. ERDC will submit for review and comment an outline for the final model investigation report. This outline will be considered a 30 percent complete draft report.

5)Model investigations draft reports. ERDC will prepare a comprehensive report summarizing the results of the model study. The report will include photographs of the model during operation. The report will note observations from the test results, draw conclusions, and explain how the conclusions were reached.

6) Raw data will be included in an appendix to the model study report. Raw data includes discharge, gate settings, forebay and tailwater elevations, and any other pertinent data recorded during the model tests.
7) Video of significant model conditions will be recorded and edited by ERDC.
8) Model investigations final report. Following review of the draft report, Walla Walla District will provide written comments to ERDC. ERDC will incorporate the comments and revise the report as necessary. The final model investigation report will include all items required in the draft report and will include comments on the draft report. The final report will include photographs and edited video clips of model simulations.

V. Deliverables.

A. Model test plan.
B. Interim data reports. The interim data reports will include the items described in Task D. 3).
C. Photographs. Both digital and film photographs will be taken to document model tests for the interim, draft, and final reports.
D. Draft and final reports. Five copies of the draft report will be provided to the POC for Walla Walla District review. Ten copies of the final report will be provided to the POC. In addition, if feasible, ERDC will provide one unbound reproducible copy and an electronic copy of the final report. Electronic copies and the edited video clips will be provided on CD-ROM media.

VI. Point of Contact. The Walla Walla District point of contact is Dan Katz, hydraulic engineer, 509-527-7533; CENWW-EN-DB-HY; Dan.M.Katz@NWW01.usace.army.mil; US Army Corps of Engineers, Walla Walla District, 201 N. 3rd Street, Walla Walla WA, 99362.

VII. Tentative Schedule

Task	Duration	Start Date	Completion Date
Model construction	in progress	in progress	31 August 99
Develop model test plan	in progress	in progress	31 August 99
Model calibration	1 week	7 September 99	10 September 99
1st Walla Walla Dist. scheduled trip	1 week	8 September 99	10 September 99
Model study kick-off meeting	1 day	8 September 99	8 September 99
Testing	3 months	13 Sept. 99	17 December 99
2nd Walla Walla Dist. scheduled trip	1 week	1 November 99	5 November 99
Model study report outline	6 months	1 August 99	20 Dec 99
3rd Walla Walla Dist. scheduled trip	1 week	Jan 00	Jan 00
4th Walla Walla Dist. scheduled trip	1 week	April 00	April 00
60-percent draft report	4 months	January 00	April 00
90-percent draft report	2 months	April 00	June 00
Final report	1 month	June 00	July 00

CEERD-HR-F 14 December 1999

Memorandum for Record

Subject: Lower Monumental Section Model - Modified Scope of Work

1. During the visit to the U.S. Army Engineer Research and Development Center's, Waterways Experiment Station on 6-10 December, Messrs. Rick Emmert, Martin Ahmann, and Dan Katz reviewed the current scope of work for the Lower Monumental section model. Based on model results and discussion, the following revision to the study plan is proposed:

I. Stilling basin erosion study

a. Tailrace material. You (the district) need to determine the type and size of tailrace material at Lower Monumental. Old sampling reports may have observations that would help. Whatever you can find...

b. We must drain, clean sump, and refill with clear water. We will add model platforms, ladders, etc.

c. We will sieve and mark appropriately sized rock as soon as the size is determined.

d. We will place scaled material in section model and determine the minimum flow (threshold flow) and tailrace velocities required for debris transport (2-D flow). (Six discharges with various tailwater elevations.) We will prepare a brief memo describing these experiments.

e. We will perform a frequency analysis of spill records (we may need help to acquire all the data back to the closure of the project during construction) to assess the occurrence of the threshold flow. We will examine the time-history of spill operations to determine how often the threshold flows occurred and with which spill patterns. (We sill summarize the analysis in a brief memo.) From this we will establish the discharge and pattern to reproduce in the section model.

f. We will modify the model to base conditions (existing design with deflectors on interior bays only). We will test a set of discharges (six discharges with various tailwater elevations) representing the likely operations contributing to debris transport and deposition in the stilling basin. We will measure velocities along the tailrace channel bottom to establish base conditions. We will map deposition in the model without the outer bay deflector and overlay model observations with the stilling basin damage surveys. We will provide a brief data report.

g. Once a deflector design is finalized from the DGAS experimentation, we will install a new deflector in the outer bay. We will test a set of discharges (six discharges with various tailwater elevations) representing the likely operations contributing to debris transport and deposition in the stilling basin. We will test a second set of discharges (six discharges with various tailwater elevations) representing the proposed operations for the modified structure.

With an outer bay deflector, velocities along the tailrace channel will be compared to the base condition. We will map deposition in the model with the outer bay deflector and compare to base conditions. We will measure the piezometric pressure on the vertical face of the deflector. If warranted, we will install a high-frequency pressure transducer and record pressure fluctuations. We will provide a brief data report.

h. We will prepare a draft report summarizing the entire study with conclusions and recommendations.

II. DGAS experimentation:

a. We will test a uniform spill over all three bays with the modified deflector (with radius) and classify performance for 2-12 ft gate openings (six discharges and various tailwater elevations). We will digitally photograph and videotape the performance. We will prepare a digital photo album. We will develop performance curves and prepare a brief data summary report.

b. Based on the performance curves, we will redesign the outside deflector and install new elevation in outside bay.

c. We will develop performance curves for all bays in operation with the newly designed outer deflector (six discharges and various tailwater elevations). We will measure velocities in and around the south side fish entrances for skimming or undulating flow (four discharges). We will digitally photograph and videotape the performance. We will prepare a digital photo album. We will develop performance curves and prepare a brief data summary report.

d. We will develop performance curves without the end bay in operation. We will digitally photograph and videotape the performance (six discharges and various tailwater elevations). We will prepare a digital photo album. We will develop performance curves and prepare a brief data summary report.

e. We will prepare a consolidated draft report with conclusions and recommendations.

2. Estimated cost to conduct the above scope of work is $315 thousand. This includes allocations for model modifications, flume improvements, instrumentation, travel expenses, two meetings at ERDC and a meeting at the district's offices or other northwest location.

Steven C. Wilhelms, PhD, PE
Engineer
Coastal and Hydraulics Laboratory

Lower Monumental Section Model
Scope of Work
Stilling Basin Erosion

Main questions to be addressed: (a) What are the flow conditions that contribute to stilling basin erosion or debris transport? (b) Are there operations that minimize debris transport and scour action that could be implemented as an interim operational strategy? (c) What are the uplift pressures on the stilling basin apron due to flow plunging into the scour hole? (d) Do the erosion mechanisms and uplift identified in this study constitute a dam safety risk?

Objective A. Determine historical cause of erosion.[1]

Configuration: Existing Deflector in Bay 2, with no other deflectors (3D[2]); no erosion in basin.

Operation: up to 230 kcfs total spill over the entire spillway (~30 kcfs/bay). Tailwater range from about el 437 to about el 452. District will review historical record to determine configurations and operational categories over the life of the project. Once the specific operations are investigated, a range of discharges and tailwater elevations will be evaluated. Table 1 shows discharges and tailwater elevations to be investigated. For each discharge, the tailwater will start at el 437 and be increased in 2.0-ft intervals to el 452. (eight tailwater els).

Table 1. Discharge and Tailwater Range for Objective A Tasks

Discharge, kcfs/bay	River Discharge without Powerhouse,[1] kcfs	River Discharge1 with Max Powerhouse, kcfs	Minimum tailwater	Maximum Tailwater
5	30	165	437	452
10	60	195	437	452
15	90	225	437	452
25	150	285	437	452
50	300	435	437	452
75	450	585	437	452

[1] Assumes uniform distribution of discharge across 6 gates.

Tasks.

a. Investigate historical operations of Lower Monumental to examine stilling basin hydraulics from closure in the early 1970s, during the 1980s, and in the late 1990s.

- ERDC will investigate up to five different operations based on the District's review of historical operations. Flow conditions in the stilling basin will be evaluated with directional yarn attached to grid points. Debris will be marked and

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[1] Due to unknown causes of erosion, this objective involves tasks also related to Objectives B, C, and D)

[2] The term "3D" refers to the use of the entire sectional model, including the non-overflow section between spillway bay 1 and the navigation lock. The term "2D" refers to the use of the divider wall extending downstream from the south training wall. This converts the model to a 2-1/2 bay, 2-D sectional model.

introduced in the tailrace to determine movement and deposition. The extent of vertical and horizontal circulation cells will be noted and velocity profiles will be measured at the end sill and at two locations in the tailrace.

b. Identify range of spillway flow and tailwater elevation associated with debris movement from downstream, over the end sill, and into the stilling basin (3D). (Similar investigation in previous Scope of Work, verified in current work).

    - ERDC will mark and distribute colored stone to simulate tailrace debris, run the model under conditions that previously promoted debris transport. The threshold discharge that causes debris transport into the stilling basin will be determined. Through the use of dye injections, ERDC will determine the extent of the circulation cell that transports material into the basin for the threshold discharge and higher discharges (Table 1). Average bottom velocities will be measured at the end sill and at two other locations downstream.

c. Observe where material originates and where it is deposited (3D). (Investigated in previous Scope of Work, verified in current work.)

    - ERDC will map the origins from whence debris was transported and the resulting deposition of material in the stilling basin to ascertain if material from one location is deposited in a specific locale.

d. Compare survey damage with debris deposition in model (3D). (Investigated in previous Scope of Work, verified in current work.)

    - ERDC will compare debris deposition patterns in the stilling basin to the existing erosion patterns. A rectangular grid will be established on the stilling basin apron to identify deposition locations.

e. Record flow patterns within the stilling basin at various flows and tailwater el's at low to moderate spillway flows (when deflectors are not overridden) (2D and 3D). (Investigated in previous Scope of Work, verified in current work).

    - ERDC will install yarn directional indicators on the stilling basin floor at grid points and record the resulting flow patterns/variations with video.

f. Investigate an erodible stilling basin floor.

    - ERDC will conduct preliminary experiments in a mixing vessel to identify a mix of materials to provide an erodible apron. The goal is to produce a mix that will resist hydraulic action, but degrade in a reasonable amount of time, when subjected to abrasion. If the mix can be developed, ERDC will then conduct experiments with an erodible stilling basin to validate the flow conditions that contributed significantly to apron erosion for three selected discharges, and two tailwater elevations.

g. Reporting. An interim data report will be prepared for Tasks a-d. A separate memorandum will be prepared on the investigation into reproducing scour on the stilling basin apron (Task e).

Objective B. Minimize erosive currents within the spillway stilling basin.

Configuration: Present spillway configuration, existing deflectors in bays 2 and 3, with no deflector in bay 1; scour hole in basin.

Operation: Large range of discharges. Experiments should include standard spill pattern and determine interim spill patterns that reduce the opportunity for scour. This would include operating only bay 1, bays 1 and 3, and only bay 3. Tailwater will range from about el 437 to about el 452. Table 2 shows discharges and tailwater elevations to be investigated.

Table 2. Discharge and Tailwater Range for Objective B Tasks

Approx Discharge kcfs/bay	River Discharge without Powerhouse[1], kcfs	River Discharge[1] with Max Powerhouse, kcfs	Minimum Tailwater	Maximum Tailwater
2.5	15	150	437	452
5	30	165	437	452
7.5	45	180	437	452
10	60	195	437	452
12.5	75	210	437	452
15	90	225	437	452
17.5	105	240	437	452
20	120	255	437	452
25	150	285	437	452
50	300	435	437	455
75	450	585	437	459

[1] Assumes uniform distribution of discharge across 6 gates.

For each discharge and operational configuration, the tailwater will start at el 437 and be increased in 2.0 ft intervals to el 452. (at least 8 tailwater els).

Tasks. Define interim operations for the period between now and when repairs to the stilling basin are completed.

Tasks for low-to-moderate spillway operation (up to about 20 kcfs) (some tasks already completed and reported in September 2000 ERDC debris report):

a. Identify range of spillway flow and tailwater elevation associated with debris movement from downstream, over the end sill, and into the stilling basin (3D). (Completed in previous work, validated in current study.)

b. Observe where material originates and where it is deposited (3D). (Completed in previous work, validated in current study.).

c. Compare survey damage with debris deposition in model (3D). (Completed in previous work, validated in current study.)

d. Record flow patterns within the stilling basin at various flows and tailwaters at low to moderate spillway flows (when deflectors are not overridden) (2D and 3D).

- ERDC will install yarn directional indicators on the stilling basin floor at grid points and record the resulting flow patterns/variations with video.

e. Record pressure and fluctuations with transducers on stilling basin floor.

- ERDC will install a set of five high-speed pressure transducers in an appropriate pattern on the stilling basin apron to measure pressure fluctuations caused by plunging flow in the stilling basin for three selected discharges, and two tailwater elevations.

f. Select operational scenario that minimizes scour action and test with erodible apron.

- If appropriate material mix has been developed, ERDC will install erodible apron in stilling basin and compare erosion to other patterns established in previous testing.

Tasks for high-flow operation (over 20 kcfs per bay):

g. Identify shape, location, and energy of upstream roller (under spillway deflectors) when spillway deflector is overridden (2D).

- ERDC will measure velocity profiles with a miniature propeller probe at the end sill and at two locations downstream to establish the vertical velocity distribution within the vertical circulation cell. The profiles will be plotted. Video clips of dye releases will be recorded to identify the central portion of the circulation cell.

h. Identify shape, location, and energy of downstream roller (circulation cell) when spillway deflector is overridden (2D).

- ERDC will measure velocity profiles with a miniature propeller probe at the end sill and at two locations downstream to define the velocity magnitudes and plot the velocities on photos to establish the flow pattern.

i. Identify shape, location and energy of plunging jet (2D).

- ERDC will install a grid of piezometer taps on the surface of the stilling basin apron to measure the mean pressure and velocity head of the plunging flow. A 2-D map of pressure distribution will be developed.

j. Correlate debris entrainment and movement to flow conditions.

- A range of debris size will be introduced to the model tailrace and the movement of the debris will be correlated to discharge and stilling basin flow conditions.

k. Measure and record pressure fluctuation on stilling basin floor.

- ERDC will install a set of five high-speed pressure transducers in an appropriate pattern on the stilling basin apron to measure pressure fluctuations caused by plunging flow in the stilling basin for three selected discharges, and two tailwater elevations.

l. Reporting. An interim data report will be drafted for tasks a-d and j. A separate data report will be drafted for tasks e and k and g-i. A data report will be drafted for task

Objective C. *Prevent movement of debris into stilling basin*

Configuration: Future spillway configuration, existing deflectors in bays 2 and 3, with newly-designed deflector in bay 1; scour hole in basin.

Operation: Three selected discharges with tailwater el's that cause the greatest transport of debris into stilling basin.

Tasks. Investigate prevention of debris movement and develop design parameters for:

a. Grouting the tailrace.
    - ERDC will determine the downstream extent of the circulation cell that transports debris into the stilling basin to estimate the extent of grouting required to stabilize the tailrace.

b. Installing rock trap.
    - ERDC will review design parameters for a rock trap (rectangular cross-section trench) and install a trap that would extend across the width of the stilling basin. ERDC will investigate the trap's efficiency relative to the "pile-up" of debris and consequential loss of trap effectiveness.

c. Raising stilling basin end sill.
    - ERDC will design an elevated end sill based on the vertical velocity distributions at the end sill. The raised end sill will be installed in the model and tested to determine its effectiveness at reducing the strength and downstream extent of the vertical circulation cell. The hydraulic performance of the elevated end sill will also be investigated over a wide range of discharge (Table 2) and tailwater els (437.0-452.0 at 2-ft interval).

d. Reporting. ERDC will draft a memorandum describing the results from experiments to investigate Objective C.

Objective D. *Potential Modified configurations*

If warranted by observations in previous experiments, the following features may be investigated:

- Modified spillway deflectors
- Riprap downstream of end sill, as far downstream as circulation cell extends.
- Baffle blocks
- Training walls

Operations. The required structure operation will be determined based on the results of previous experimental work.

Tasks. Tasks required for this effort will depend upon the objectives and configurations to be investigated.

Data collection. Data collection and analysis will depend upon the objectives and configurations to be investigated, but may include:

- Tailrace water velocities
    - D/S of the stilling basin
    - Within the stilling basin at low-moderate flow, and at high flow
- Stilling basin uplift forces
- Piezometers
- Transducers

Reporting. Draft interim reports will be identified at such time that objective and tasks are more clearly identified.

Tasks, Operations, Data Collection, and Analysis

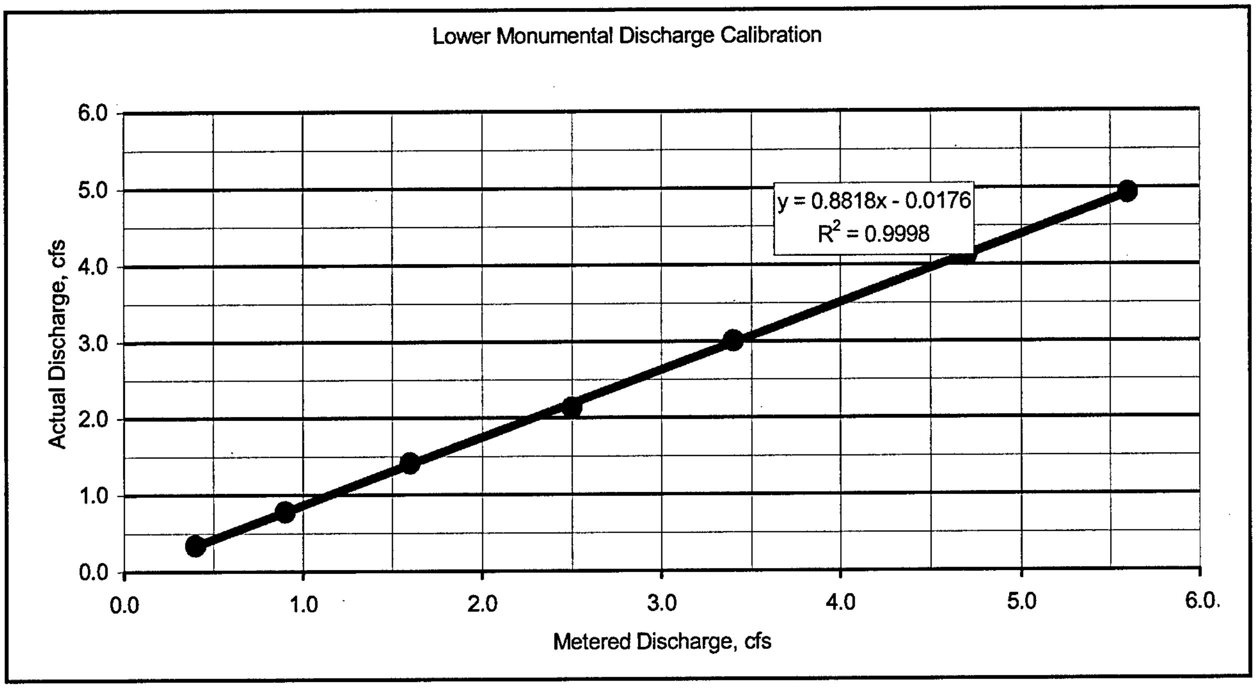
Task	Discharge Range kcfs/bay	No. Q's	No. TW's	Data and Analysis
Early configuration				
A.a. 5 Historical operations	3<q<30	5	3	Qmin, velocities, and cell dimensions origin map and deposition map video record
A.b. ID range of flow that transports debris	3<q<75	6	3	Qmin, velocities, and cell dimensions
A.c. Observe origin and deposition	3<q<75	6	3	origin map and deposition map
A.d. Compare damage and deposition				overlay deposition and damage
A.e. Yarn to measure S/B patterns	3<q<25	5	8	video record
A.f. Erodible S/B	TBD	3	2	damage map
A.g. Reporting				performance analysis
Present Configuration				
B.a. ID range of flow that transports debris	3<q<5	2	2	qmin
B.b. Observe origin and deposition	3<q<25	3	1	origin map and deposition map
B.c. Compare damage and deposition				overlay deposition and damage
B.d. Yarn to measure S/B patterns	20<q<25	2	8	video record
B.e. Pressure fluctuations	TBD	3	2	uplift analysis
B.f. Erodible S/B	TBD	2	2	damage map
B.g. Vert US circulation cell	q>25	3	5	cell velocities and cell dimensions
B.h. Vert DS circulation cell	q>25	3	5	cell velocities and cell dimensions
B.i. Plunging jet energy	q>20	4	2	mean pressure distribution
B.j. Correlate debris and flow	q>25	3	3	rate of debris movement
B.k. Pressure fluctuations	TBD	3	2	uplift analysis
B.l. Reporting				performance analysis
Alternatives to Exclude Debris				
C.a. DS extent of circ cell	4<q<25	5	3	cell dimensions
C.b. Rock Trap	4<q<25	4	1	trap efficiency
C.c. Elevated end sill	4<q<25	4	5	cell dimensions
C.d. Reporting				performance analysis

The following time estimate is furnished regarding the work effort on Lower Monumental Section Model described by the Nov 2000 Scope of Work v2.

Cost Estimate for Lower Monumental Section Model Based on Nov 2000 Scope of Work v2		
Task	**Time, weeks**	**Cost $K**
Model Prep and Mod	3	$22
A	7	$59
B	8	$59
C	4	$32
Total	22	$172
Costs include 3 meetings in Vicksburg for study review.		

Appendix B
Paddle Meter Discharge Calibration

Lower Monumental Paddle Meter Discharge Calibration				
Meter Reading cfs	**Tank Fill Depth ft**	**Tank Surface Area ft^2**	**Time to Fill sec**	**Actual Discharge cfs**
0.4	1	300.7	882	0.34
0.9	1	300.7	386	0.78
1.6	1	300.7	213	1.41
2.5	1	300.7	141	2.13
3.4	1	300.7	100	3.01
4.7	1	300.7	73	4.12
5.6	1	300.7	61	4.93



Appendix C
Photo Album

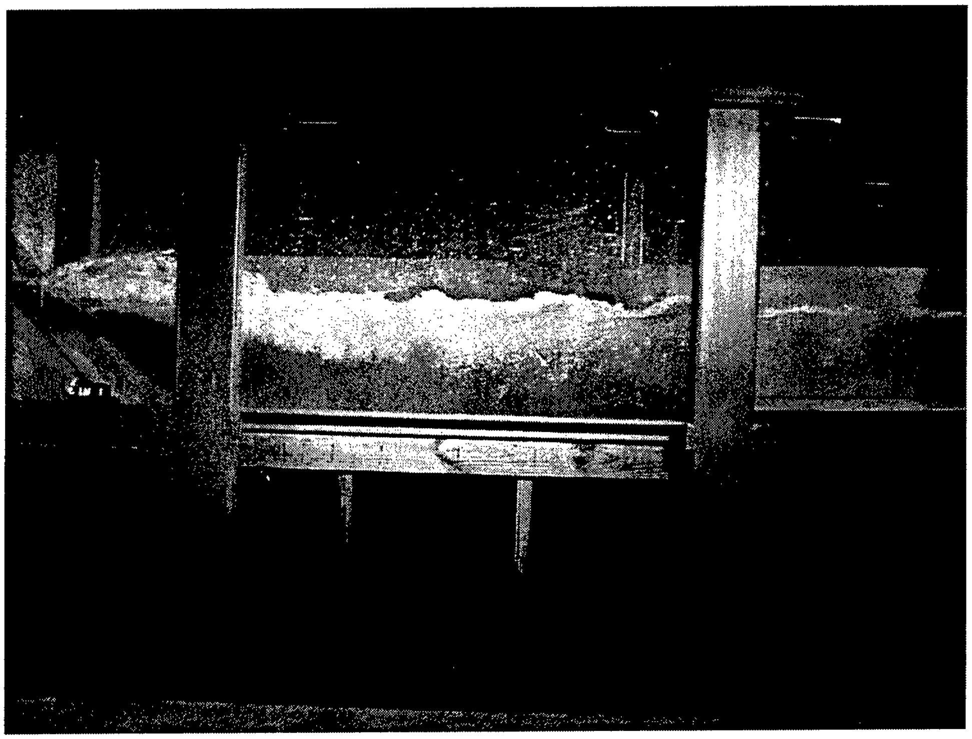


Figure C1. Type I deflector. Plunging flow. Gate opening – 2 ft, discharge – 4.2kcfs/bay, pool elevation – 537, tailwater elevation – 435

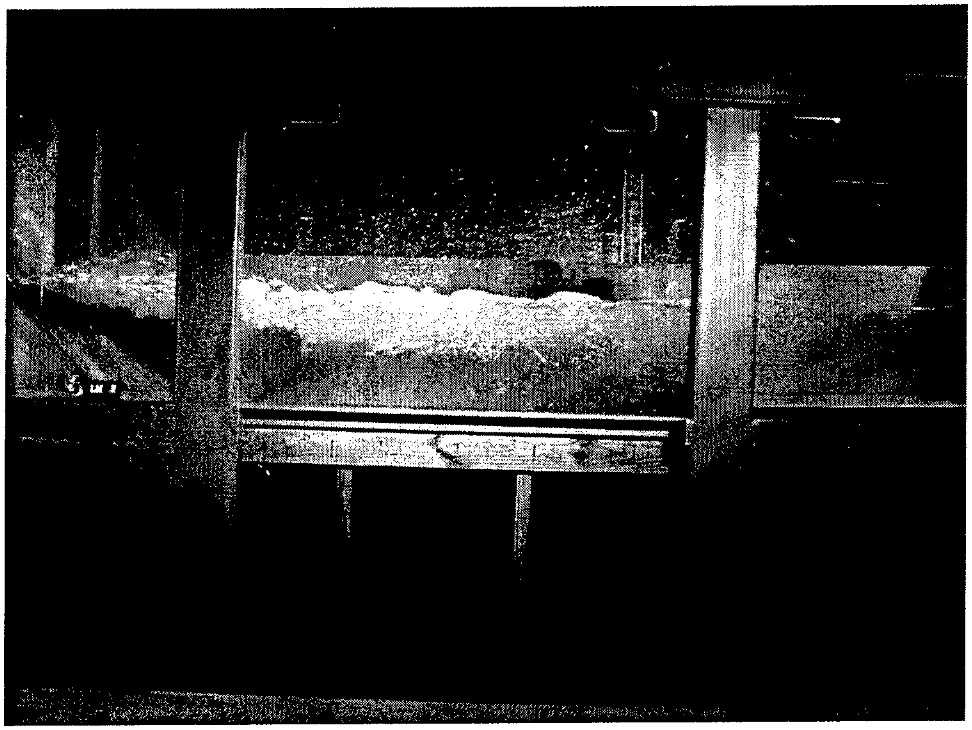


Figure C2. Type I deflector. Skimming surface jet. Gate opening – 2 ft, discharge – 4.2 kcfs/bay, pool elevation – 537, tailwater elevation – 437

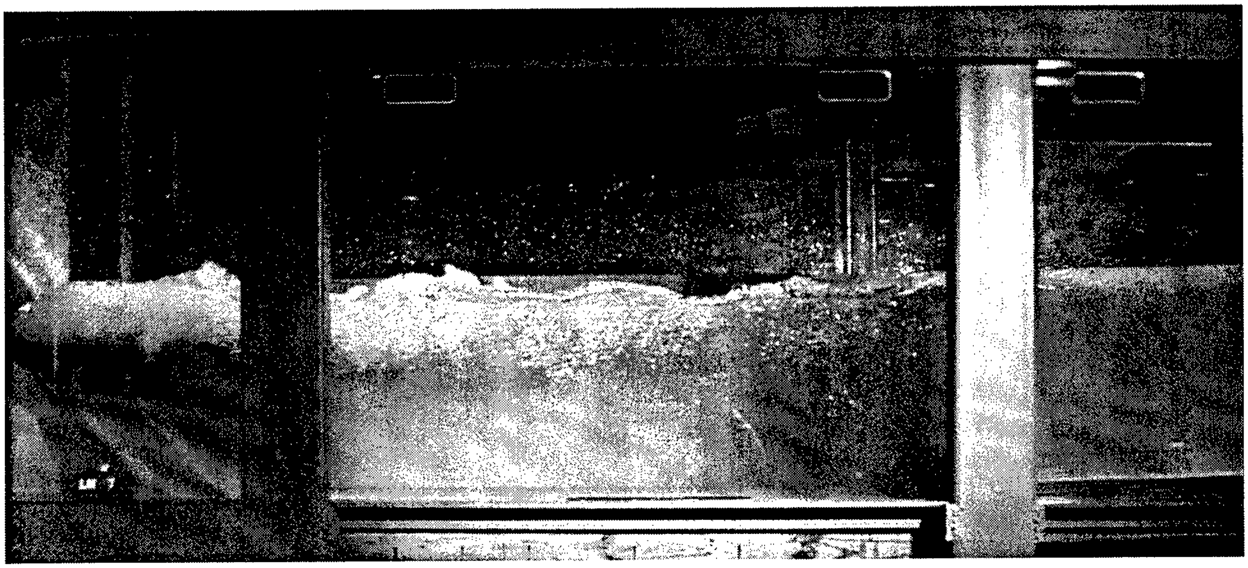


Figure C3. Type I deflector. Surface jump. Gate opening – 2 ft, discharge – 4.2 kcfs/bay, pool elevation – 537, tailwater elevation – 447

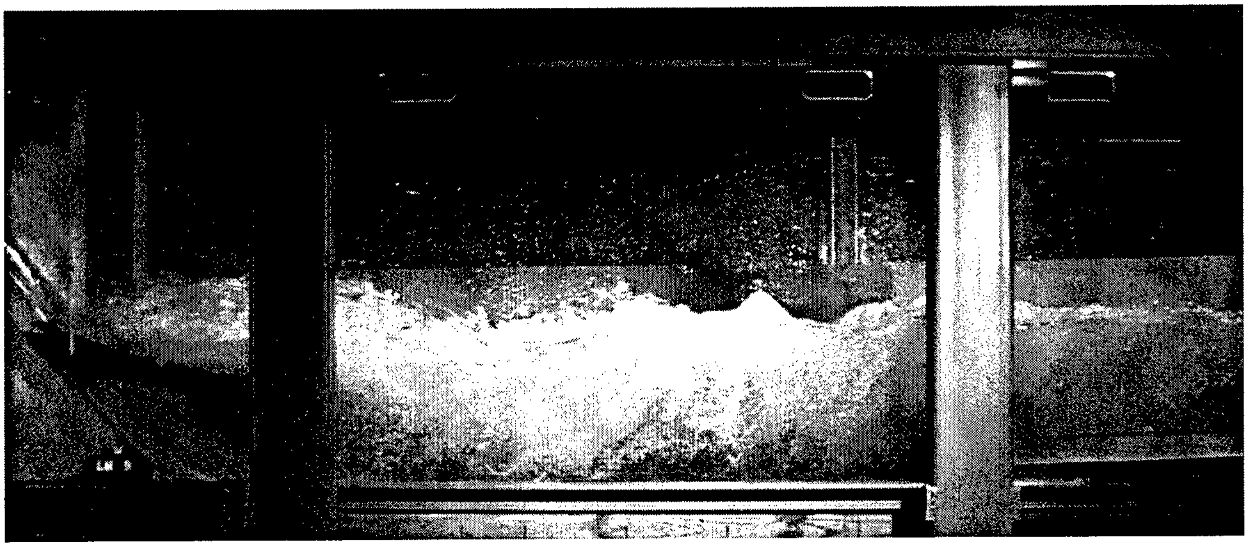


Figure C4. Type I deflector. Plunging jet. Gate opening – 4 ft, discharge – 6.7 kcfs/bay, pool elevation – 537, tailwater elevation – 438

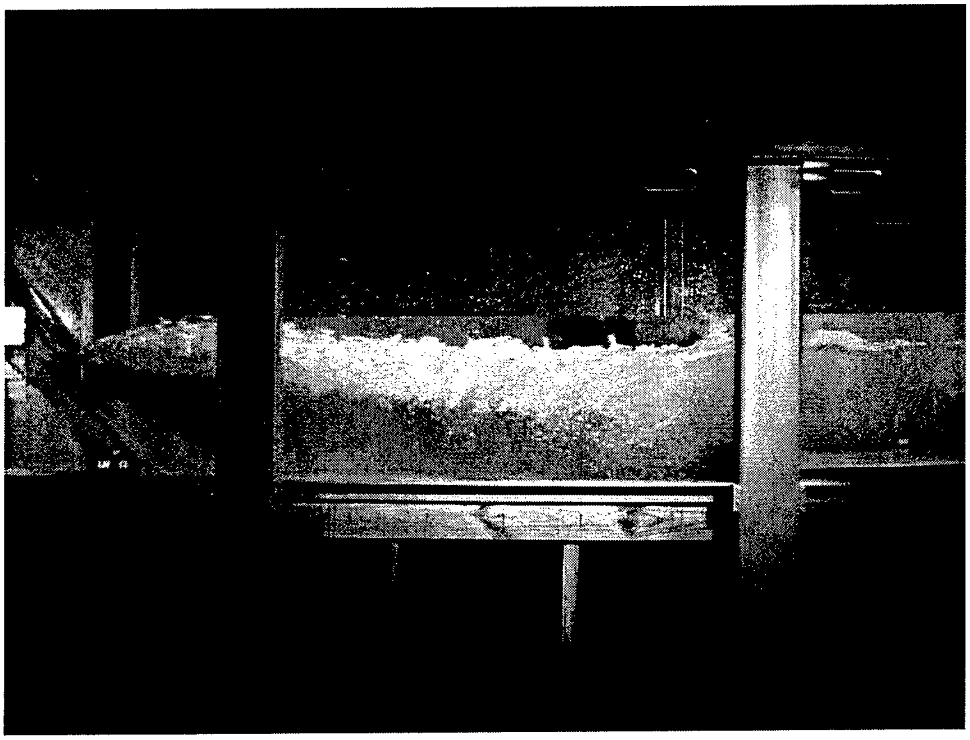


Figure C5. Type I deflector. Skimming surface jet. Gate opening – 4 ft, discharge – 6.7 kcfs/bay, pool elevation – 537, tailwater elevation – 444

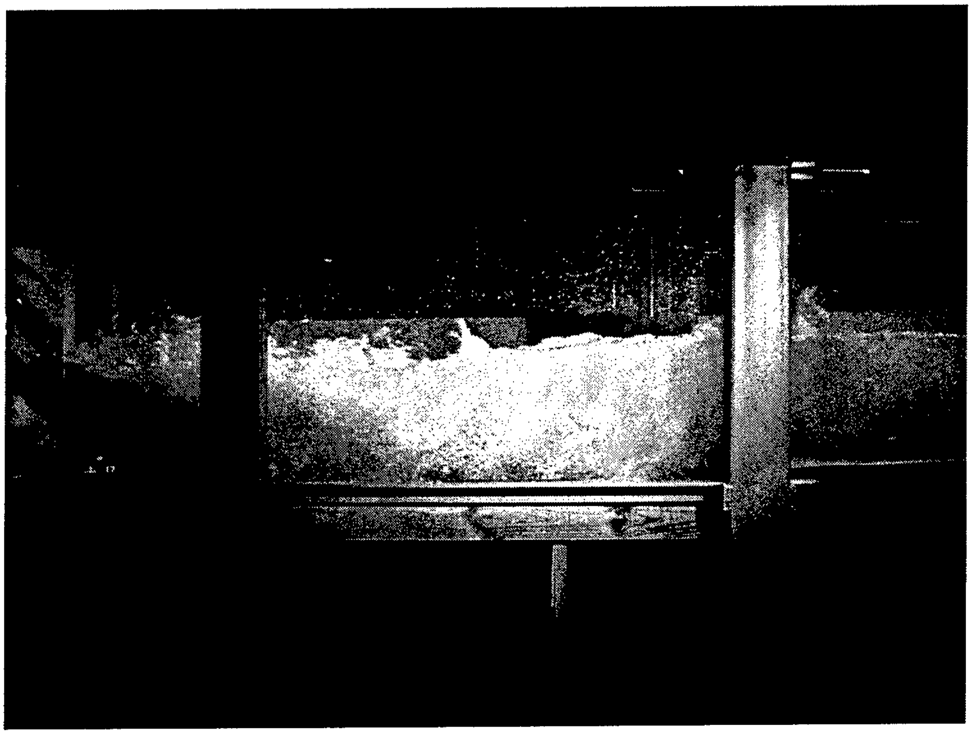


Figure C6. Type I deflector. Plunging jet. Gate opening – 6 ft, discharge – 10.2 kcfs/bay, pool elevation – 537, tailwater elevation – 444

Figure C7. Type I deflector. Skimming surface jet. Gate opening – 6 ft, discharge – 10.2 kcfs/bay, pool elevation – 537, tailwater elevation – 444

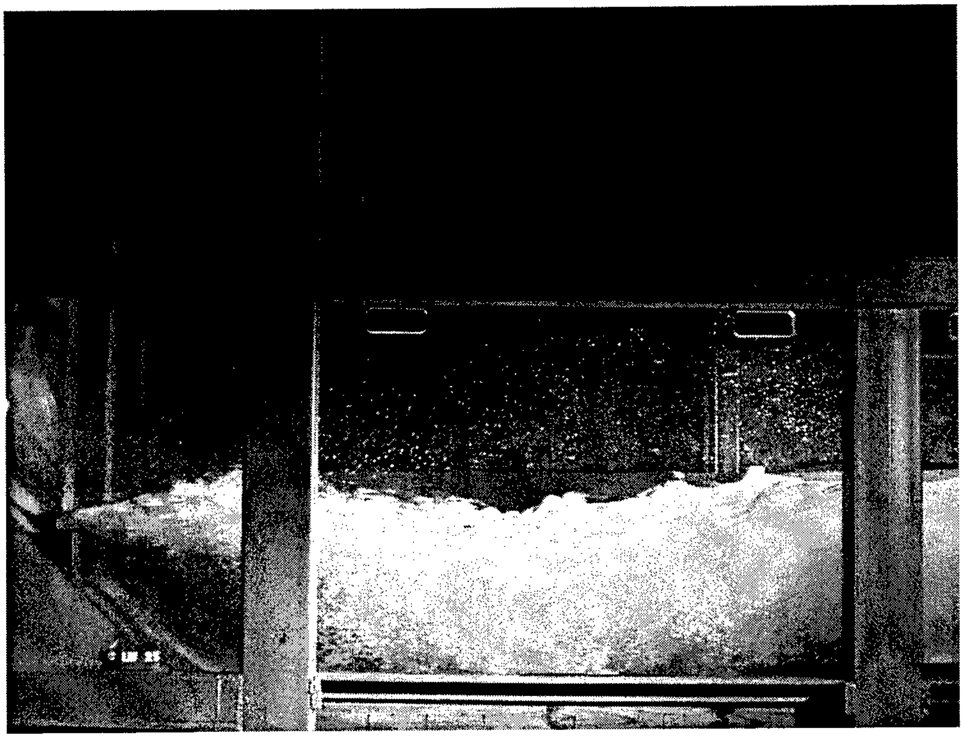


Figure C8. Type I deflector. Plunging jet. Gate opening – 8 ft, discharge – 13.8 kcfs/bay, pool elevation – 537, tailwater elevation – 448

Figure C9. Type I deflector. Ramped surface jet. Gate opening – 8 ft, discharge – 13.8 kcfs/bay, pool elevation – 537, tailwater elevation – 456

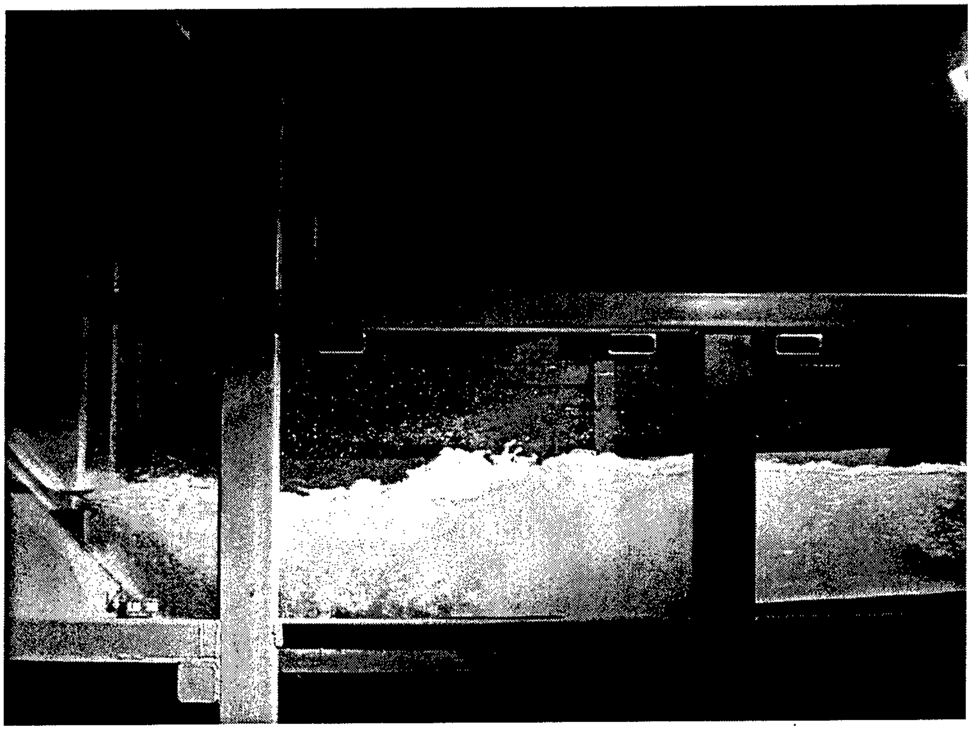


Figure C10. Type I deflector. Plunging jet. Gate opening – 10 ft, discharge – 18.2 kcfs/bay, pool elevation – 537, tailwater elevation – 447

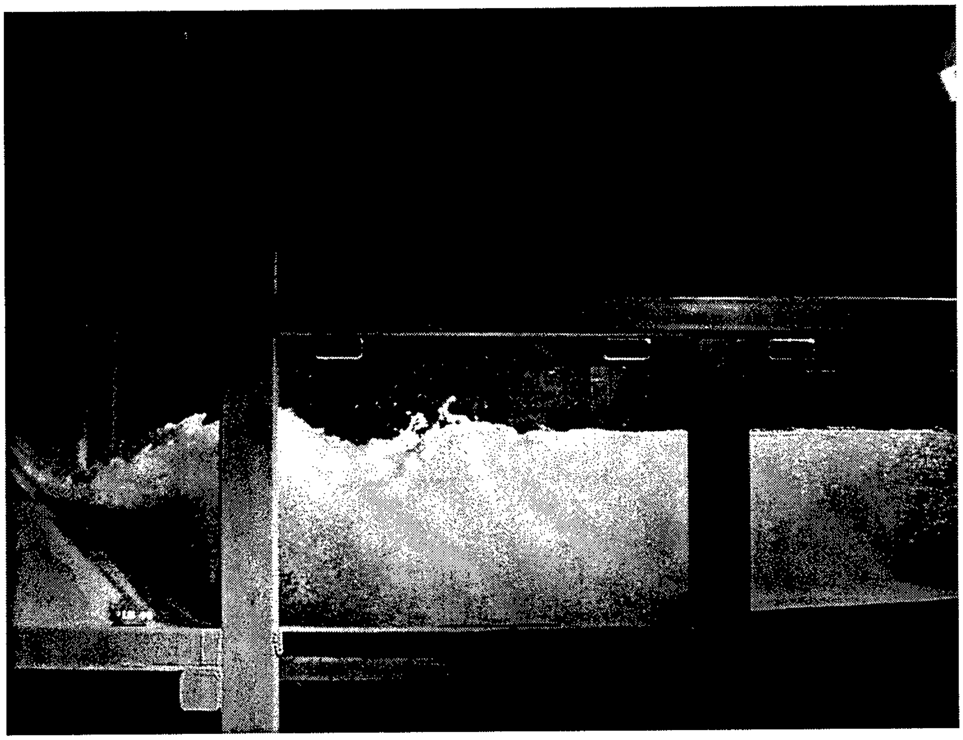


Figure C11. Type I deflector. Plunging jet. Gate opening – 10 ft, discharge – 18.2 kcfs/bay, pool elevation – 537, tailwater elevation – 463

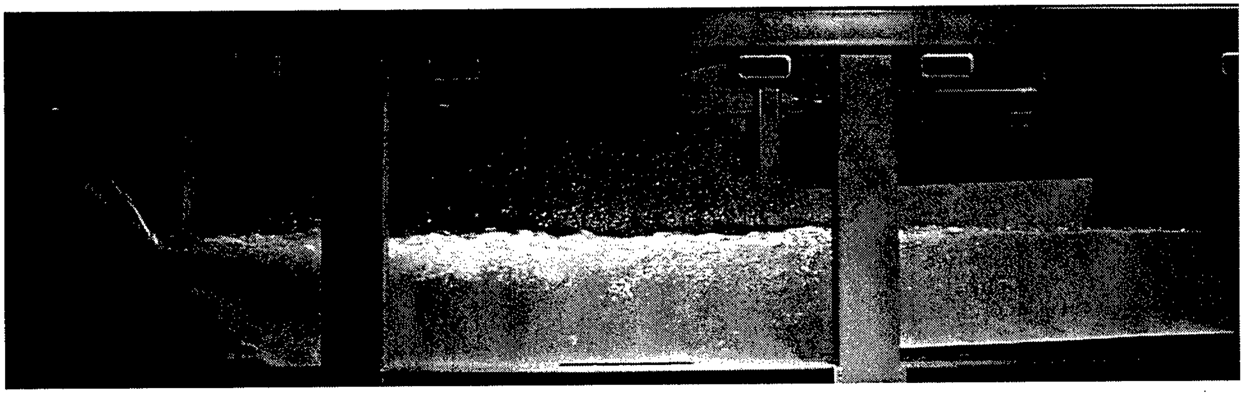


Figure C12. Type II deflector. Skimming surface jet. Gate opening – 2 ft, discharge – 4.2 kcfs/bay, pool elevation – 537, tailwater elevation – 439

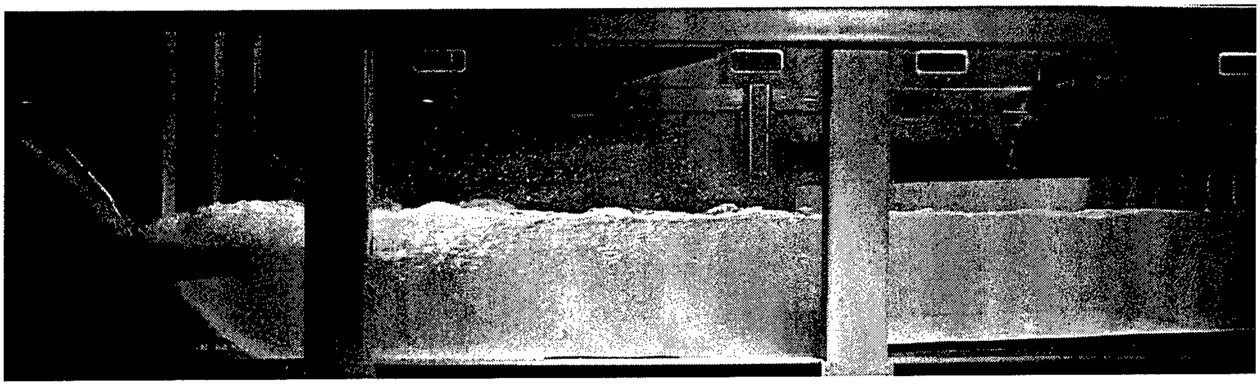


Figure C13. Type II deflector. Surface jump. Gate opening – 2 ft, discharge – 4.2 kcfs/bay, pool elevation – 537, tailwater elevation – 445

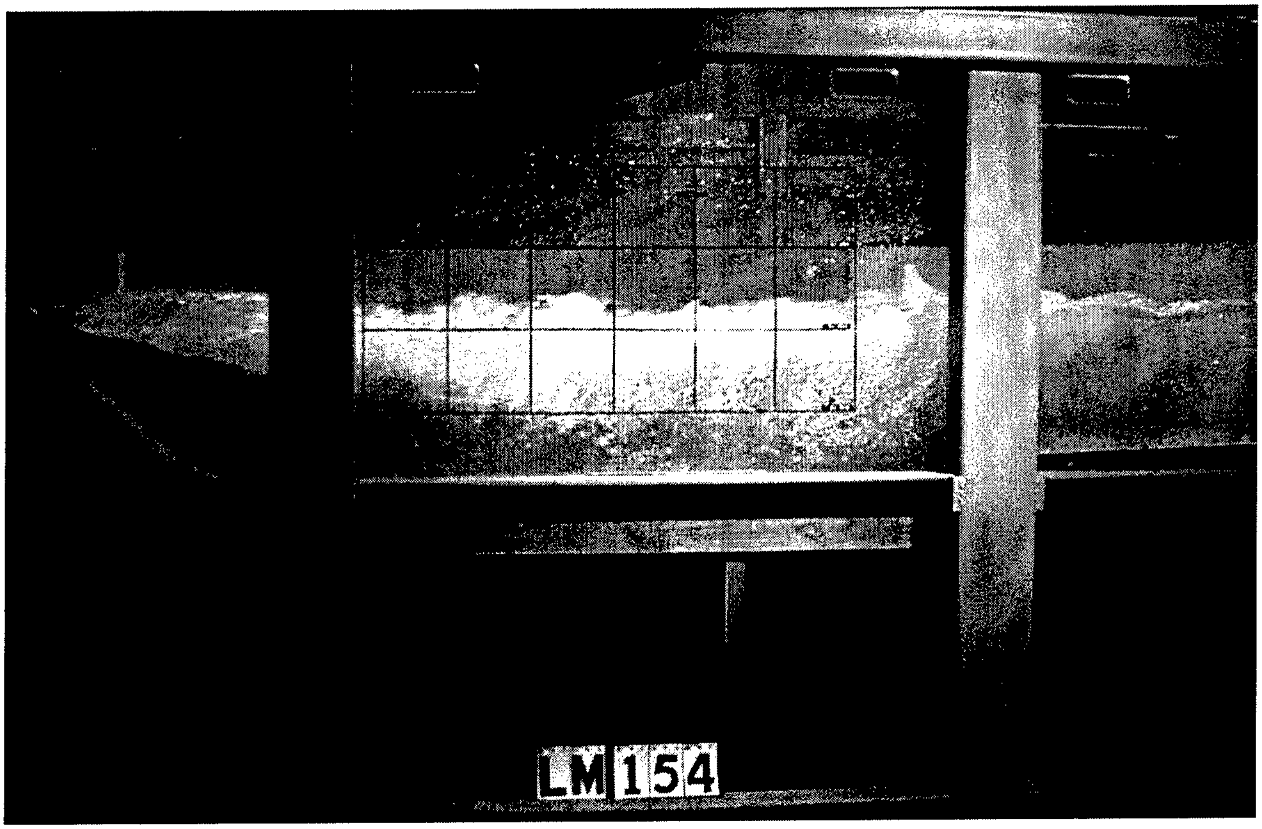


Figure C14. Type II deflector. Plunging jet. Gate opening – 4 ft, discharge – 6.7 kcfs/bay, pool elevation – 537, tailwater elevation – 439

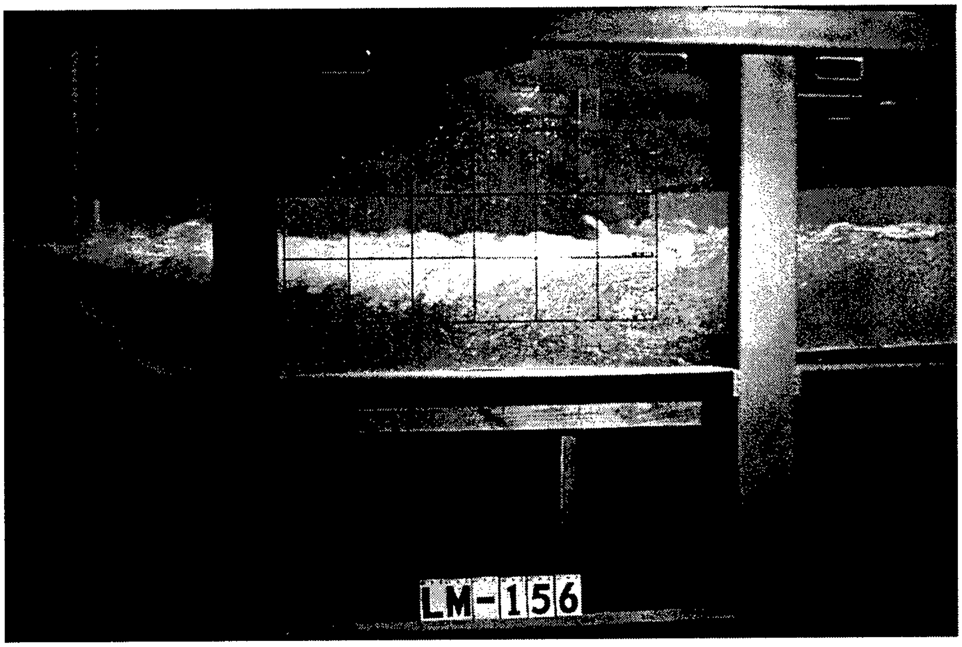


Figure C15. Type II deflector. Skimming surface jet. Gate opening – 4 ft, discharge – 6.7 kcfs/bay, pool elevation – 537, tailwater elevation – 442

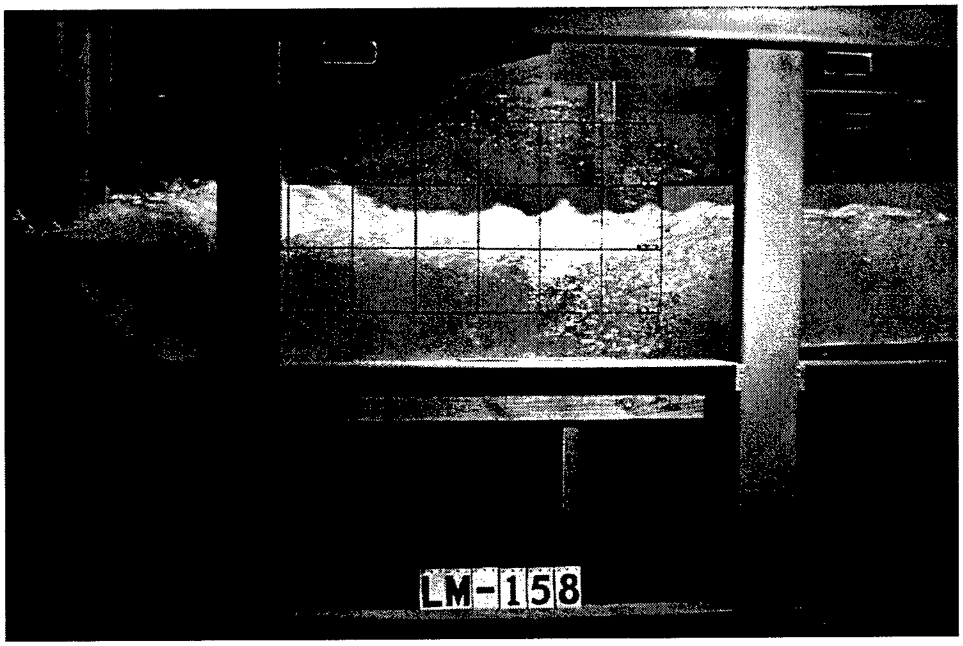


Figure C16. Type II deflector. Ramped surface jet. Gate opening – 4 ft, discharge – 6.7 kcfs/bay, pool elevation – 537, tailwater elevation – 446

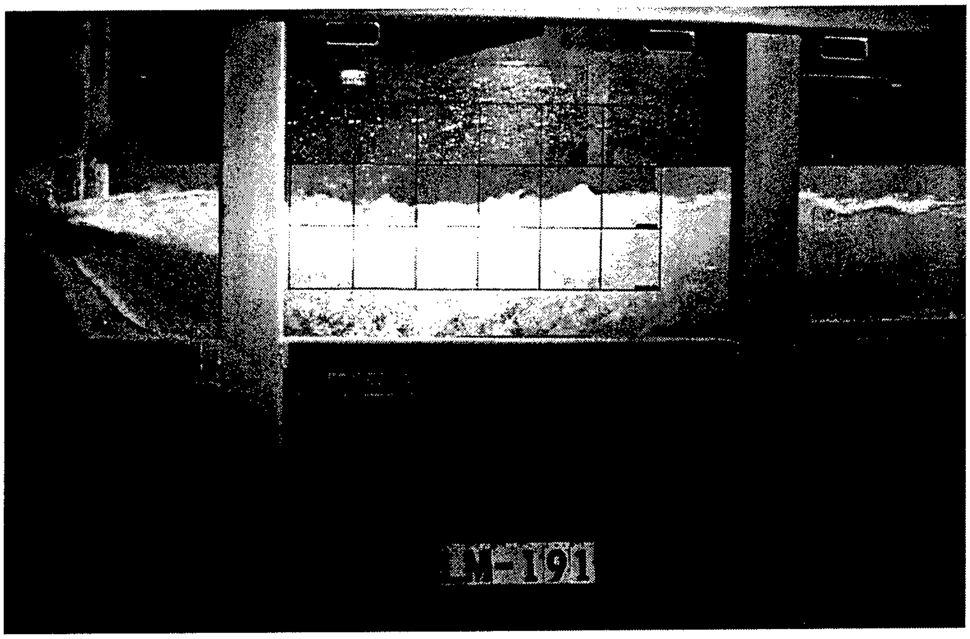


Figure C17. Type II deflector. Plunging jet. Gate opening – 6 ft, discharge – 10.2 kcfs/bay, pool elevation – 537, tailwater elevation – 442

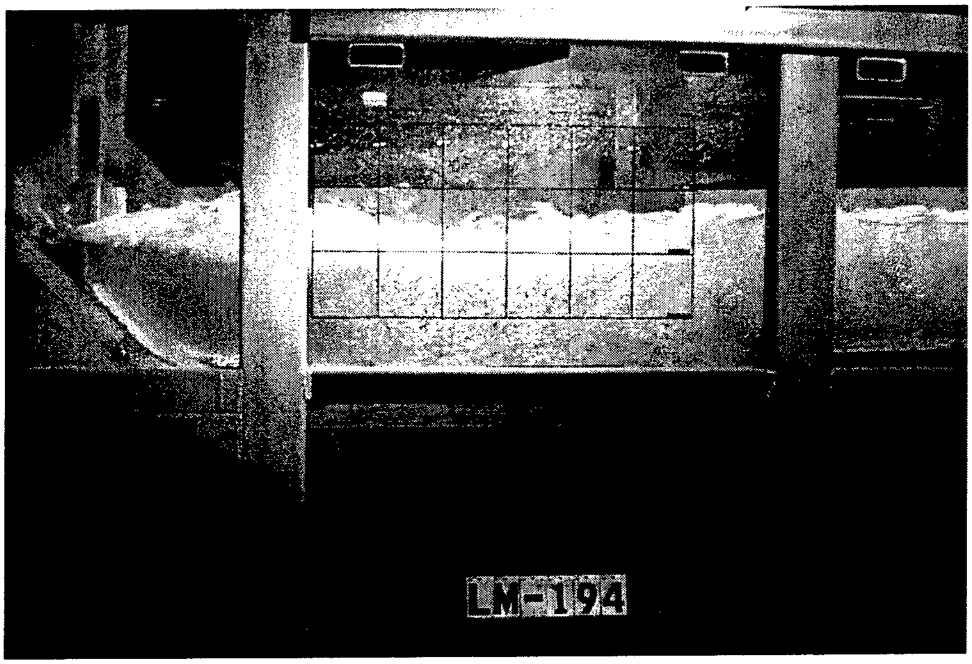


Figure C18. Type II deflector. Skimming surface jet. Gate opening – 6 ft, discharge – 10.2 kcfs/bay, pool elevation – 537, tailwater elevation – 448

Figure C19. Type II deflector. Surface jump. Gate opening – 6 ft, discharge – 10.2 kcfs/bay, pool elevation – 537, tailwater elevation – 452

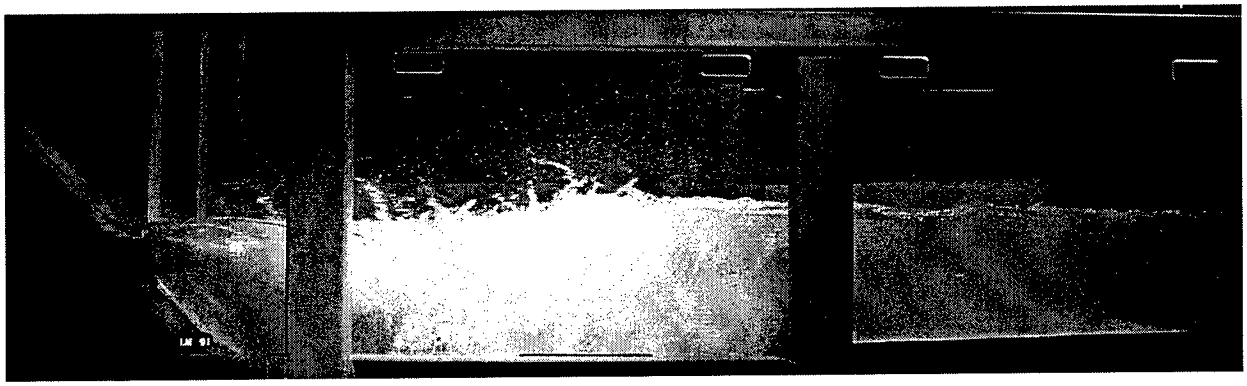


Figure C20. Type II deflector. Plunging jet. Gate opening – 8 ft, discharge – 13.8 kcfs/bay, pool elevation – 537, tailwater elevation – 451

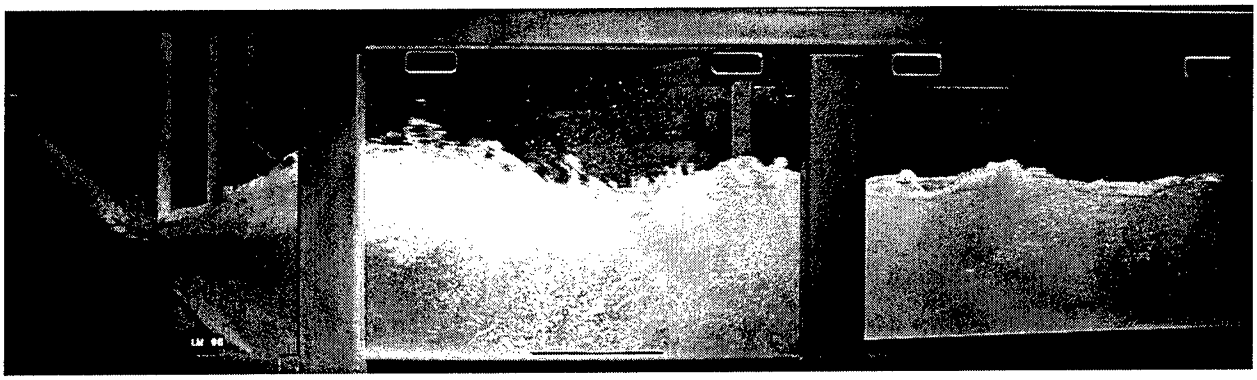


Figure C21. Type II deflector. Ramped surface jet. Gate opening – 8 ft, discharge – 13.8 kcfs/bay, pool elevation – 537, tailwater elevation – 461

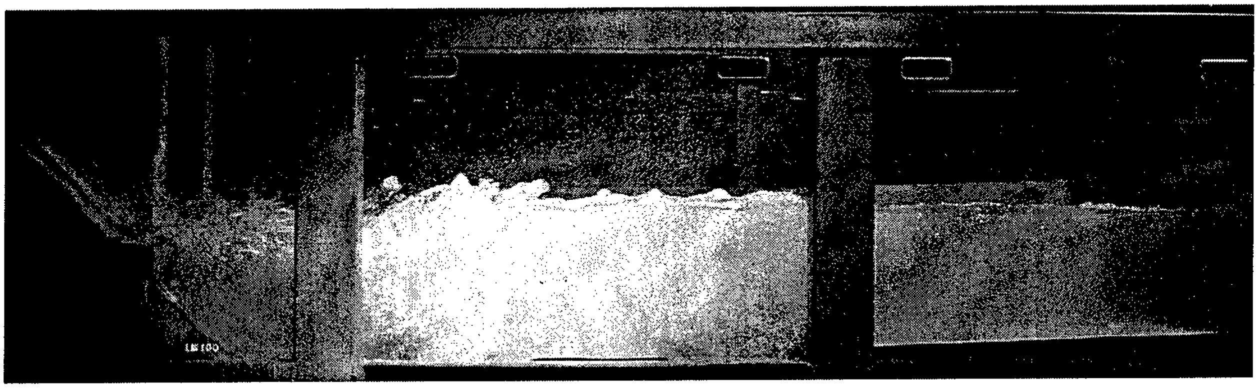


Figure C22. Type II deflector. Plunging jet. Gate opening – 10 ft, discharge – 18.2 kcfs/bay, pool elevation – 537, tailwater elevation – 453

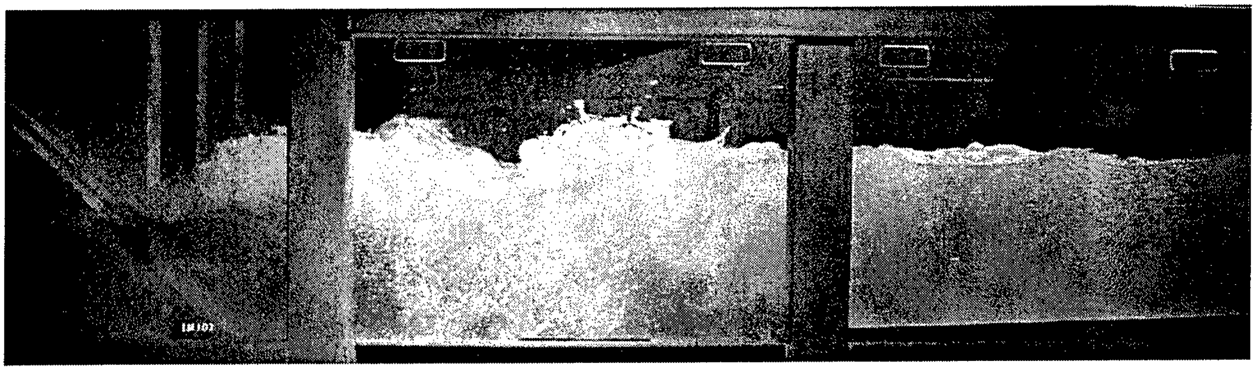


Figure C23. Type II deflector. Surface jump. Gate opening – 10 ft, discharge – 18.2 kcfs/bay, pool elevation – 537, tailwater elevation – 467

Appendix D
Model Observations

Table D1
Type I Deflector at El 434.0

Gate Opening, ft	Discharge/Bay Prototype, kcfs	Headwater, ft	Tailwater, ft	Classification
2	4.2	537	435.0	1
2	4.2	537	437.0	3
2	4.2	537	439.0	3
2	4.2	537	441.0	3
2	4.2	537	443.0	4
2	4.2	537	445.0	4
2	4.2	537	447.0	6
2	4.2	537	449.0	7
4	6.7	537	438.0	1
4	6.7	537	440.0	1
4	6.7	537	442.0	2
4	6.7	537	444.0	3
4	6.7	537	446.0	3
4	6.7	537	448.0	4
4	6.7	537	450.0	5
6	10.2	537	440.0	1
6	10.2	537	443.5	1
6	10.2	537	444.0	2
6	10.2	537	446.0	3
6	10.2	537	448.0	3
6	10.2	537	450.0	3
8	13.8	537	442.0	1
8	13.8	537	444.0	1
8	13.8	537	446.0	1
8	13.8	537	448.0	1
8	13.8	537	450.0	2
8	13.8	537	452.0	4
8	13.8	537	454.0	5
8	13.8	537	456.0	5
8	13.8	537	458.0	6
8	13.8	537	460.0	7
10	18.2	537	447.0	1
10	18.2	537	449.0	1
10	18.2	537	451.0	1
10	18.2	537	453.0	1
10	18.2	537	455.0	4
10	18.2	537	457.0	4
10	18.2	537	459.0	5
10	18.2	537	461.0	5
10	18.2	537	463.0	6
10	18.2	537	465.0	7

Table D2
Type II Deflector at El 434.0

Gate Opening, ft	Discharge/Bay Prototype, kcfs	Headwater, ft	Tailwater, ft	Classification
1	1.8	537	434	1
1	1.8	537	436	3
1	1.8	537	438	4
1	1.8	537	440	5
1	1.8	537	442	6
1	1.8	537	444	7
2	4.2	537	435	2
2	4.2	537	437	3
2	4.2	537	439	3
2	4.2	537	441	4
2	4.2	537	443	5
2	4.2	537	445	6
2	4.2	537	447	7
3	5.6	537	437	1
3	5.6	537	439	3
3	5.6	537	441	3
3	5.6	537	443	1
3	5.6	537	443	4
3	5.6	537	445	3
3	5.6	537	445	5
3	5.6	537	447	3
3	5.6	537	447	6
3	5.6	537	449	4
3	5.6	537	449	7
3	5.6	537	451	5
3	5.6	537	453	5
3	5.6	537	455	6
3	5.6	537	457	7
4	6.7	537	439	1
4	6.7	537	440	2
4	6.7	537	442	3
4	6.7	537	442	2
4	6.7	537	444	4
4	6.7	537	446	2
4	6.7	537	446	5
4	6.7	537	448	3
4	6.7	537	448	5
4	6.7	537	450	4
4	6.7	537	450	6

(Sheet 1 of 4)

Table D2 (Continued)

Gate Opening, ft	Discharge/Bay Prototype, kcfs	Headwater, ft	Tailwater, ft	Classification
4	6.7	537	452	5
4	6.7	537	452	7
4	6.7	537	454	5
5	8.5	537	440	1
5	8.5	537	442	1
5	8.5	537	444	2
5	8.5	537	446	2
5	8.5	537	446	3
5	8.5	537	448	2
5	8.5	537	448	4
5	8.5	537	450	3
5	8.5	537	450	5
5	8.5	537	452	3
5	8.5	537	452	6
5	8.5	537	454	3
5	8.5	537	454	7
5	8.5	537	456	5
5	8.5	537	458	5
5	8.5	537	460	6
5	8.5	537	462	7
6	10.2	537	442	1
6	10.2	537	444	2
6	10.2	537	446	3
6	10.2	537	448	3
6	10.2	537	450	4
6	10.2	537	450	4
6	10.2	537	451	5
6	10.2	537	452	4
6	10.2	537	452	6
6	10.2	537	454	7
7	12.0	537	442	1
7	12.0	537	444	1
7	12.0	537	446	1
7	12.0	537	448	1
7	12.0	537	450	4
7	12.0	537	452	5
7	12.0	537	454	6
7	12.0	537	456	7
8	13.8	537	445	1
8	13.8	537	447	1

(Sheet 2 of 4)

Table D2 (Continued)

Gate Opening, ft	Discharge/Bay Prototype, kcfs	Headwater, ft	Tailwater, ft	Classification
8	13.8	537	447	1
8	13.8	537	449	1
8	13.8	537	449	2
8	13.8	537	451	1
8	13.8	537	451	2
8	13.8	537	453	2
8	13.8	537	453	4
8	13.8	537	455	2
8	13.8	537	455	4
8	13.8	537	457	4
8	13.8	537	457	5
8	13.8	537	459	5
8	13.8	537	459	5
8	13.8	537	461	5
8	13.8	537	461	6
8	13.8	537	463	7
8	13.8	537	463	7
8	13.8	537	465	7
10	18.2	537	451	1
10	18.2	537	453	1
10	18.2	537	455	2
10	18.2	537	457	2
10	18.2	537	459	4
10	18.2	537	461	5
10	18.2	537	463	5
10	18.2	537	465	5
10	18.2	537	467	6
10	18.2	537	469	7
12	21.9	537	450	1
12	21.9	537	452	1
12	21.9	537	452	1
12	21.9	537	454	1
12	21.9	537	454	1
12	21.9	537	456	1
12	21.9	537	456	1
12	21.9	537	458	1
12	21.9	537	458	2
12	21.9	537	460	4
12	21.9	537	460	4
12	21.9	537	462	4

(Sheet 3 of 4)

Table D2 (Concluded)

Gate Opening, ft	Discharge/Bay Prototype, kcfs	Headwater, ft	Tailwater, ft	Classification
12	21.9	537	462	5
12	21.9	537	464	5
12	21.9	537	464	5
12	21.9	537	466	5
12	21.9	537	466	5
12	21.9	537	467	5
12	21.9	537	468	5
12	21.9	537	470	6
12	21.9	537	472	7

(Sheet 4 of 4)

Appendix E
Pressure Measurements

Table E1
Pressure Measurements

Gate Opening ft	Discharge/ Bay Prototype kcfs	Headwater ft	Tailwater ft	Pressure 1	Pressure 2	Pressure 3	Pressure 4	Pressure 5	Pressure 6	Pressure 7
2	4.24	537	435.0	430.5	N/A	430.0	430.5	431.0	432.8	432.0
2	4.24	537	437.0	440.5	N/A	440.2	440.2	440.0	444.2	441.0
2	4.24	537	439.0	445.5	N/A	445.0	444.7	444.6	450.3	446.5
2	4.24	537	441.0	428.5	428.5	430.5	434.0	438.0	453.0	440.0
2	4.24	537	443.0	430.0	N/A	429.2	429.4	430.7	435.0	433.5
2	4.24	537	445.0	429.0	N/A	428.0	430.5	433.0	440.0	437.5
2	4.24	537	447.0	446.5	447.2	446.7	446.1	447.2	448.8	449.1
2	4.24	537	449.0	439.0	N/A	437.5	439.0	440.5	443.5	444.0
4	7.77	537	438.0	433.2	N/A	432.0	432.0	434.6	441.0	440.0
4	7.42	537	440.0	434.0	N/A	432.5	433.0	435.0	441.0	439.0
4	7.42	537	442.0	440.2	440.0	439.8	439.8	440.2	441.0	441.6
4	7.77	537	444.0	432.0	431.0	431.5	435.0	440.0	446.0	442.0
4	7.77	537	446.0	433.8	433.0	432.5	433.0	435.5	439.0	441.8
4	7.42	537	448.0	443.8	443.5	443.0	442.8	443.2	445.0	445.5
4	7.77	537	450.0	455.0	N/A	455.5	457.0	460.0	461.0	460.0
6	11.31	537	440.0	436.0	N/A	435.0	435.7	435.0	441.0	439.0
6	11.66	537	443.5	438.5	437.5	437.5	437.5	438.0	439.5	441.5
6	11.31	537	444.0	455.5	455.2	454.5	455.5	455.5	457.5	457.5
6	11.31	537	446.0	442.5	N/A	442.2	442.2	442.3	447.5	443.2
6	11.31	537	448.0	445.1	N/A	445.0	445.2	445.3	450.0	446.0

(Continued)

Table E1 (Concluded)

Gate Opening ft	Discharge/ Bay Prototype kcfs	Headwater ft	Tailwater ft	Pressure 1	Pressure 2	Pressure 3	Pressure 4	Pressure 5	Pressure 6	Pressure 7
6	11.31	537	450.0	447.6	N/A	447.5	447.5	447.8	448.5	443.5
8	15.19	537	442.0	435.5	435.5	433.5	434.5	435.5	440.0	442.5
8	15.19	537	444.0	441.5	N/A	441.0	441.0	441.0	444.0	446.0
8	15.19	537	446.0	451.0	N/A	451.3	451.5	455.5	455.5	456.0
8	15.19	537	448.0	433.0	N/A	432.5	432.5	433.0	435.0	433.5
8	15.19	537	450.0	437.3	N/A	437.0	437.3	437.0	432.0	437.4
8	15.19	537	452.0	431.5	N/A	436.0	435.0	440.5	445.5	446.5
8	15.19	537	454.0	432.2	N/A	431.5	431.3	432.5	436.4	435.0
8	15.19	537	456.0	434.5	N/A	433.8	433.6	433.5	437.5	435.7
8	15.19	537	458.0	450.0	449.8	449.3	449.7	450.1	451.3	451.8
8	15.19	537	460.0	448.0	N/A	447.5	447.5	448.5	450.0	452.0
10	19.08	537	447.0	435.2	N/A	435.0	435.0	434.8	437.5	435.5
10	19.08	537	449.0	437.5	N/A	442.1	442.0	442.2	447.0	442.6
10	19.08	537	451.0	438.5	N/A	438.0	438.0	438.0	442.0	440.0
10	19.08	537	453.0	440.0	N/A	440.0	439.0	439.0	444.0	441.0
10	19.08	537	455.0	435.0	N/A	435.0	436.0	439.0	433.0	446.0
10	19.08	537	457.0	445.0	N/A	443.5	443.5	444.0	445.0	448.0
10	19.08	537	459.0	436.7	N/A	436.6	436.3	436.2	440.3	437.6
10	19.08	537	461.0	439.6	N/A	439.2	439.0	438.8	443.3	439.5
10	19.08	537	463.0	437.0	N/A	435.0	446.0	438.0	441.5	445.0
10	19.08	537	465.0	456.0	N/A	454.0	460.0	463.0	464.0	470.0

Appendix F
Sizing of Model Debris

The threshold velocity for transport of the 1-ft-diam material in the prototype was computed with the Ishbosh relationship (USACE 1987).[1] The threshold velocity was scaled for the model using Froudian scaling criteria: $V_m = V_p\ (L_r^{1/2})$ where V_m and V_p are model and prototype velocities, respectively and L_r is the model-to-prototype scale $\left(\frac{1}{40}\right)$. This approach resulted in the following calculations:

Critical velocity for 1-ft-diam rock:

$$V_c\big|_p = 1.12\left[2g\left(\frac{\gamma_s - \gamma_w}{\gamma_w}\right)\right]^{1/2} D_{50}{}^{1/2}\big|_p \qquad \text{(F1)}$$

where $V_c\big|_p$ is the critical velocity for 1.0-ft rock movement; g is gravitational acceleration of 32.2 ft/sec^2; γ_s and γ_w are the specific weights of rock at 170 lb/ft^3 and water at 62.4 lb/ft^3; and $D_{50}\big|_p$ = 1.0 ft. Substituting these values into Equation F1 gives:

$$V_c\big|_p = 11.8 \text{ ft/sec}$$

We now adjust this full-scale critical velocity to model dimensions:

$$V_c\big|_m = V_c\big|_p L_r^{1/2} = V_c\big|_p \left(\frac{1}{40}\right)^{1/2} = 1.9 \text{ ft/sec}$$

Substituting $V_c\big|_m$ for $V_c\big|_p$ and $D_{50}\big|_m$ for $D_{50}\big|_p$ and solving for $D_{50}\big|_m$, we can compute the critical rock size in model dimensions with Equation F1:

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[1] All references cited in this appendix are listed in the References section at the end of the main text.

$$D_{50}\big|_m = 0.026 \text{ ft} = 0.31 \text{ in.}$$

Thus, a 3/8-in. rock size was selected for movement testing in the 1:40-scale section model.

Appendix G
Table of Experimental Conditions

Table G1
Experimental Conditions for Lower Monumental Stilling Basin Pressure Measurements

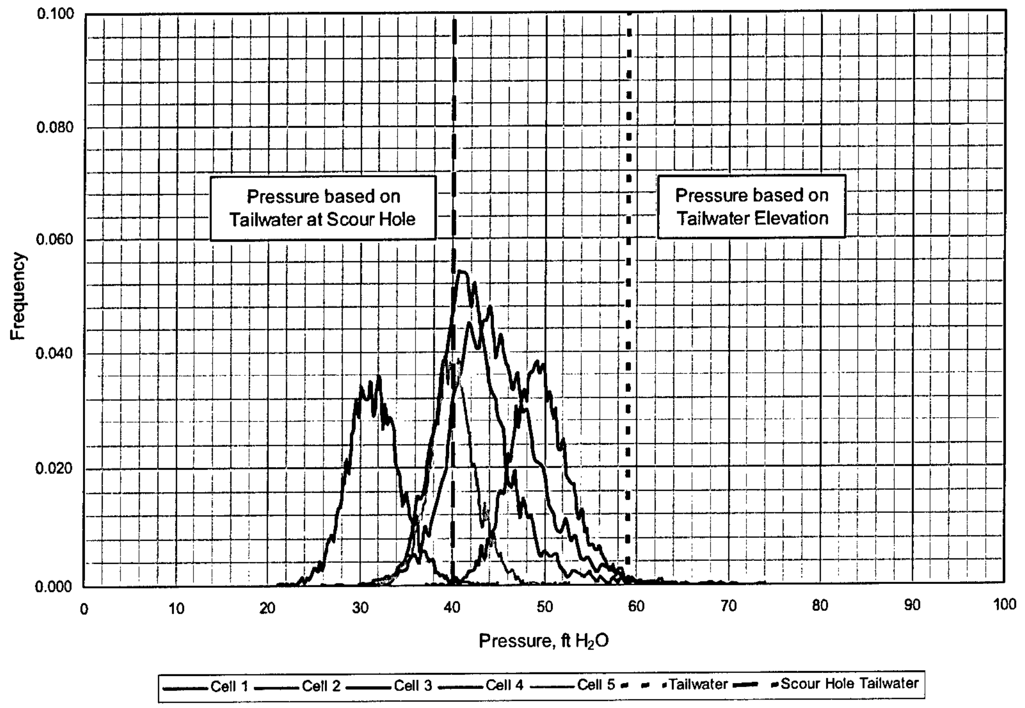
Discharge kcfs/bay	Gate Opening ft	Pool El	Tailwater El	Tailwater El at Fish Entrance	Comments
6.5	3.5	537.0	441.00	440.8	No Deflector on End Bay, Type 1 Scour Hole
6.5	3.5	537.0	441.00	440.8	No Deflector on End Bay, Type 1 Scour Hole
6.5	3.5	537.0	441.00	440.8	End Gate Closed, No Deflector on End Bay, Type 1 Scour Hole
6.5	3.5	537.0	441.00	440.8	End Gate Closed, No Deflector on End Bay, Type 1 Scour Hole
6.5	3.5	537.0	441.00	440.8	End Gate Closed, No Deflector on End Bay, 2000 Scour Hole
6.5	3.5	537.0	441.00	440.8	End Gate Closed, No Deflector on End Bay, 2000 Scour Hole
6.5	3.5	537.0	441.00	440.8	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
6.5	3.5	537.0	441.00	440.8	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
29.0	16.5	537.0	451.00	450.4	No Deflector on End Bay, Type 1 Scour Hole
29.0	16.5	537.0	451.00	450.4	No Deflector on End Bay, Type 1 Scour Hole
29.0	16.5	537.0	451.00	440.8	End Gate Closed, No Deflector on End Bay, Type 1 Scour Hole
29.0	16.5	537.0	451.00	440.8	End Gate Closed, No Deflector on End Bay, Type 1 Scour Hole
29.0	16.5	537.0	451.00	448.0	No Deflector on End Bay, 2000 Scour Hole
29.0	16.5	537.0	451.00	448.0	No Deflector on End Bay, 2000 Scour Hole
29.0	16.5	537.0	451.00	448.0	End Gate Closed, No Deflector on End Bay, 2000 Scour Hole
29.0	16.5	537.0	451.00	448.0	End Gate Closed, No Deflector on End Bay, 2000 Scour Hole
29.0	16.5	537.0	451.00	448.0	End Gate Closed, No Deflector on End Bay, 2000 Scour Hole
29.0	16.5	537.0	451.06	451.0	No Deflector on End Bay, Type 1 Scour Hole
29.0	16.5	537.0	451.06	451.0	No Deflector on End Bay, Type 1 Scour Hole
29.0	16.5	537.0	454.00	451.0	End Gate Closed, No Deflector on End Bay, Type 1 Scour Hole
29.0	16.5	537.0	454.00	451.0	End Gate Closed, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	459.00	N/A	Unable to Measure TW at Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	459.00	N/A	Unable to Measure TW at Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	447.00	N/A	Unable to Measure TW at the Fish Entrance, Aerated Nappe, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	447.00	N/A	Unable to Measure TW at the Fish Entrance, Aerated Nappe, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole

(Continued)

Table G1 (Concluded)

Discharge, kcfs/bay	Gate Opening, ft	Pool El	Tailwater El	Tailwater El at Fish Entrance	Comments
34.0	20.0	540.0	451.00	N/A	Unable to Measure TW at Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	451.00	N/A	Unable to Measure TW at Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	455.00	N/A	Unable to Measure TW at Fish Entrance, Unstable Plunge, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	455.00	N/A	Unable to Measure TW at Fish Entrance, Unstable Plunge, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	463.00	N/A	Unable to Measure TW at Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	463.00	N/A	Unable to Measure TW at Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	468.00	N/A	Unable to Measure TW at the Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
34.0	20.0	540.0	468.00	N/A	Unable to Measure TW at the Fish Entrance, All Gates Open, No Deflector on End Bay, Type 1 Scour Hole
50.0	23.0	539.0	457.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
50.0	23.0	539.0	457.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
50.0	23.0	539.0	462.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
50.0	23.0	539.0	462.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
50.0	23.0	539.0	465.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
50.0	23.0	539.0	465.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	540.0	461.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	540.0	461.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	450.0	466.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	450.0	466.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	450.0	466.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	540.0	456.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	540.0	456.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	540.0	466.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole
84.0	Full	540.0	466.00	N/A	End Gate Opened, No Deflector on End Bay, 2000 Scour Hole

Appendix H
Stilling Basin Pressure Frequency Distributions and Cumulative Frequency Distributions



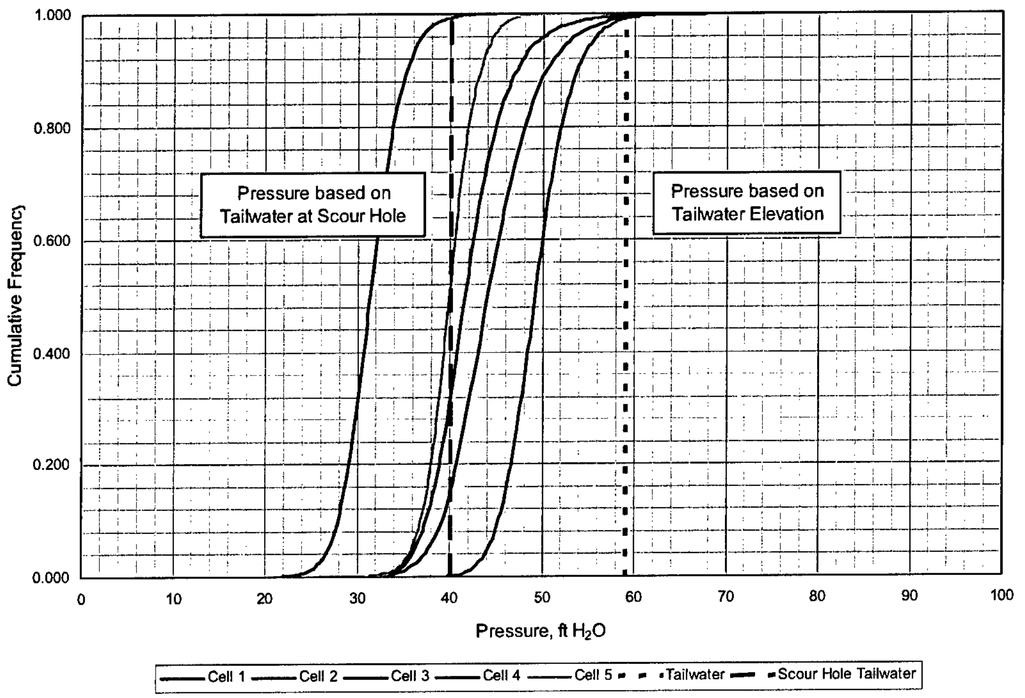


Figure H1. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, no deflector on end bay, center line bay 2

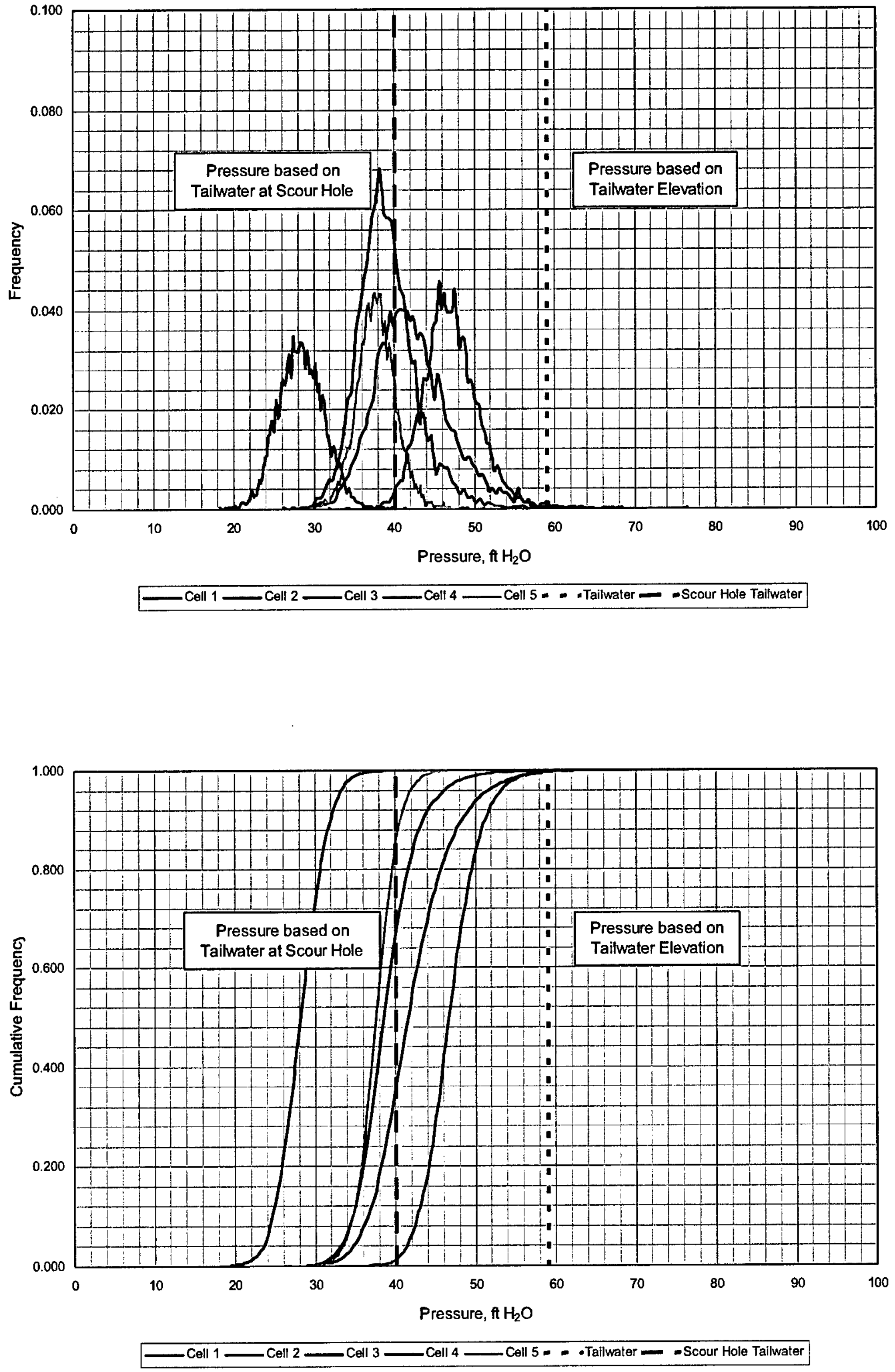
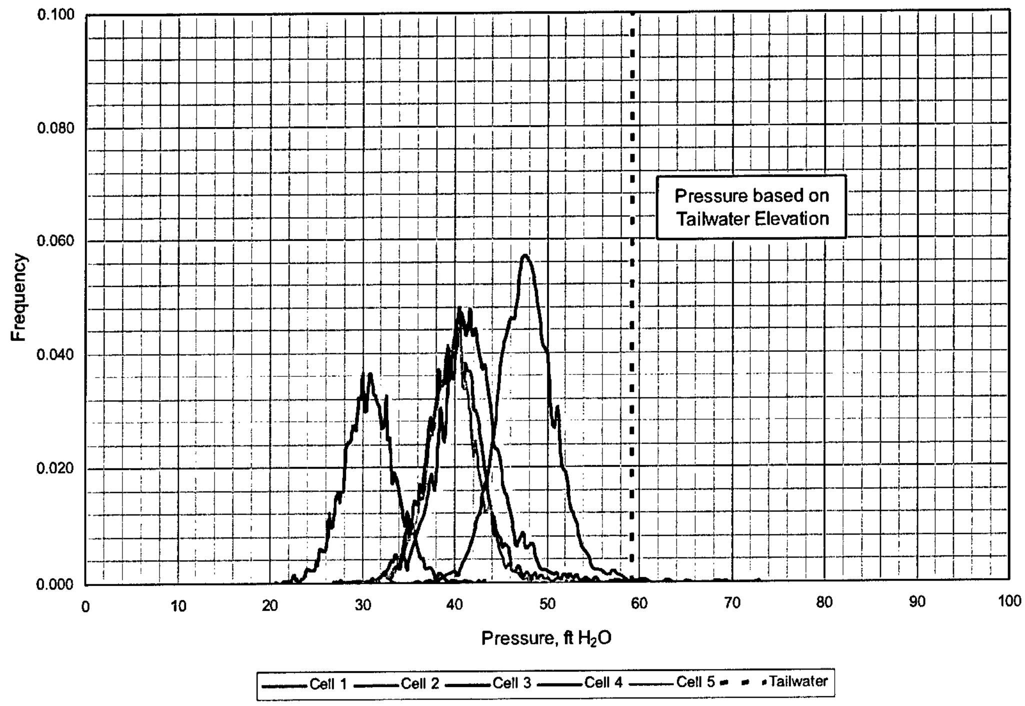


Figure H2. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, TW el at fish entrance = 450.4, no deflector on end bay, center line bay 2



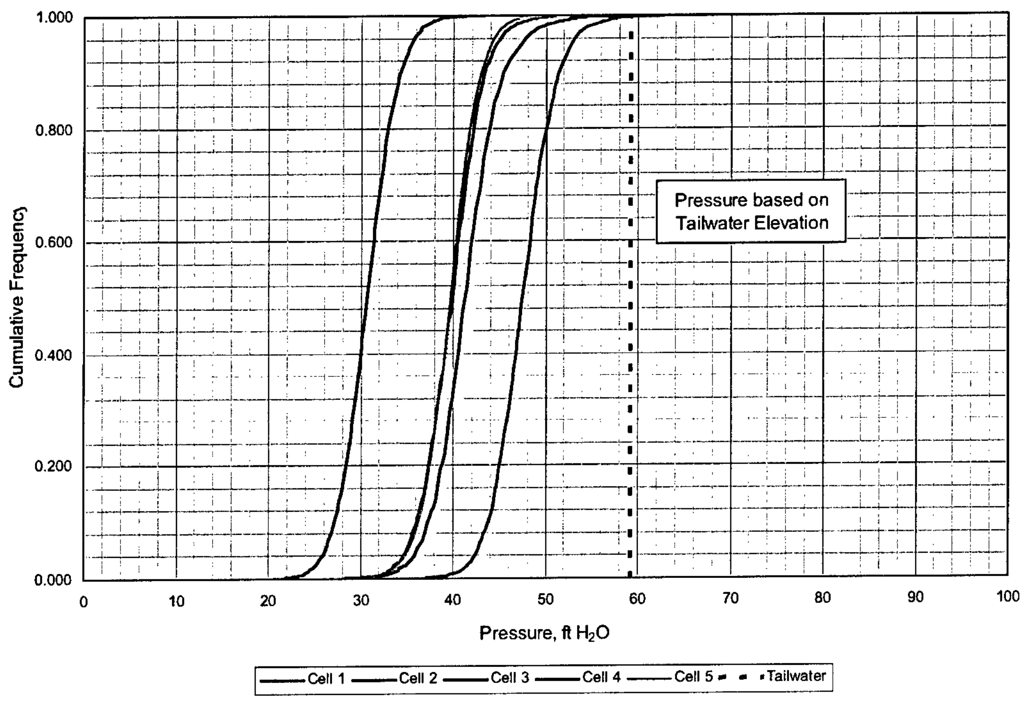
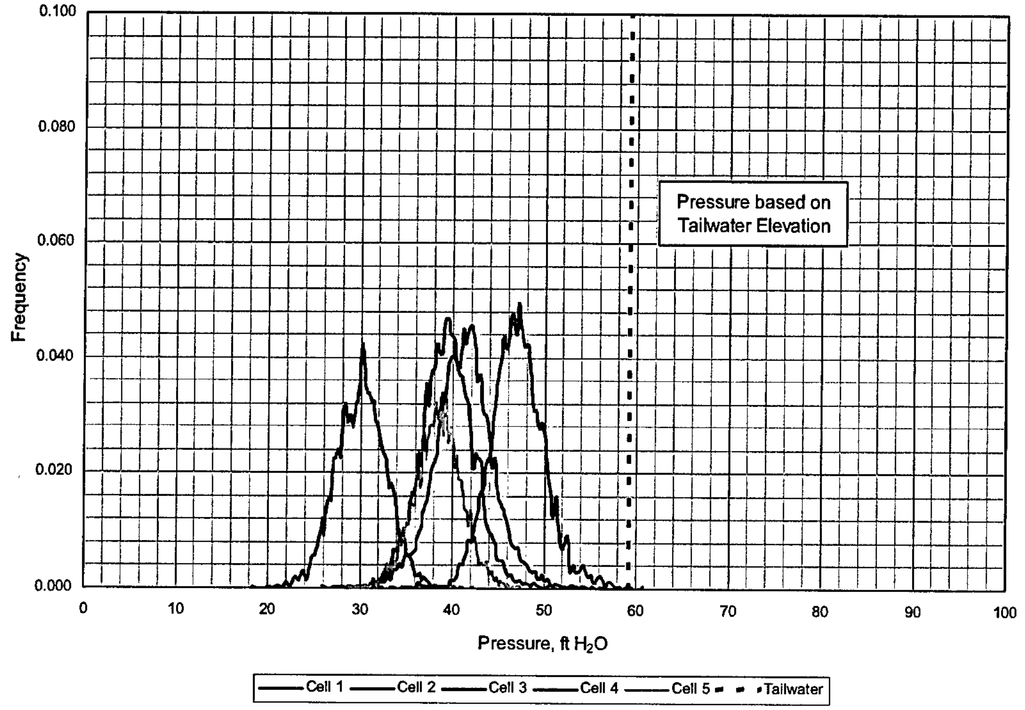


Figure H3. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.06, TW at fish entrance = 451.0, no deflector on end bay, center line bay 2



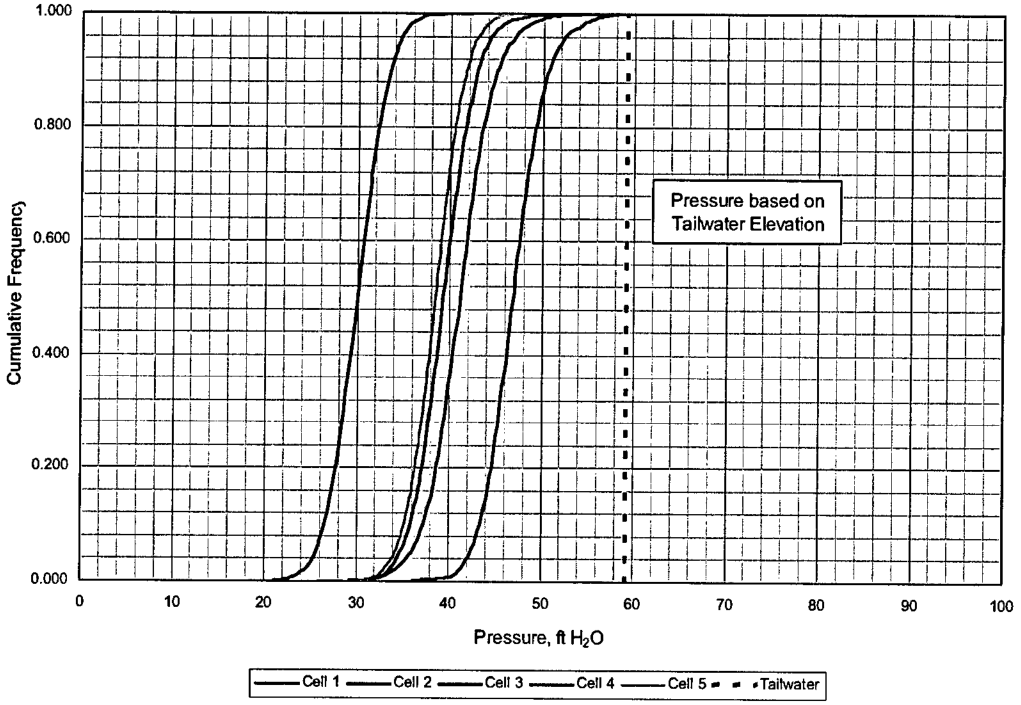
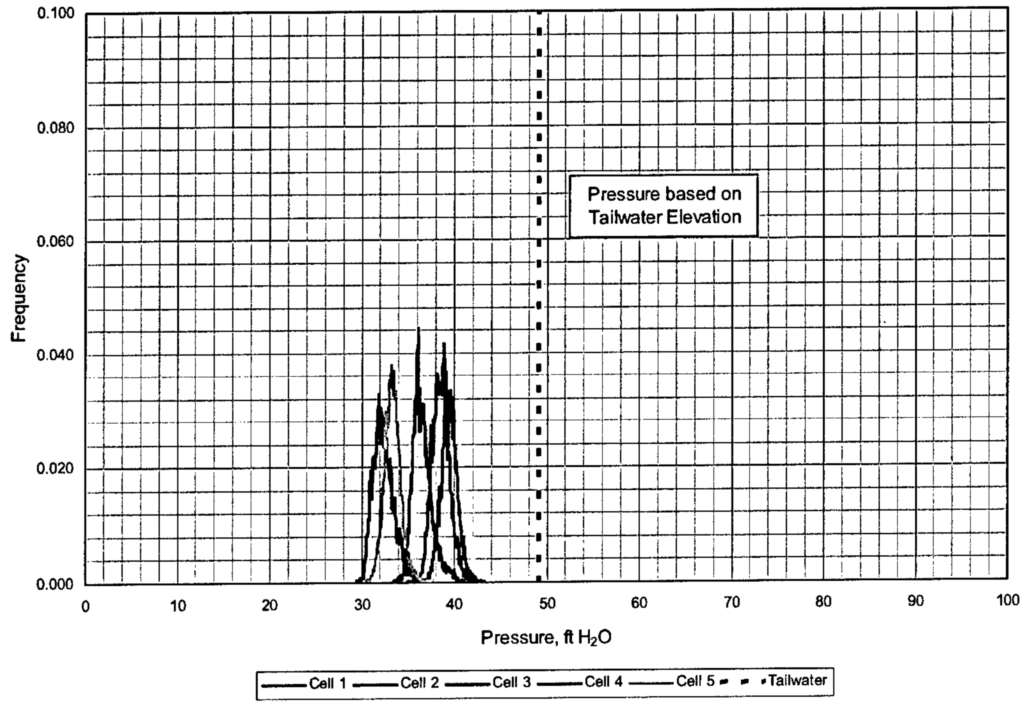


Figure H4. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.06, TW at fish entrance = 451.0, no deflector on end bay, center line bay 2



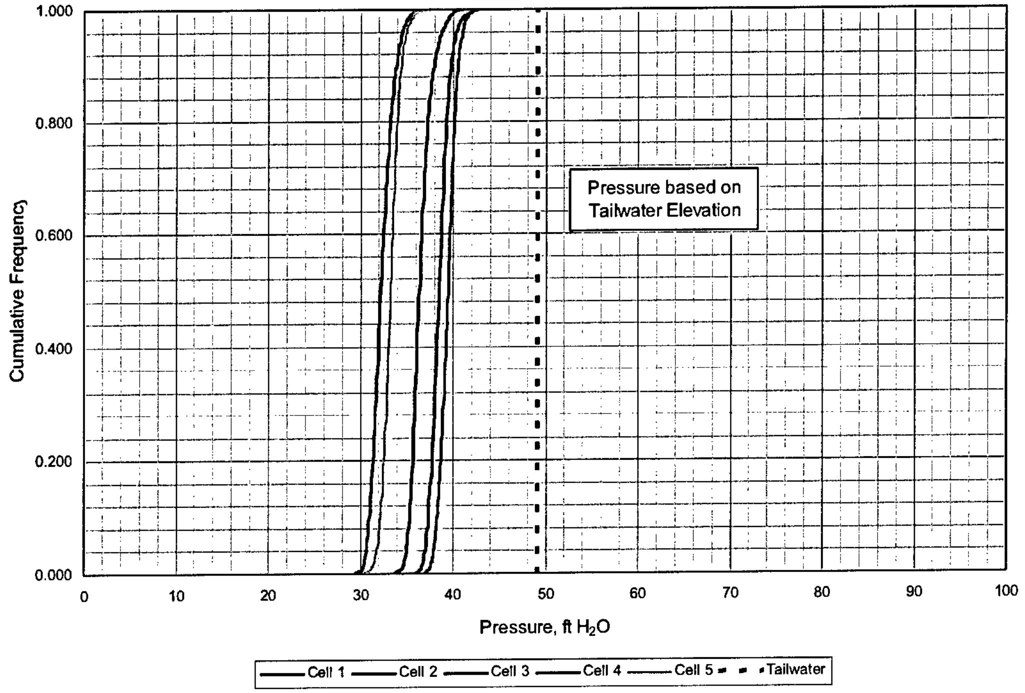


Figure H5. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, no deflector on end bay, center line bay 2

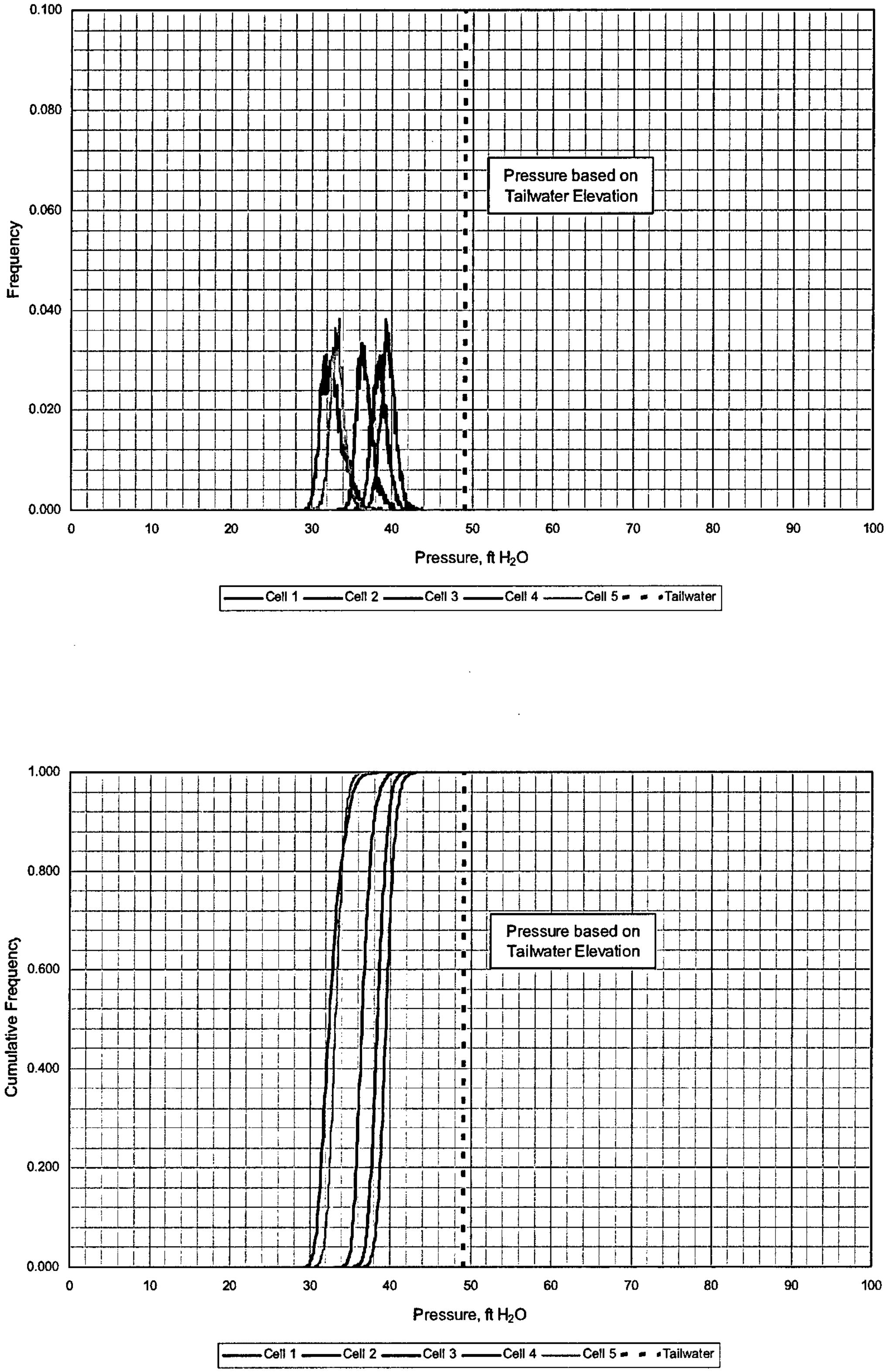
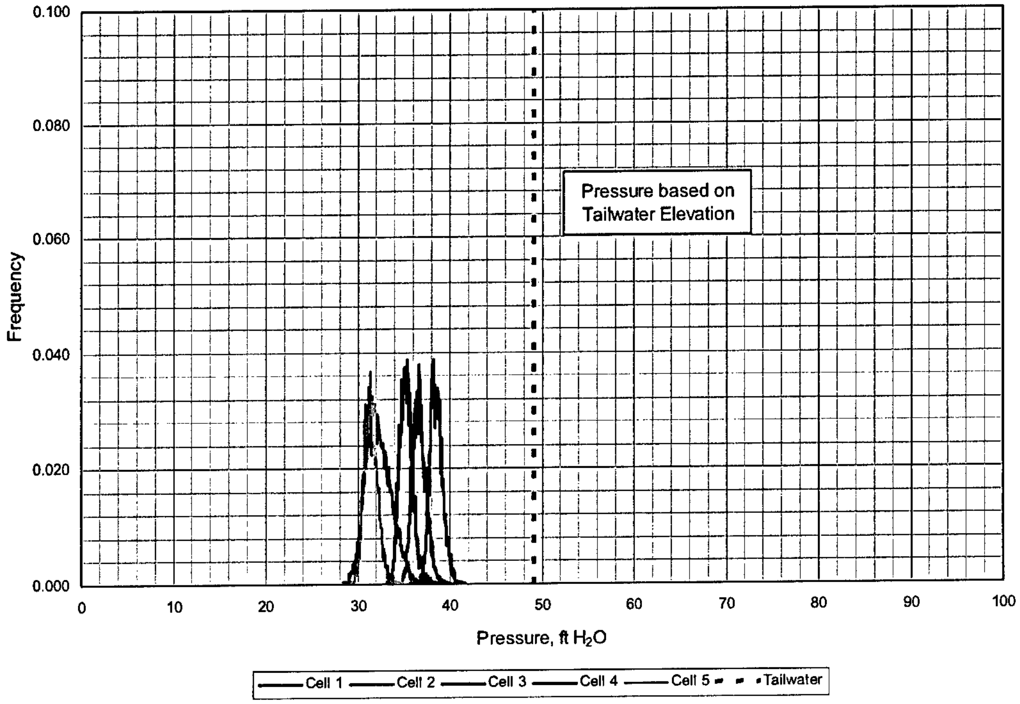


Figure H6. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, no deflector on end bay, center line bay 2



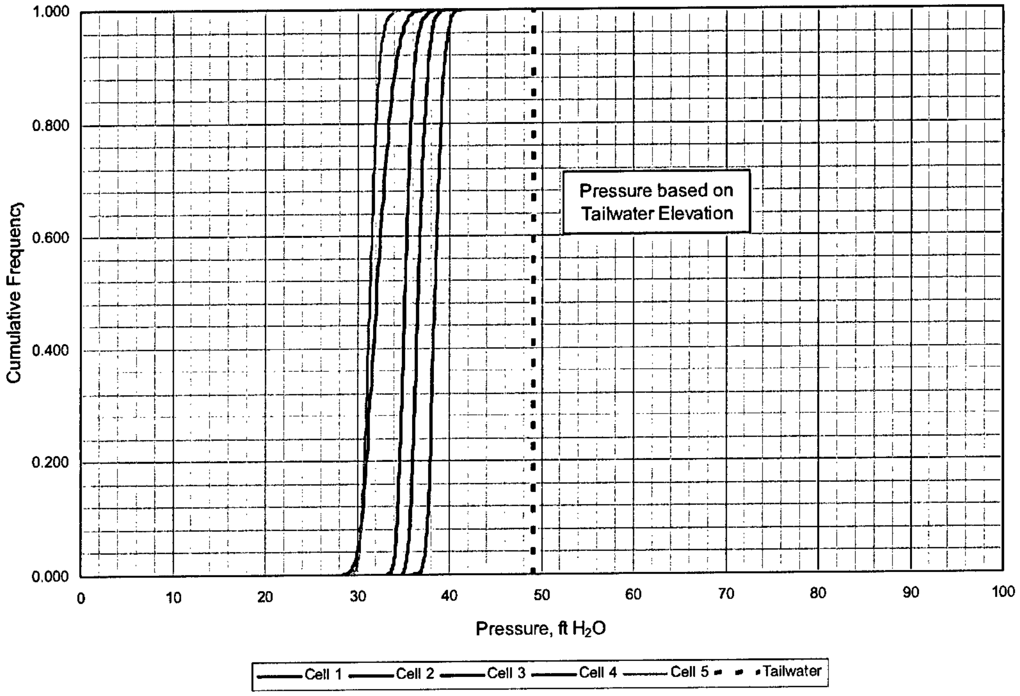
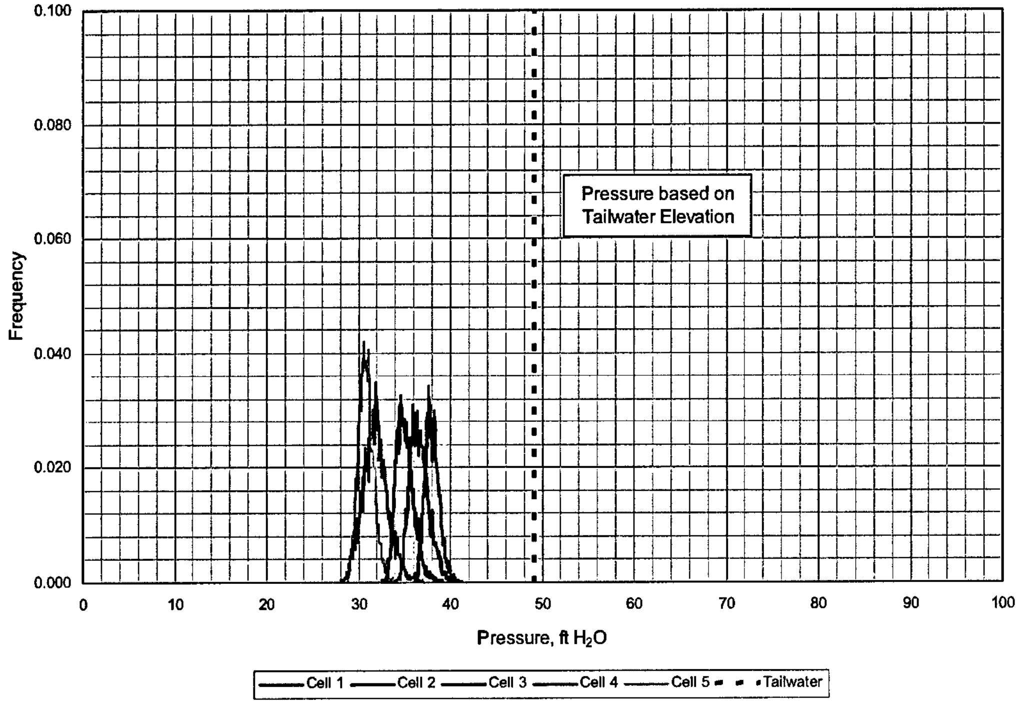


Figure H7. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, end gate closed, no deflector on end bay, center line bay 2



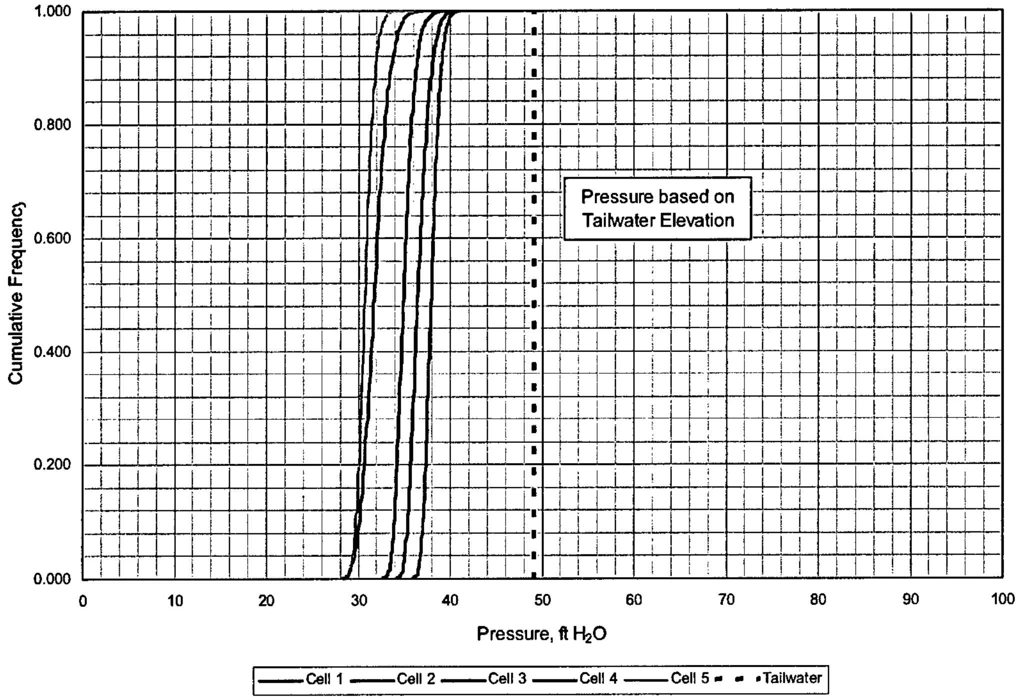
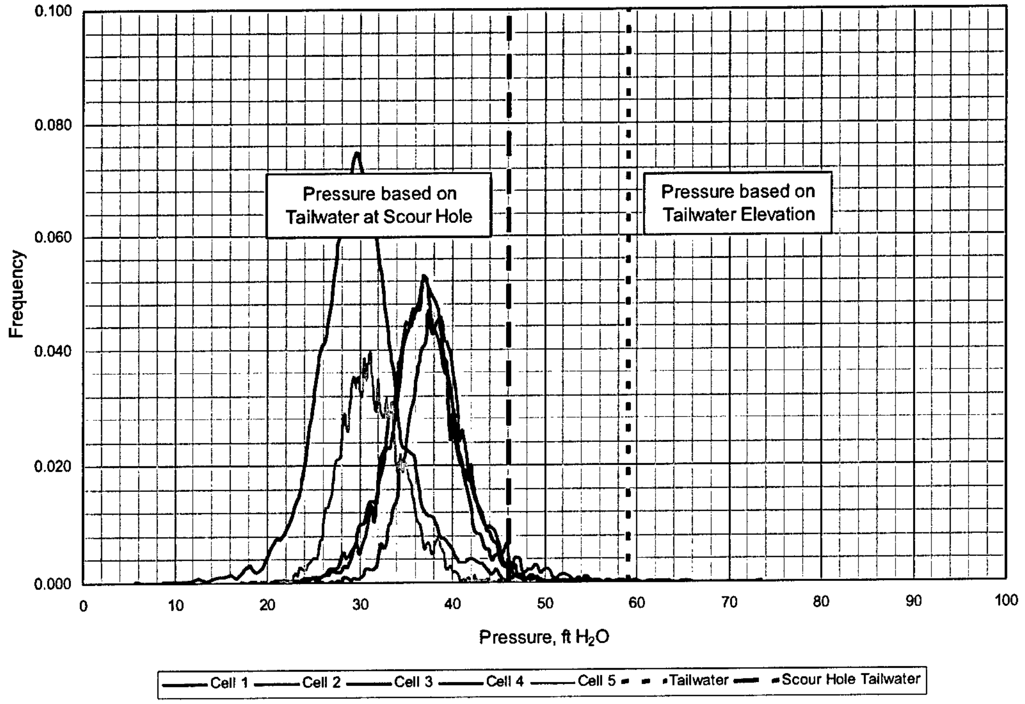


Figure H8. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, end gate closed, no deflector on end bay, center line bay 2



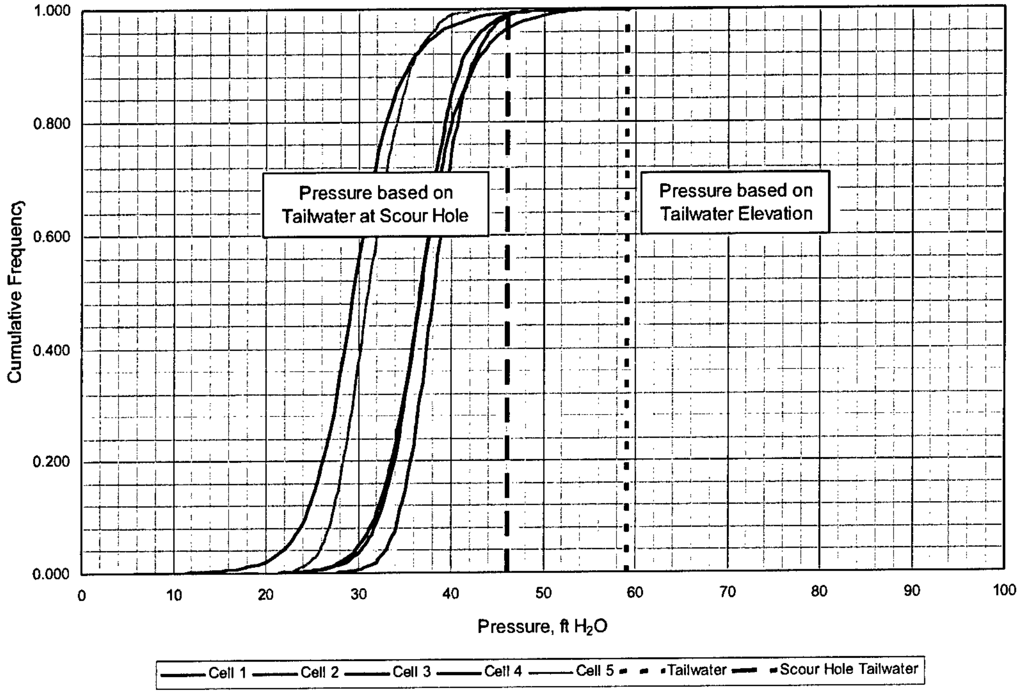


Figure H9. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, TW at fish entrance = 448.0, end gate closed, no deflector on end bay, center line bay 2

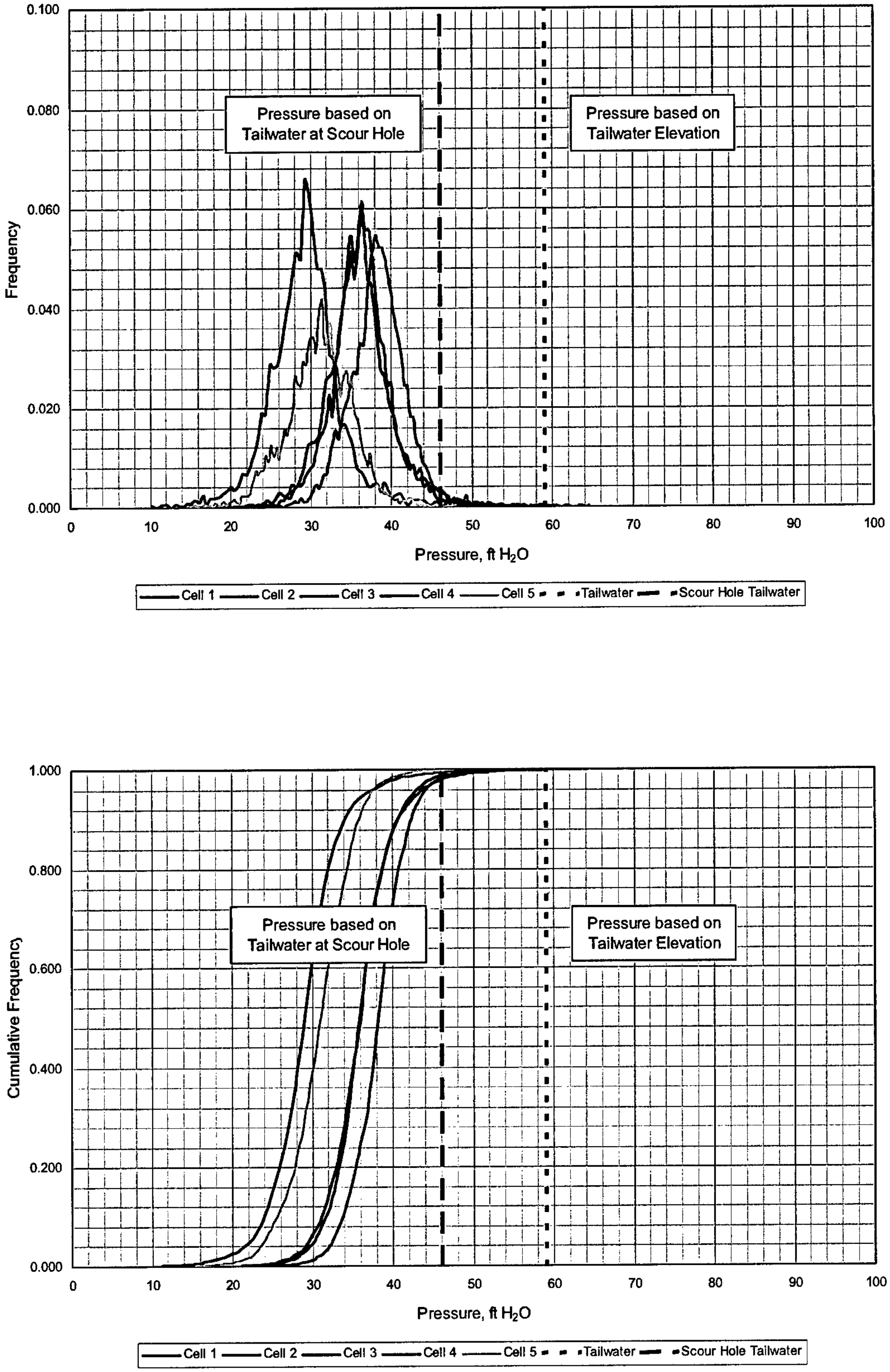


Figure H10. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, TW at fish entrance = 448.0, end gate closed, no deflector on end bay, center line bay 2

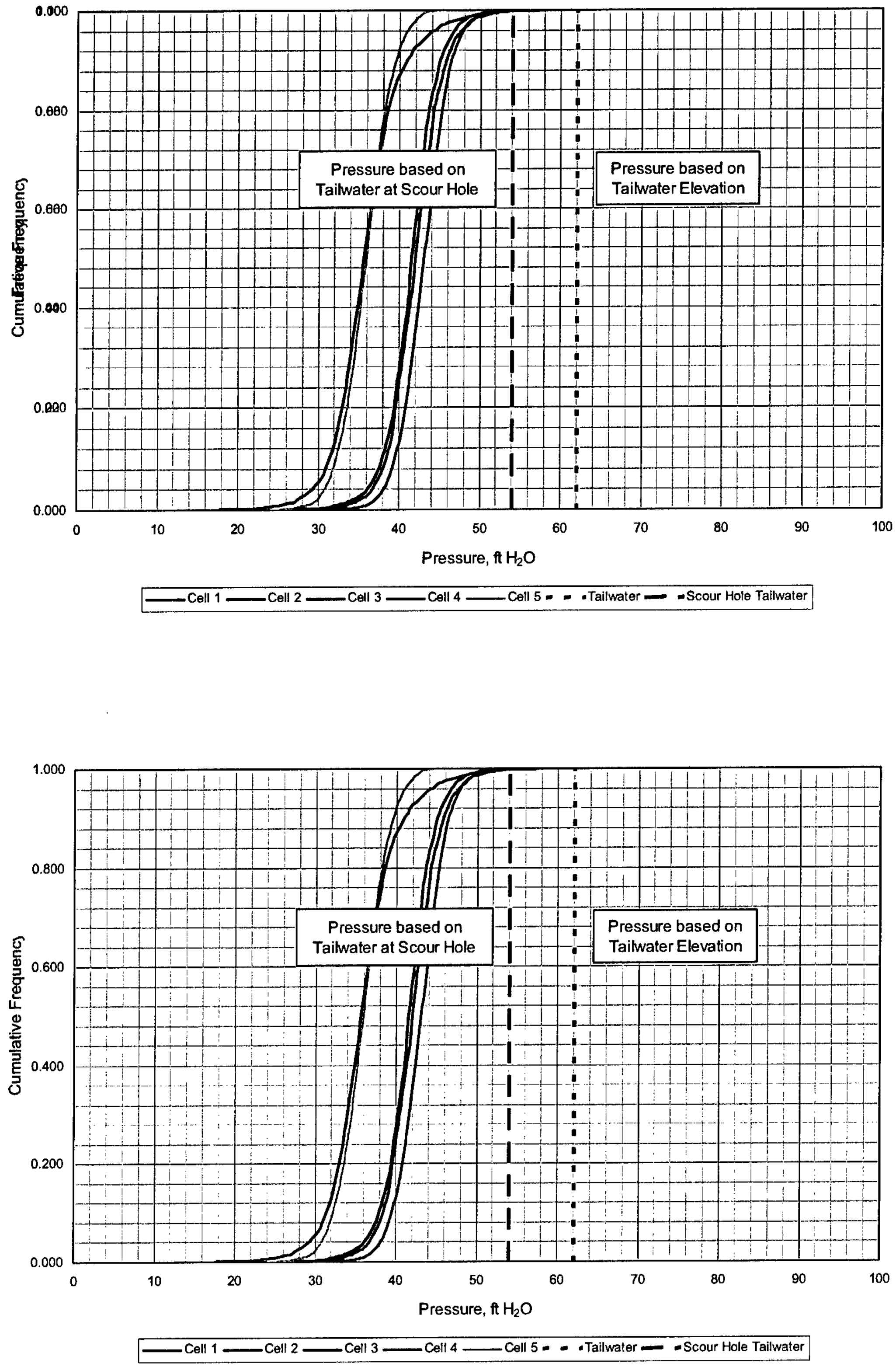
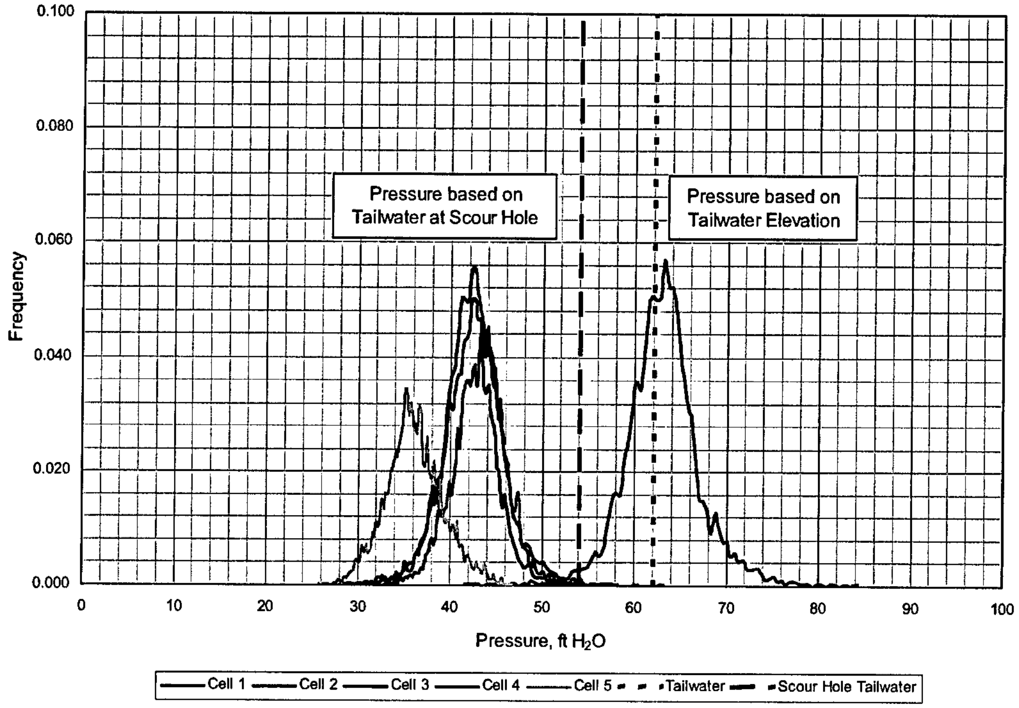


Figure H11. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 454.0, TW at fish entrance = 451.0, end gate closed, no deflector on end bay, center line bay 2



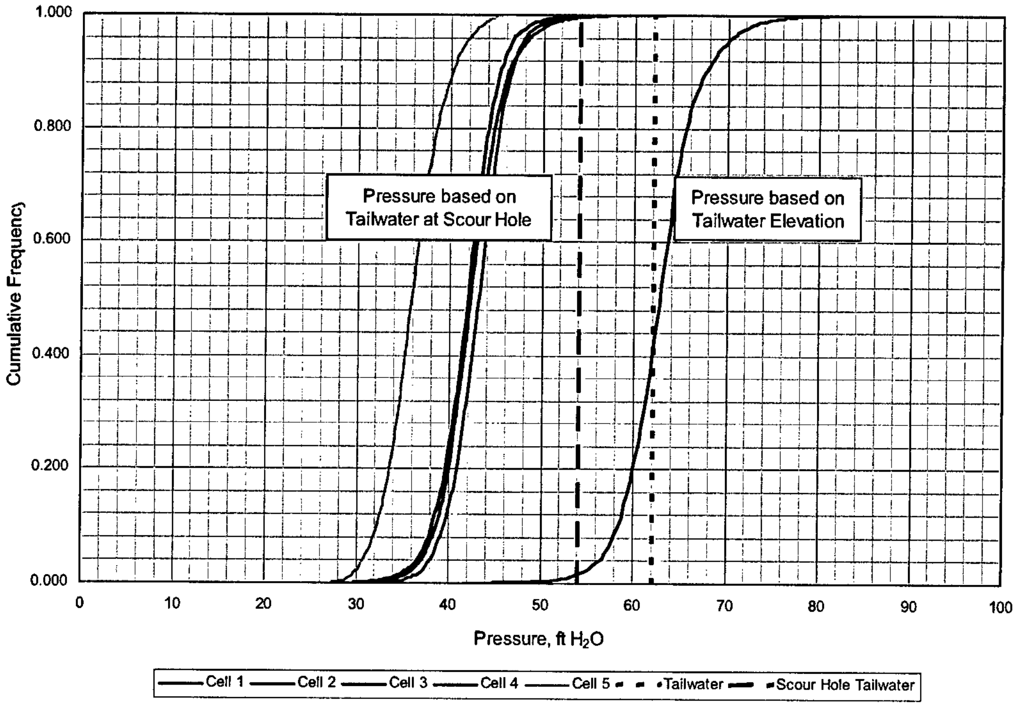
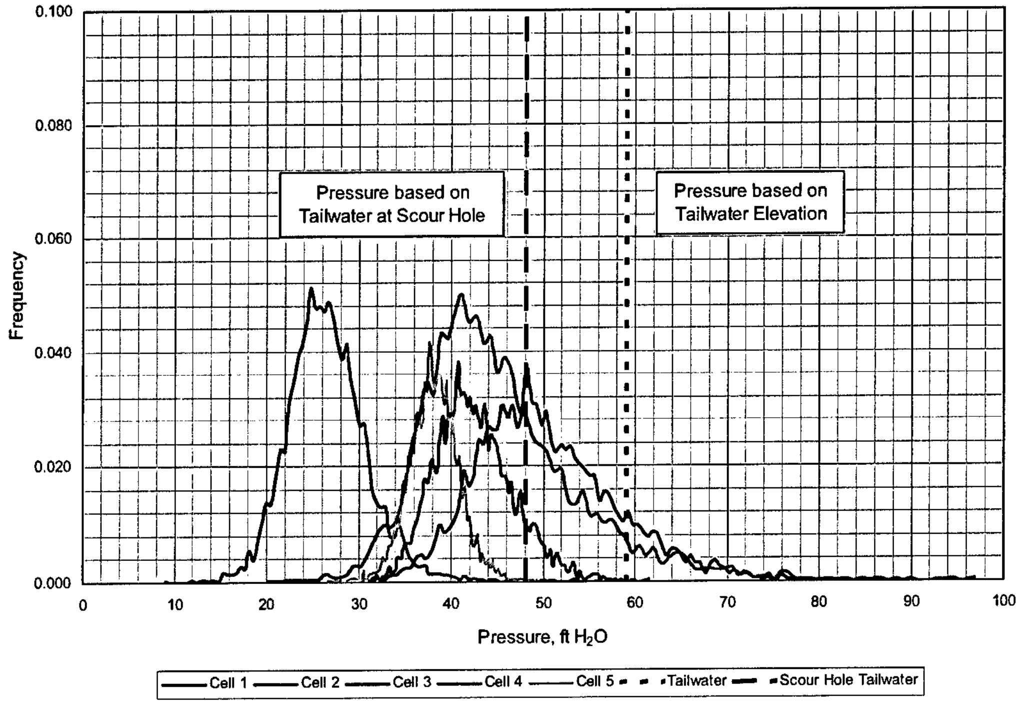


Figure H12. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 454.0, TW at fish entrance = 451.0, end gate closed, no deflector on end bay, center line bay 2



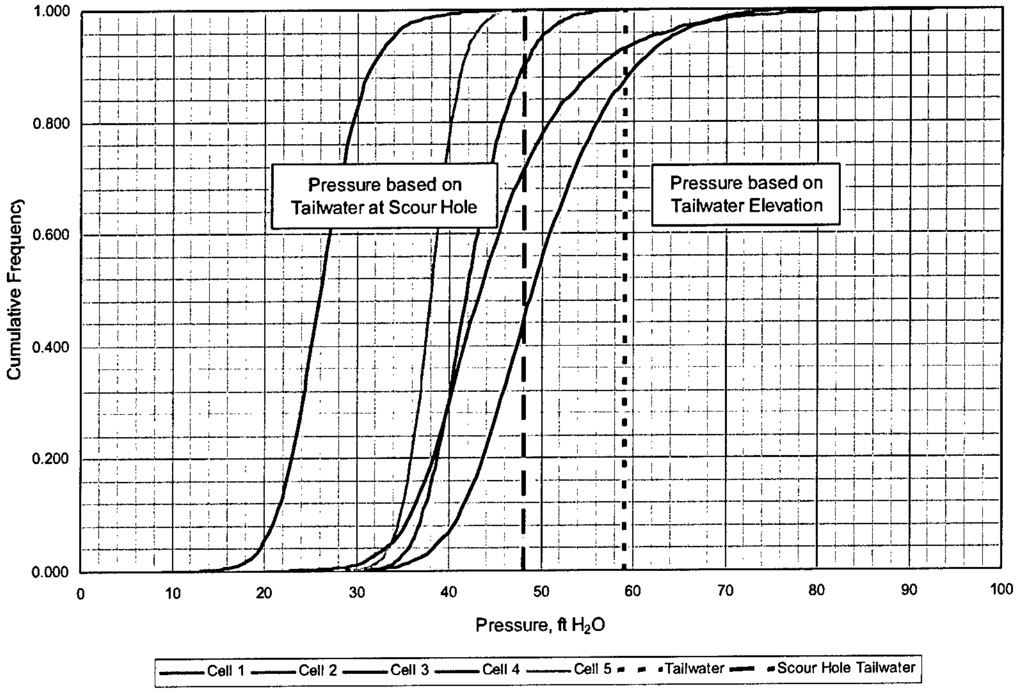
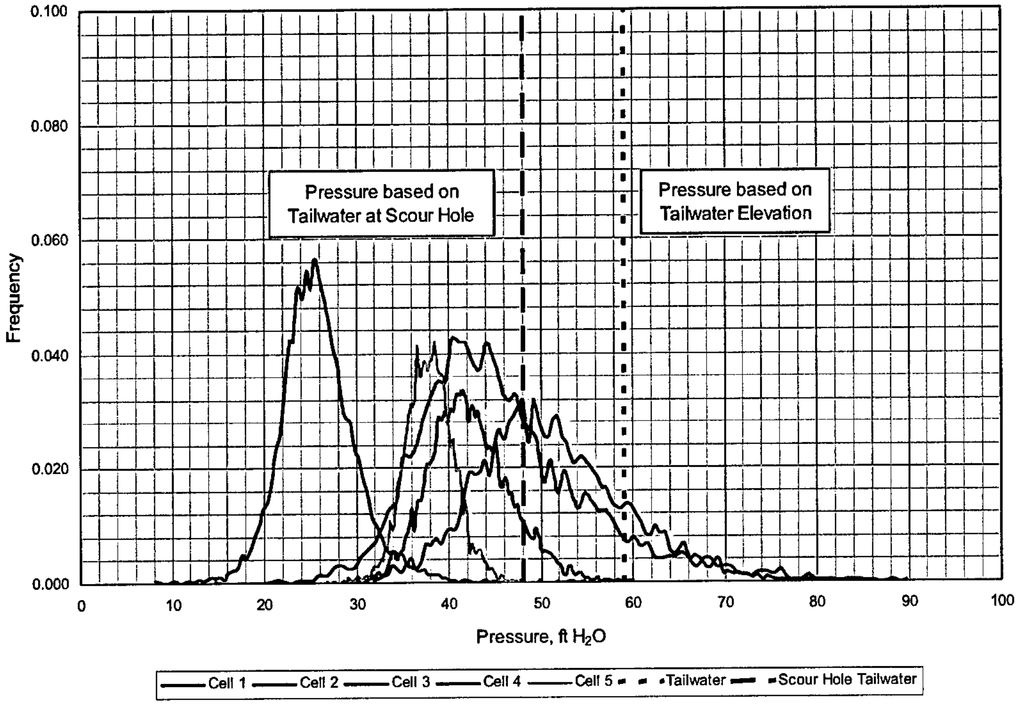


Figure H13. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 451.0, unable to measure TW at fish entrance, all gates open, no deflector on end bay, center line bay 2



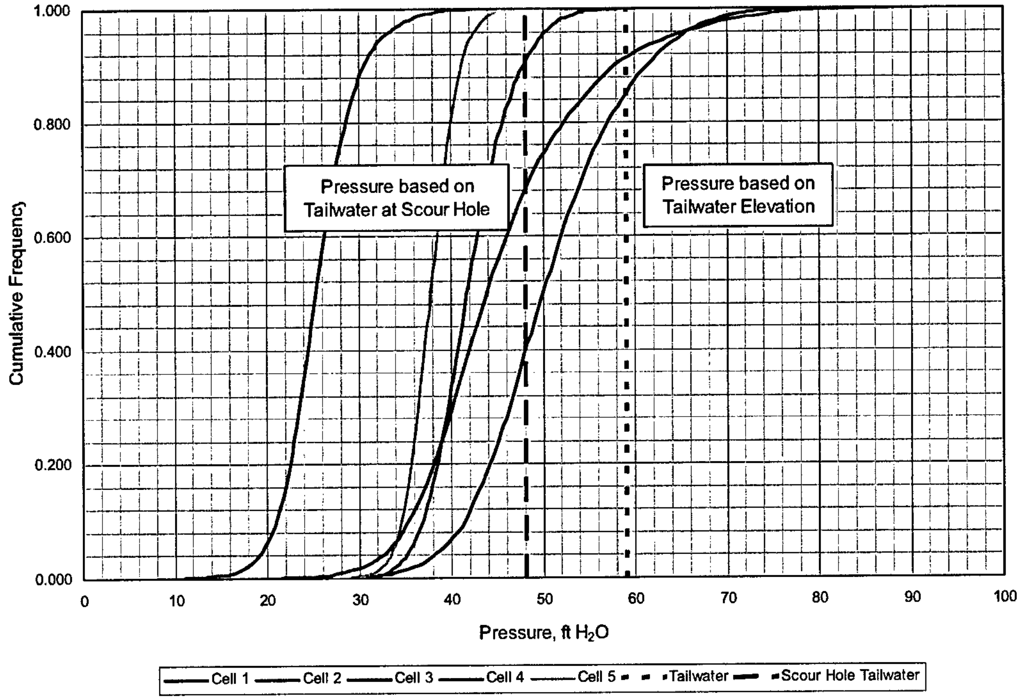
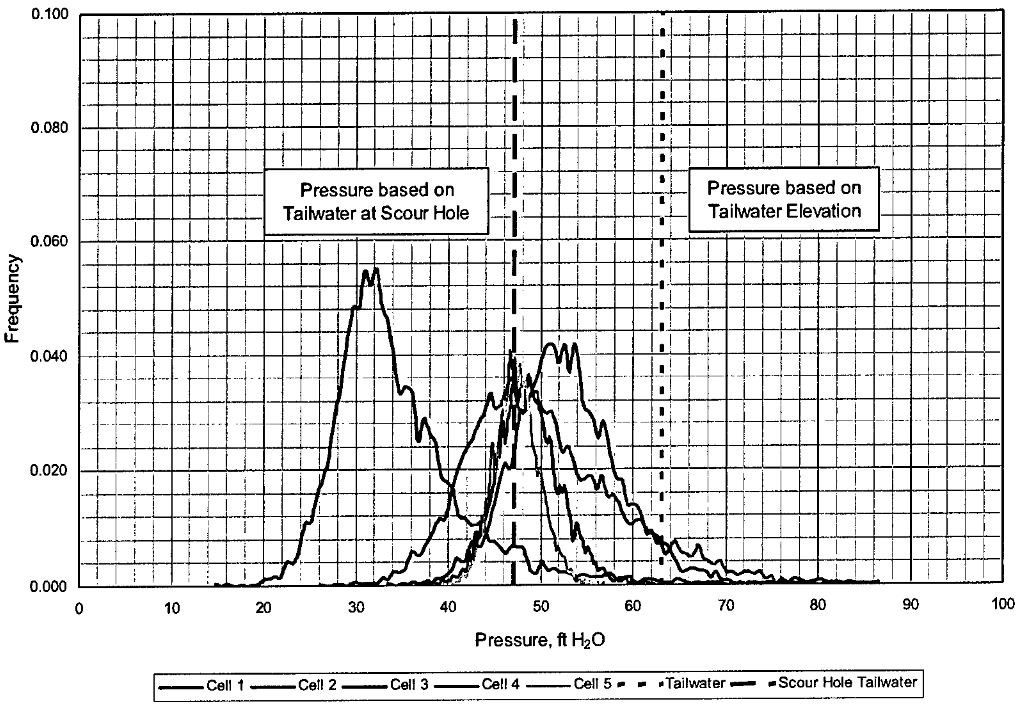


Figure H14. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 451.0, unable to measure TW at fish entrance, all gates open, no deflector on end bay, center line bay 2



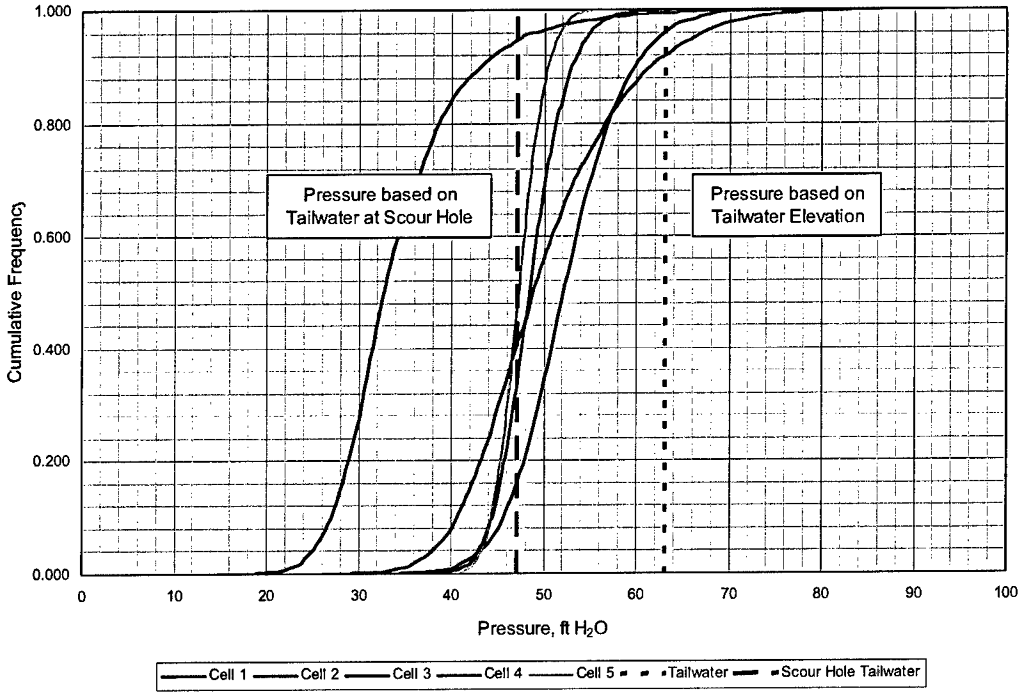
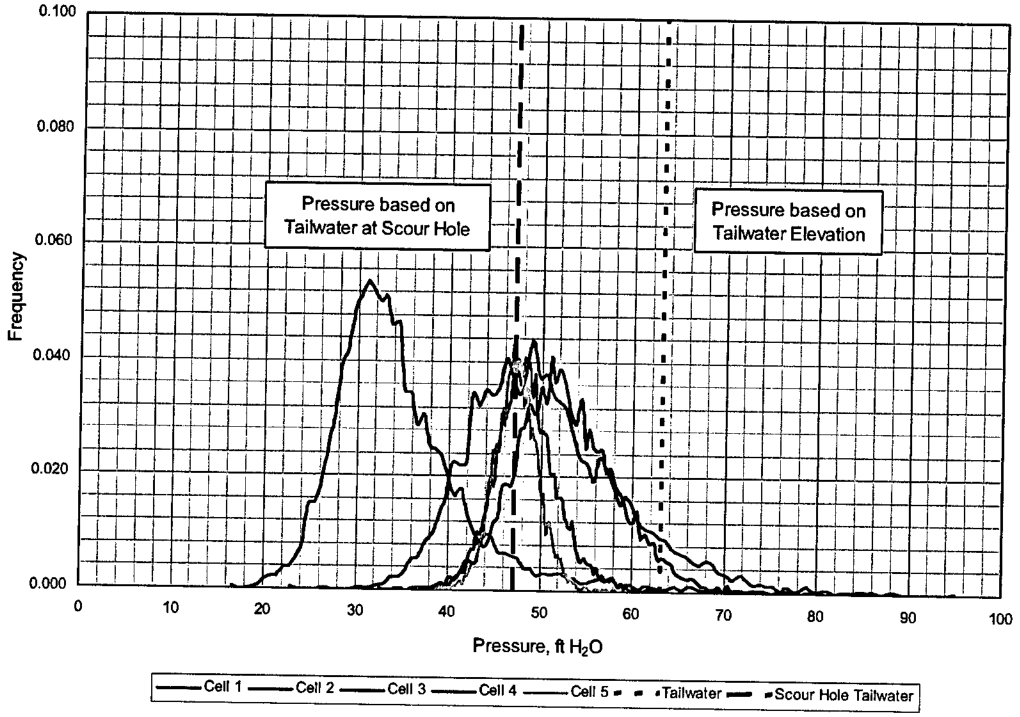


Figure H15. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 455.0, unable to measure TW at fish entrance, unstable plunge, all gates open, no deflector on end bay, center line bay 2



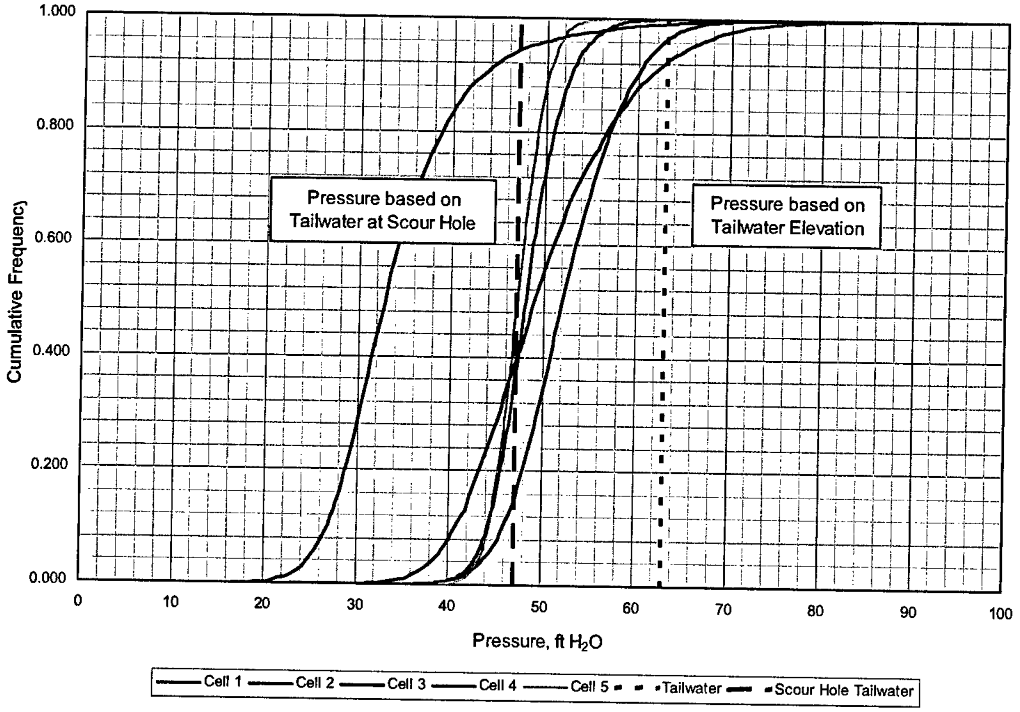
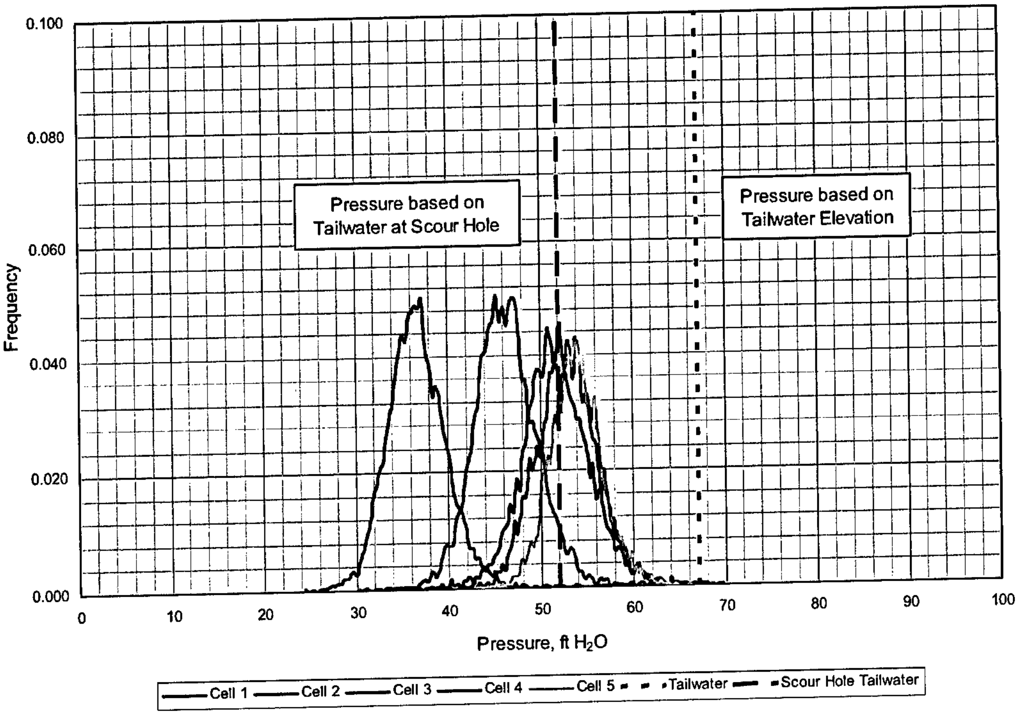


Figure H16. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 455.0, unable to measure TW at fish entrance, unstable plunge, all gates open, no deflector on end bay, center line bay 2



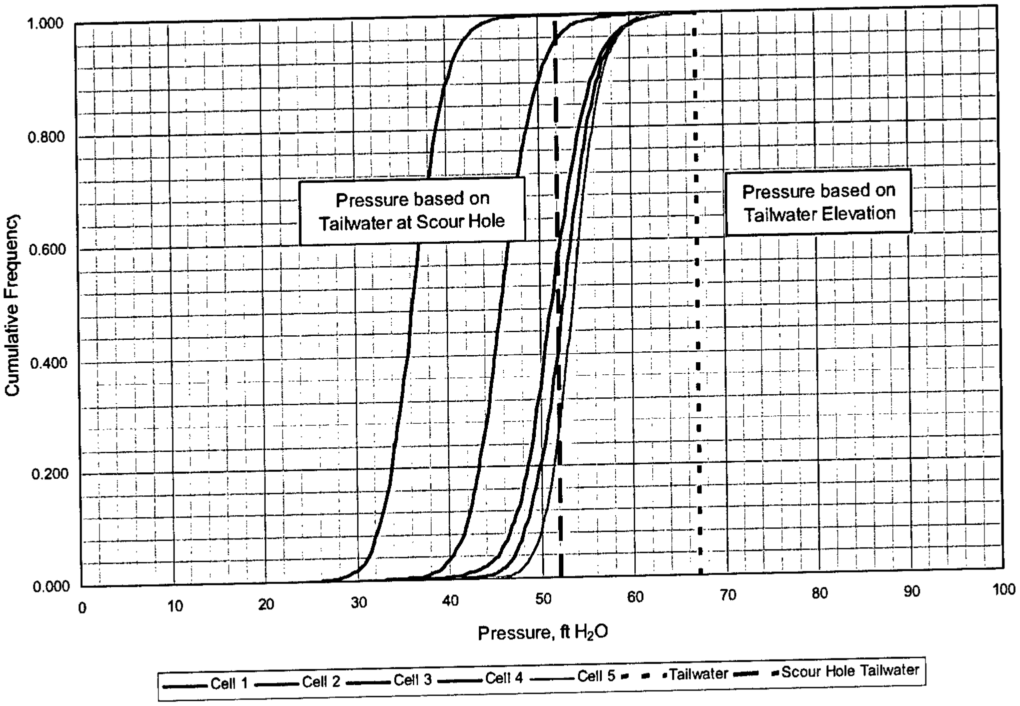
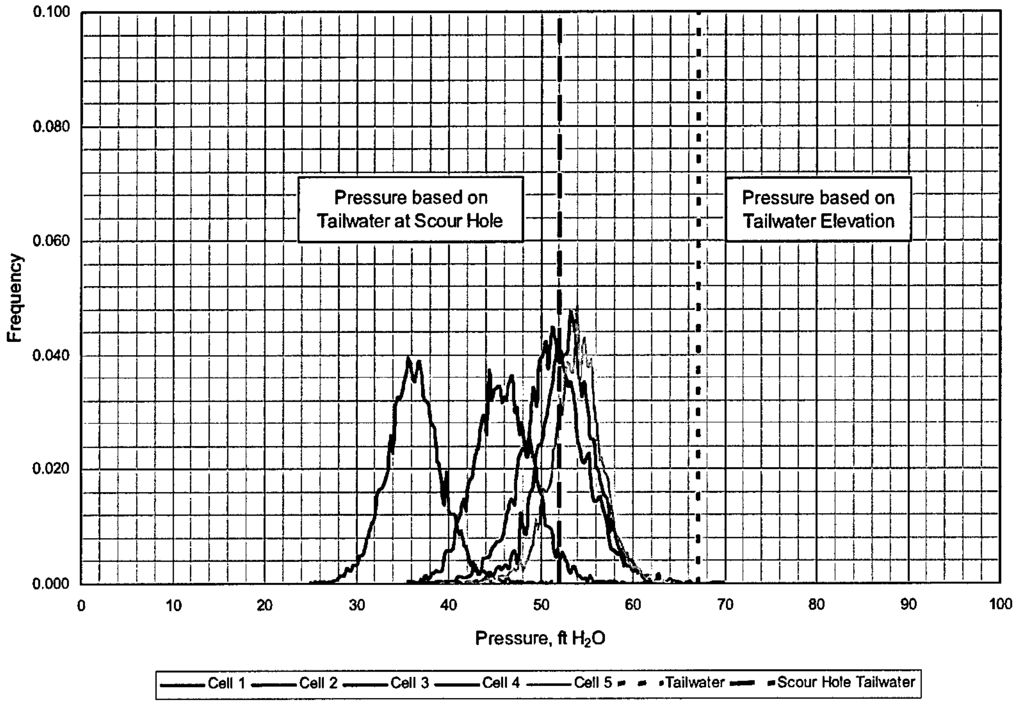


Figure H17. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 459.0, unable to measure TW at fish entrance, all gates open, no deflector on end bay, center line bay 2



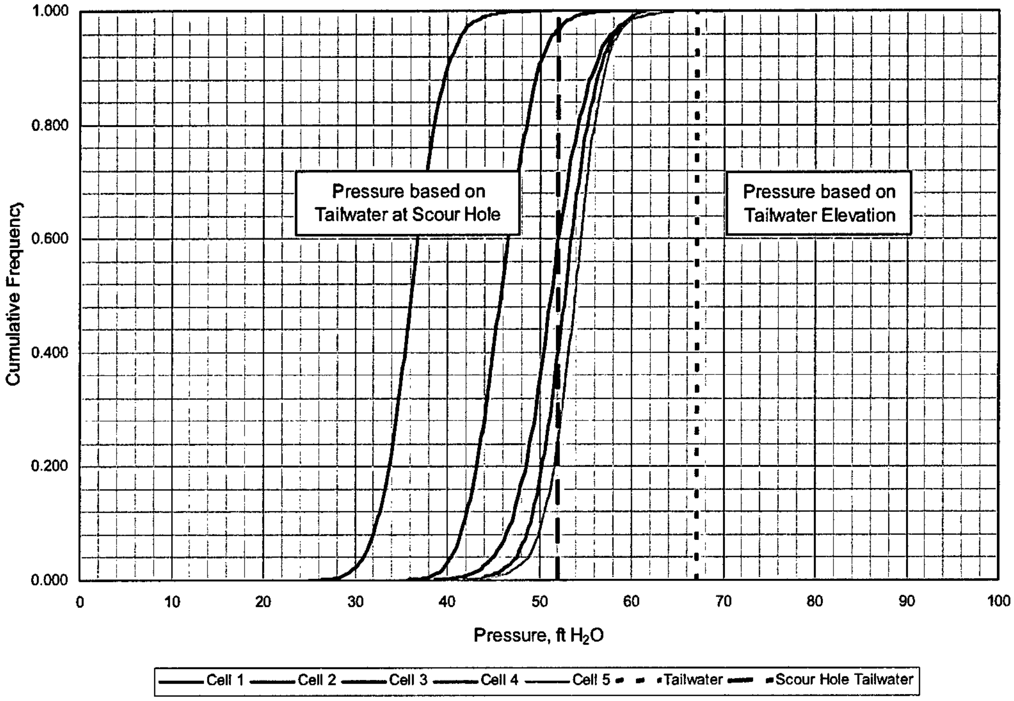
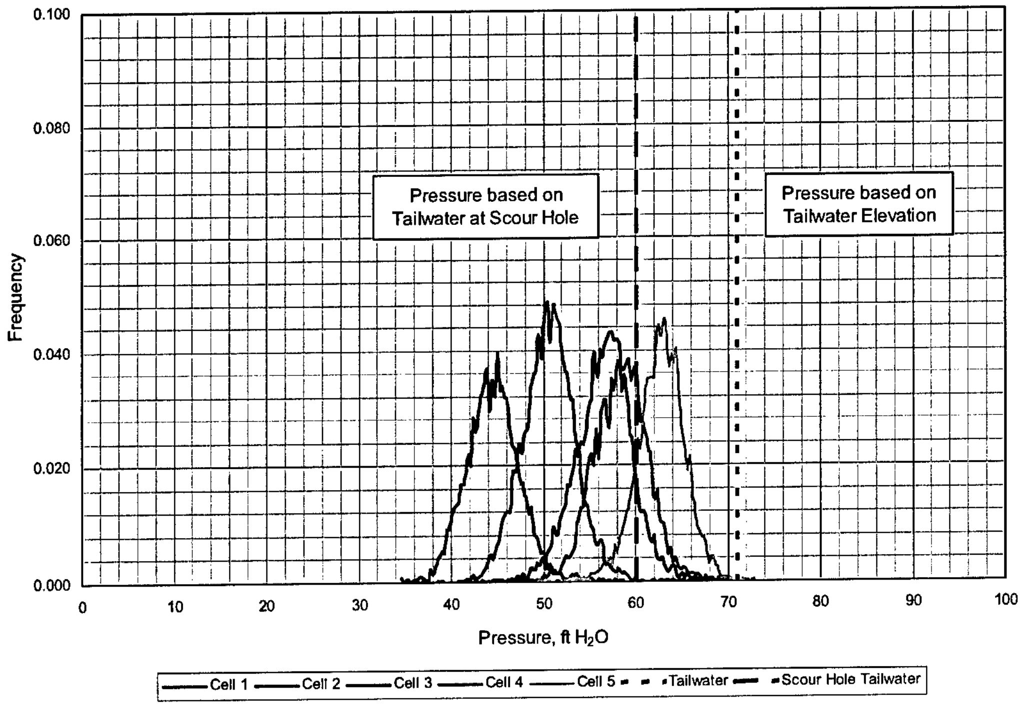


Figure H18. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 459.0, unable to measure TW at fish entrance, all gates open, no deflector on end bay, center line bay 2



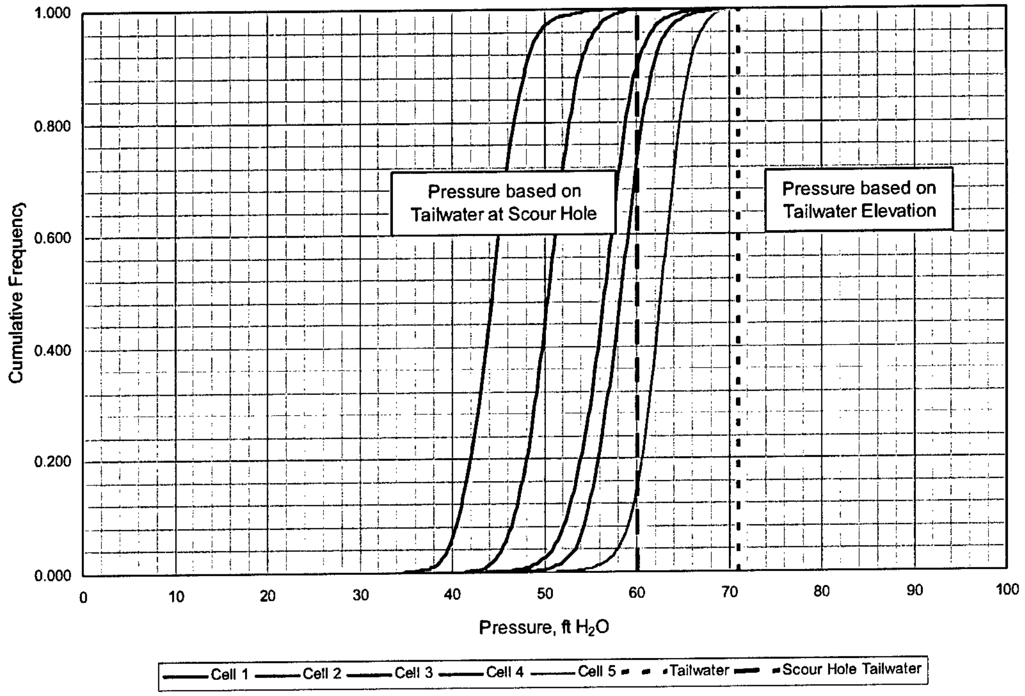
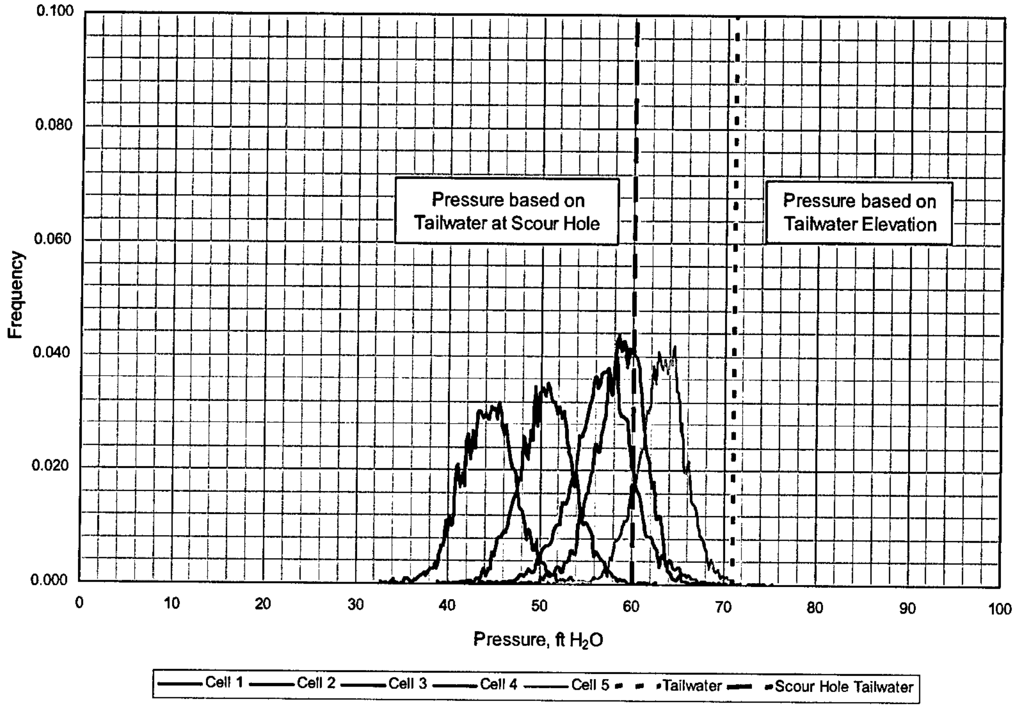


Figure H19. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 463.0, unable to measure TW at fish entrance, all gates open, no deflector on end bay, center line bay 2



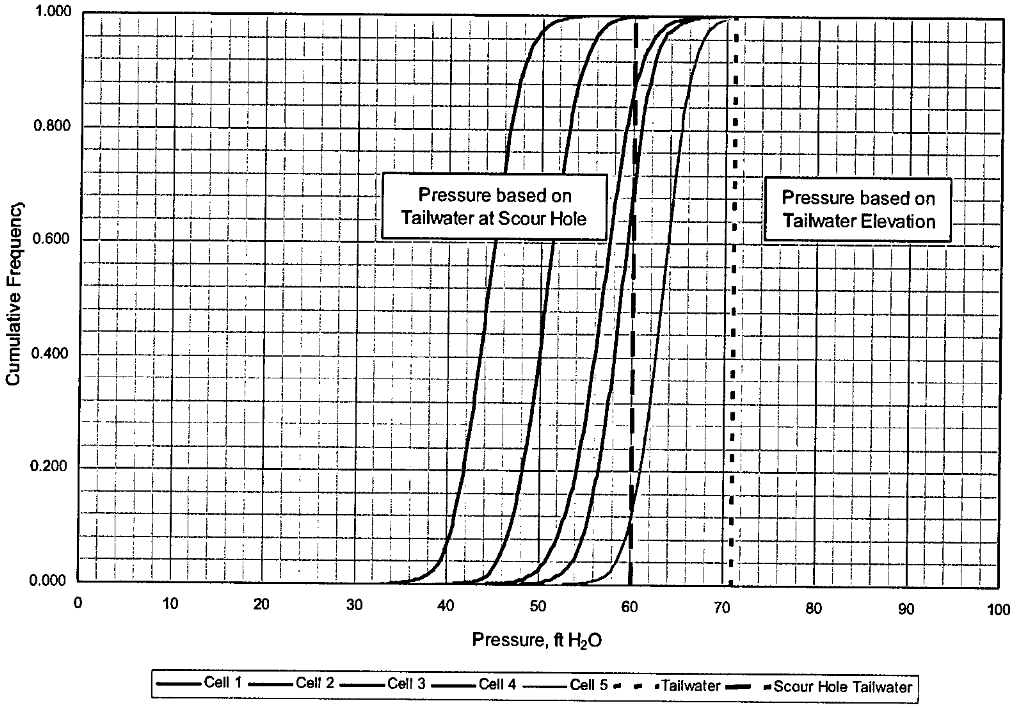
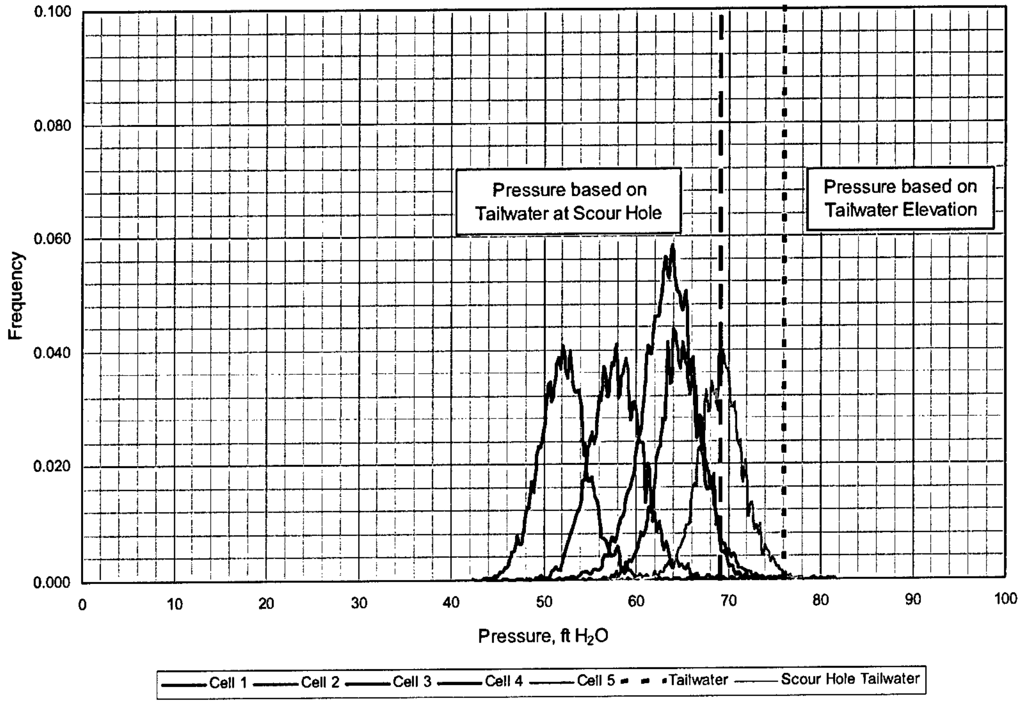


Figure H20. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 463.0, unable to measure TW at fish entrance, all gates open, no deflector on end bay, center line bay 2



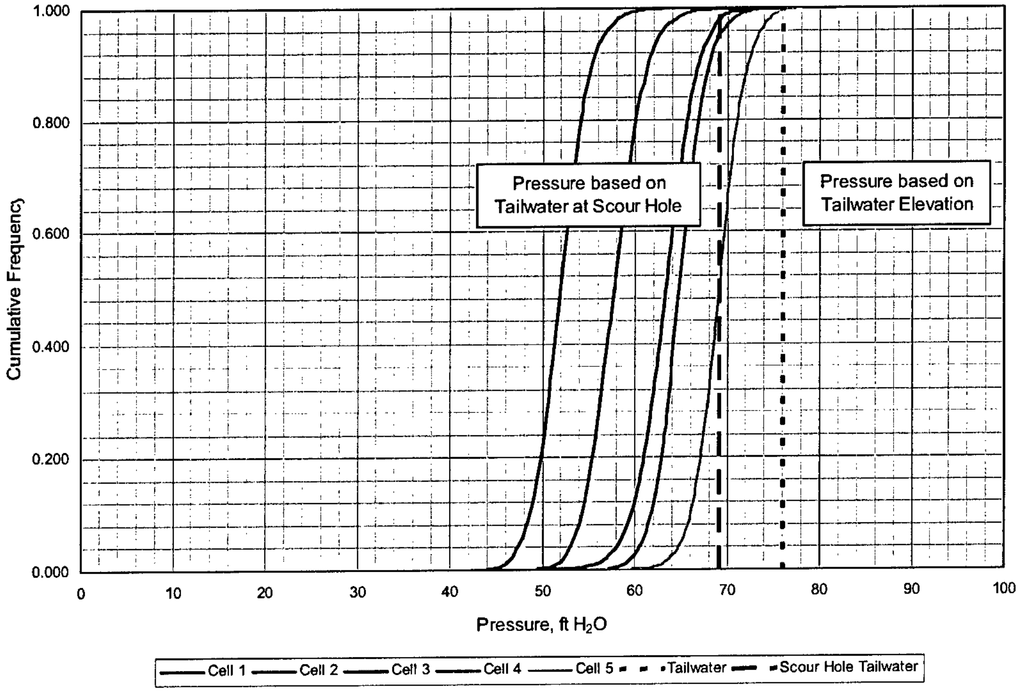
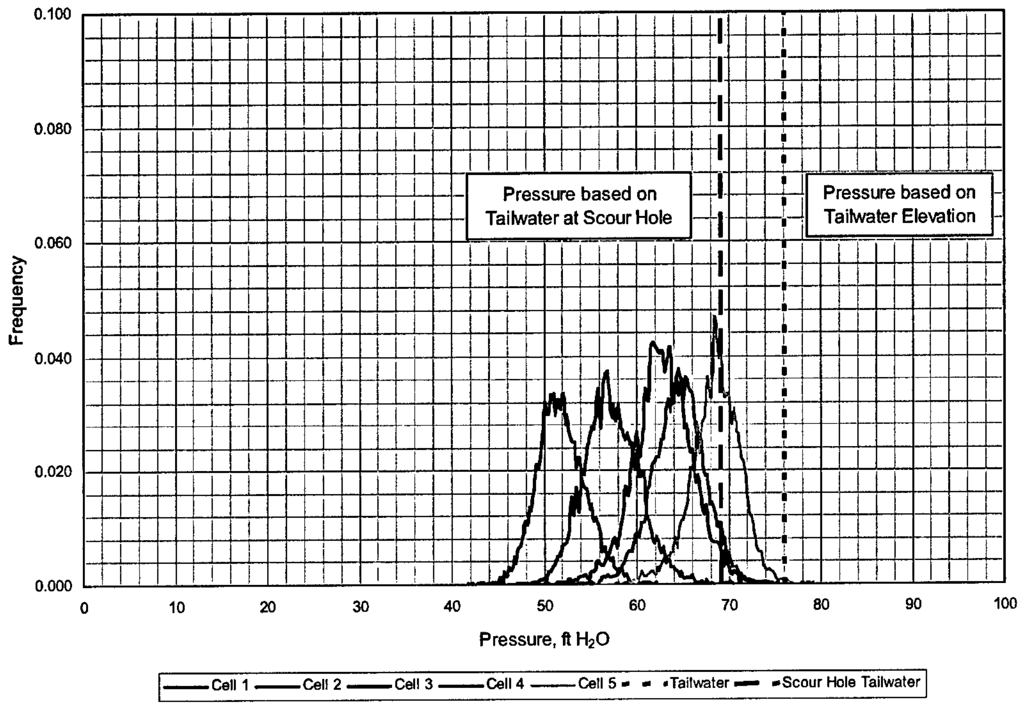


Figure H21. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 468.0, unable to measure TW at the fish entrance, all gates open, no deflector on end bay, center line bay 2



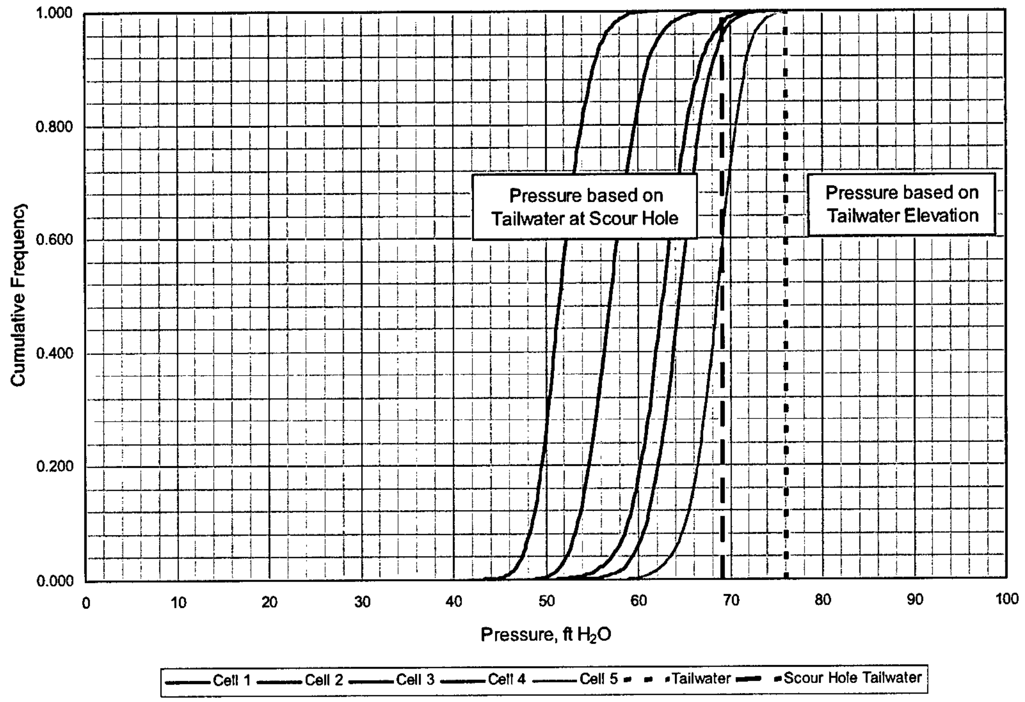
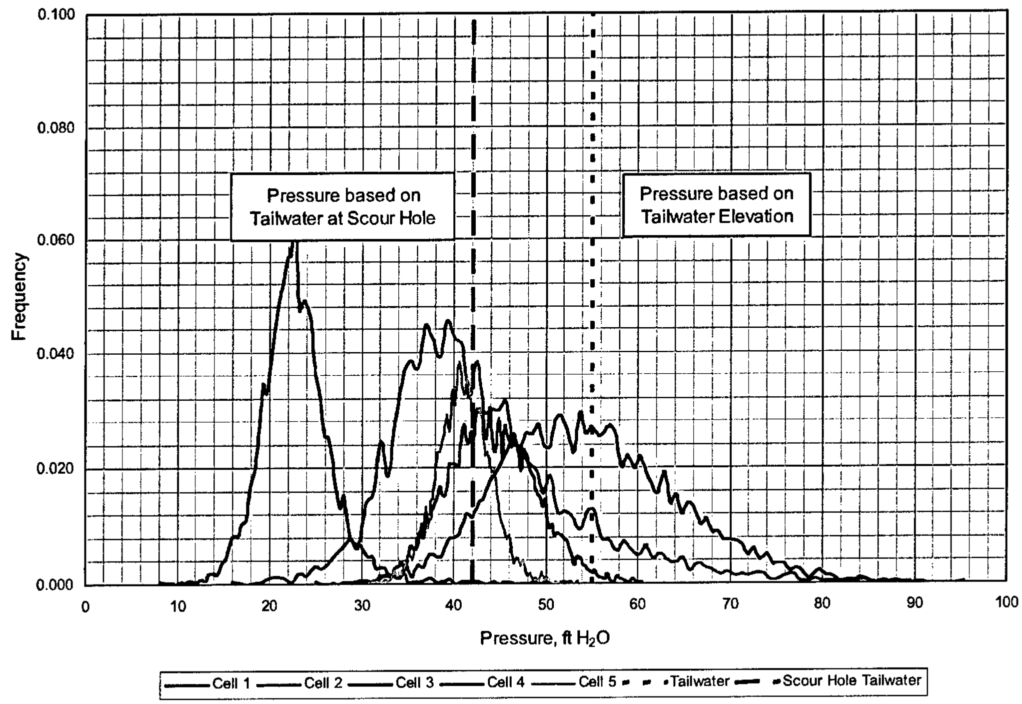


Figure H22. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 468.0, unable to measure TW at the fish entrance, all gates open, no deflector on end bay, center line bay 2



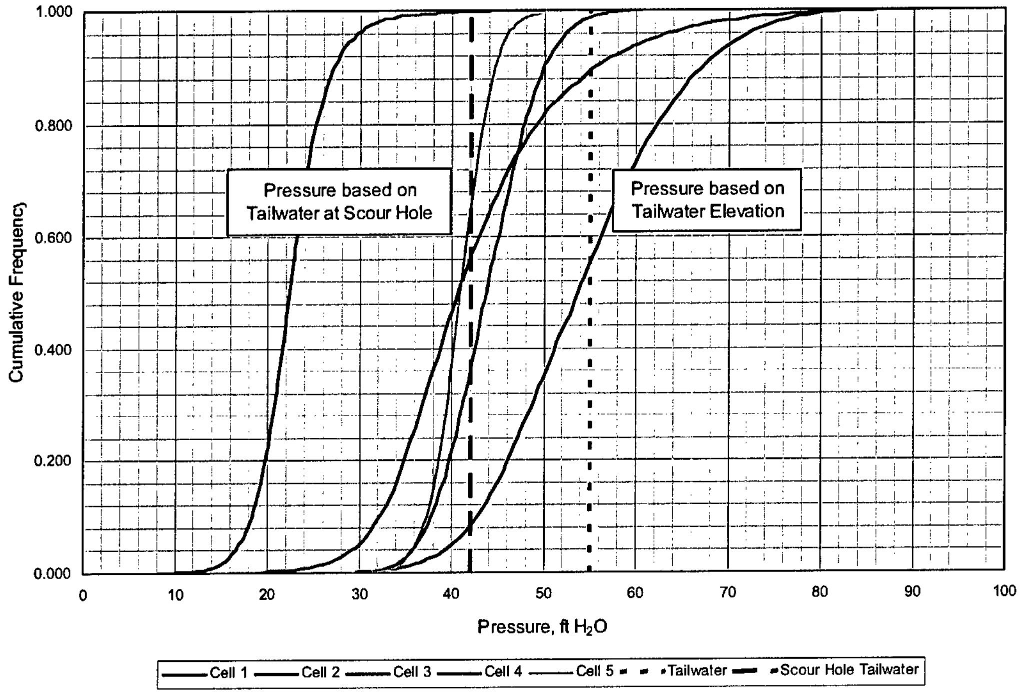
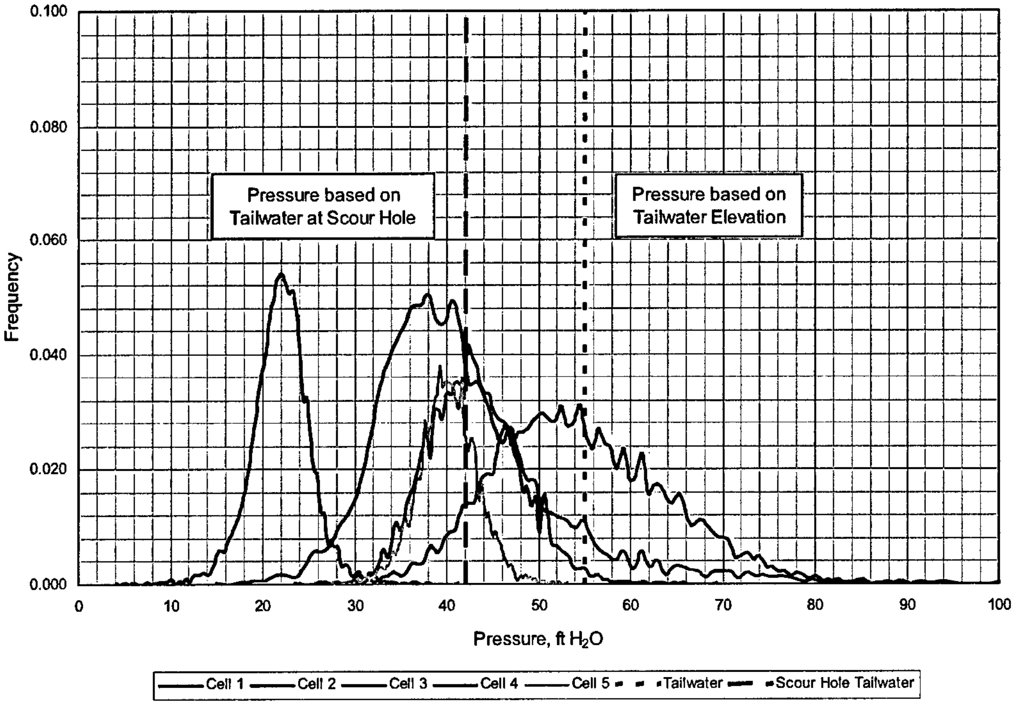


Figure H23. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 447.0, unable to measure TW at the fish entrance, aerated nappe, all gates open, no deflector on end bay, center line bay 2



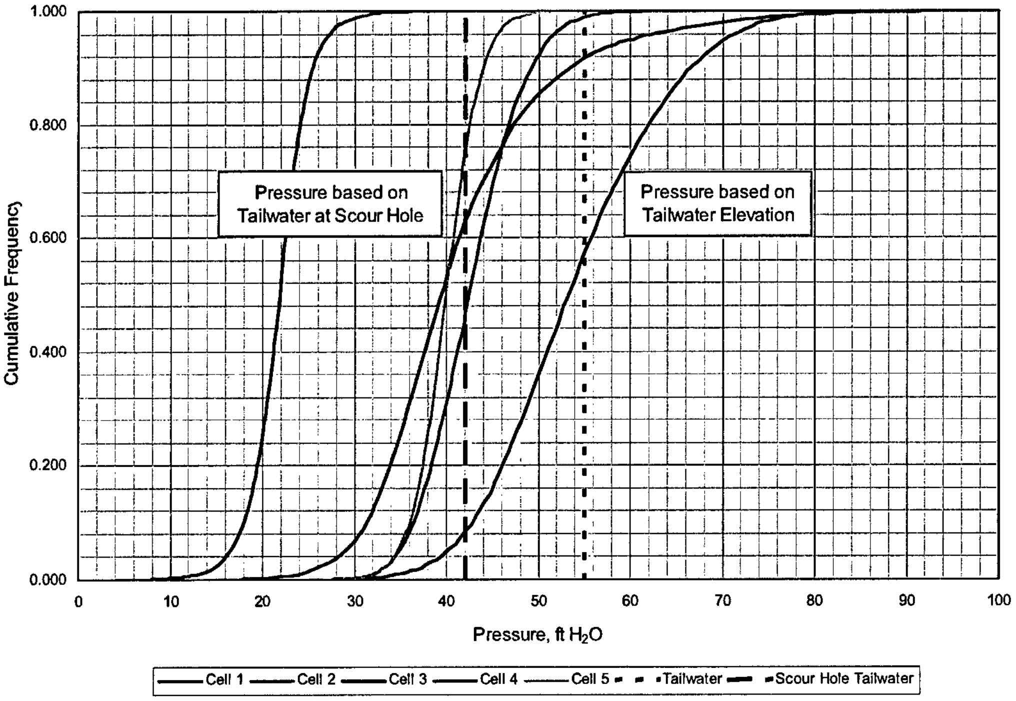
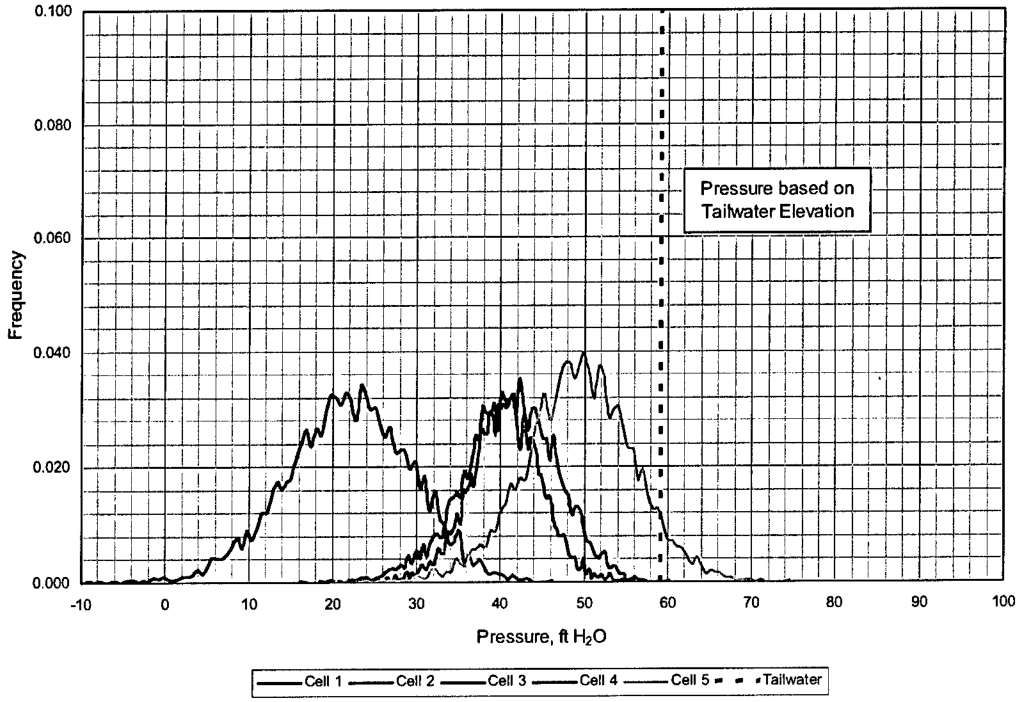


Figure H24. Lower Monumental stilling basin pressure investigation. 34 kcfs per bay, gate opening = 20.0, pool el. = 540.0, TW el = 447.0, unable to measure TW at the fish entrance, aerated nappe, all gates open, no deflector on end bay, center line bay 2



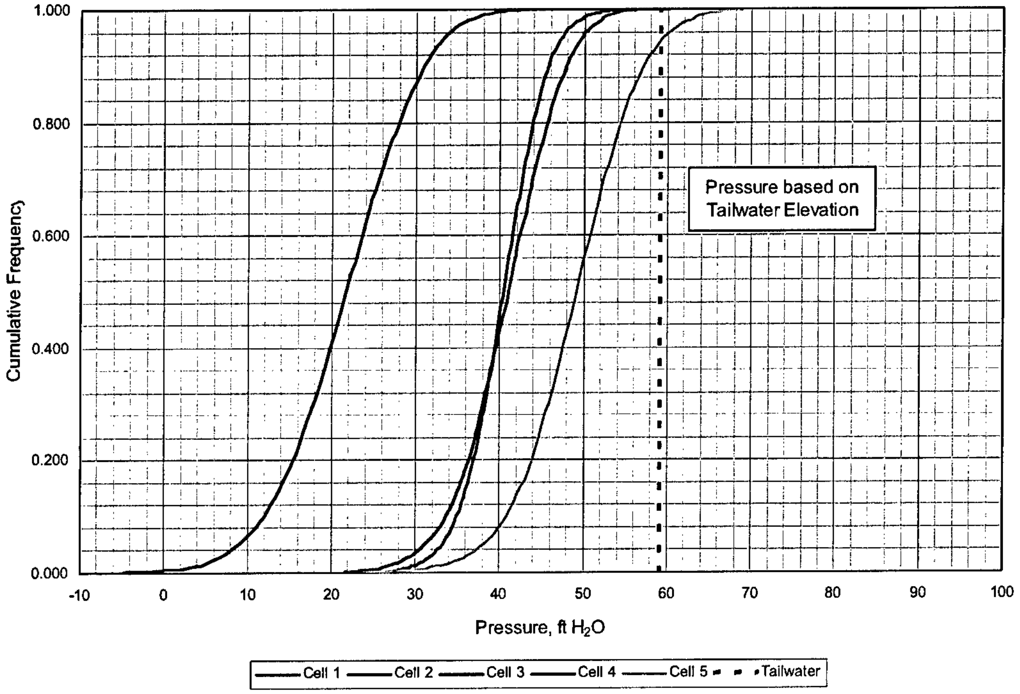
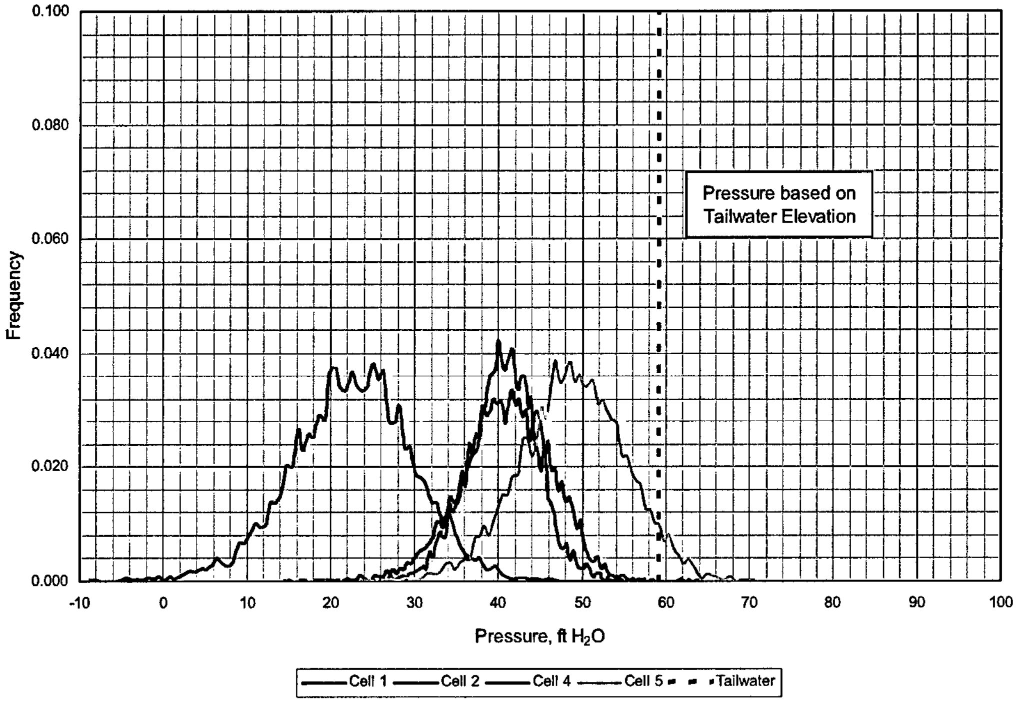


Figure H25. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, tw at fish entrance = 448.0, no deflector on end bay, year 2000 scour hole



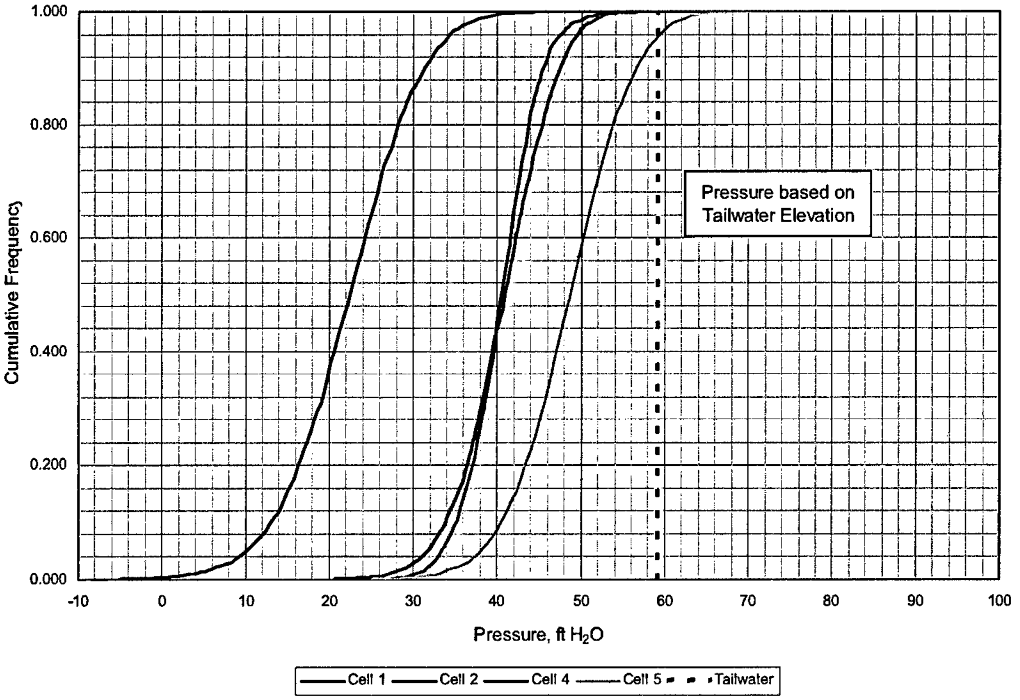
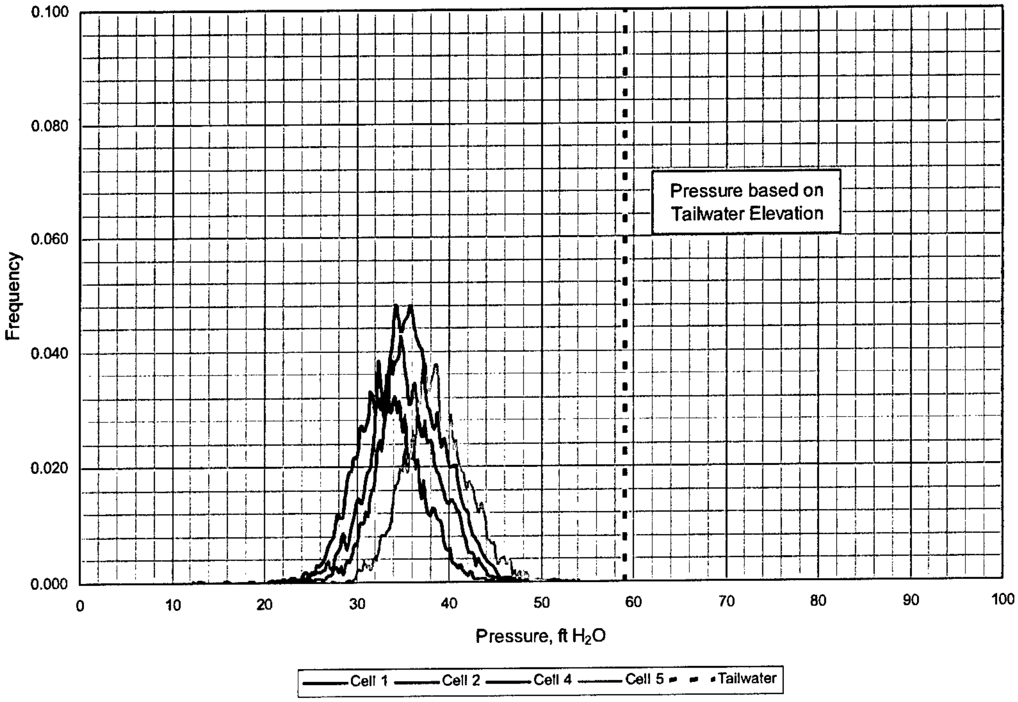


Figure H26. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, TW at fish entrance = 448.0, no deflector on end bay, year 2000 scour hole



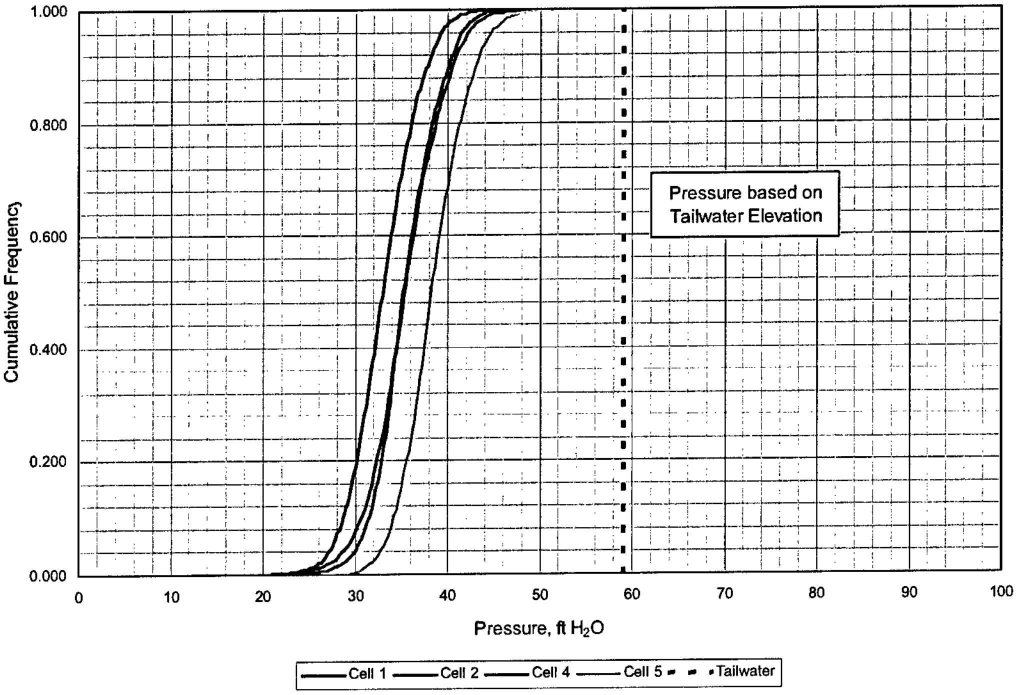
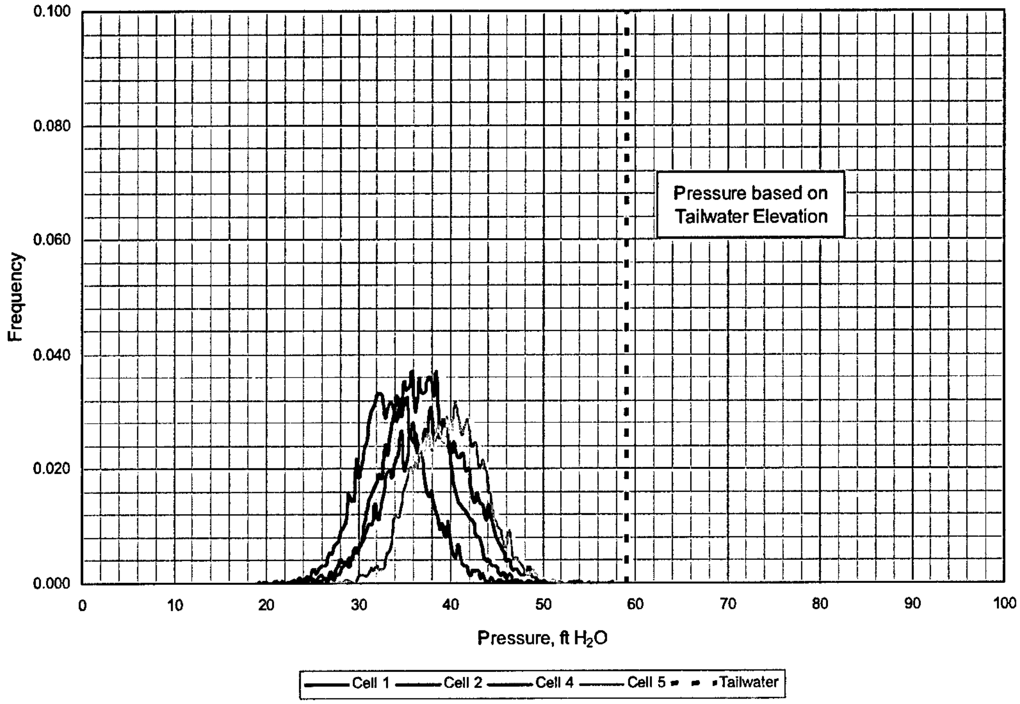


Figure H27. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, TW at fish entrance = 448.0, end gate closed, no deflector on end bay, year 2000 scour hole



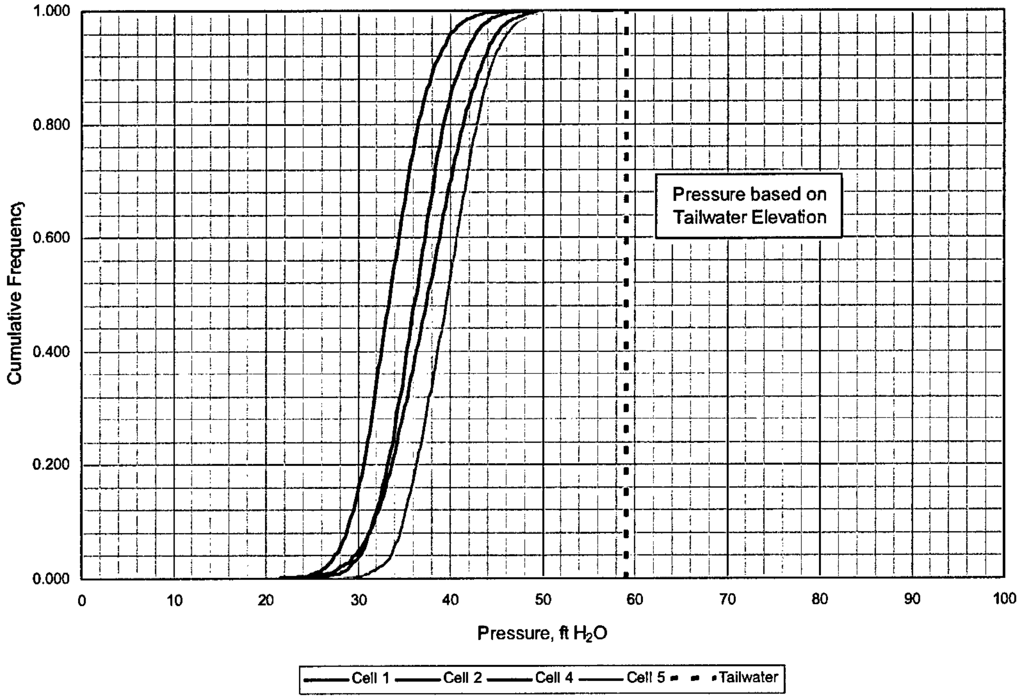
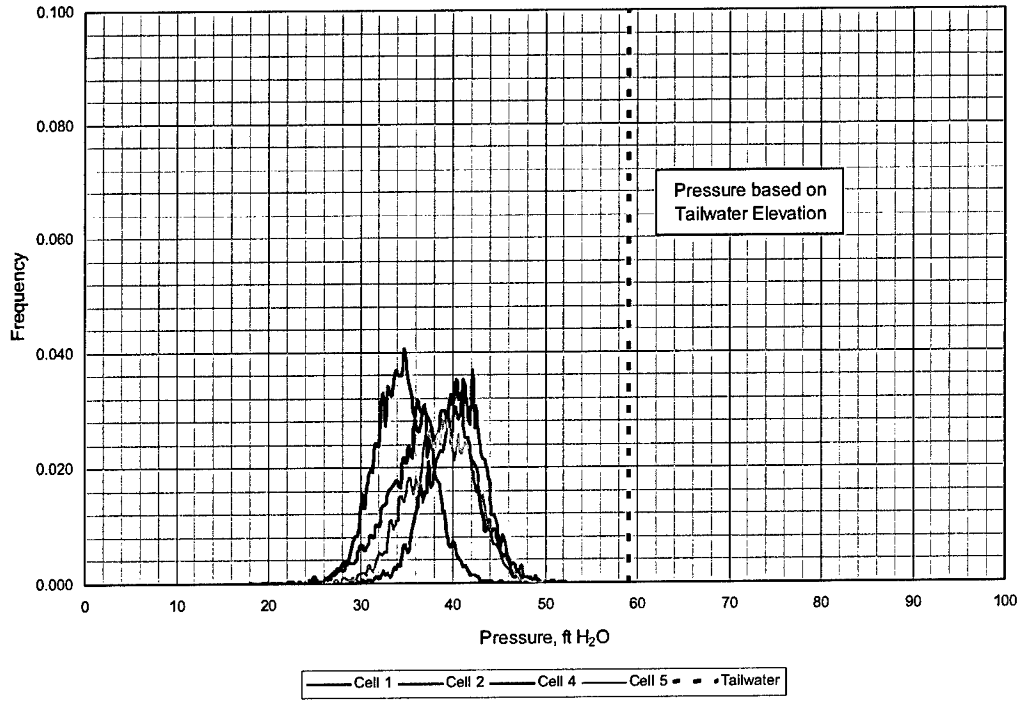


Figure H28. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, TW at fish entrance = 448.0, end gate closed, no deflector on end bay, year 2000 scour hole



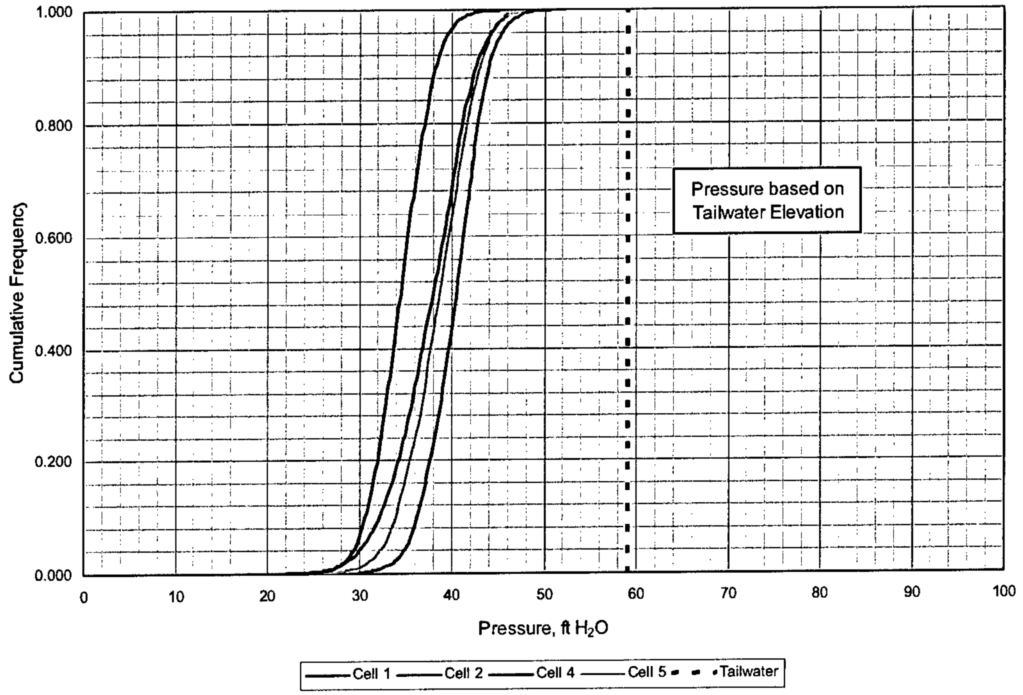
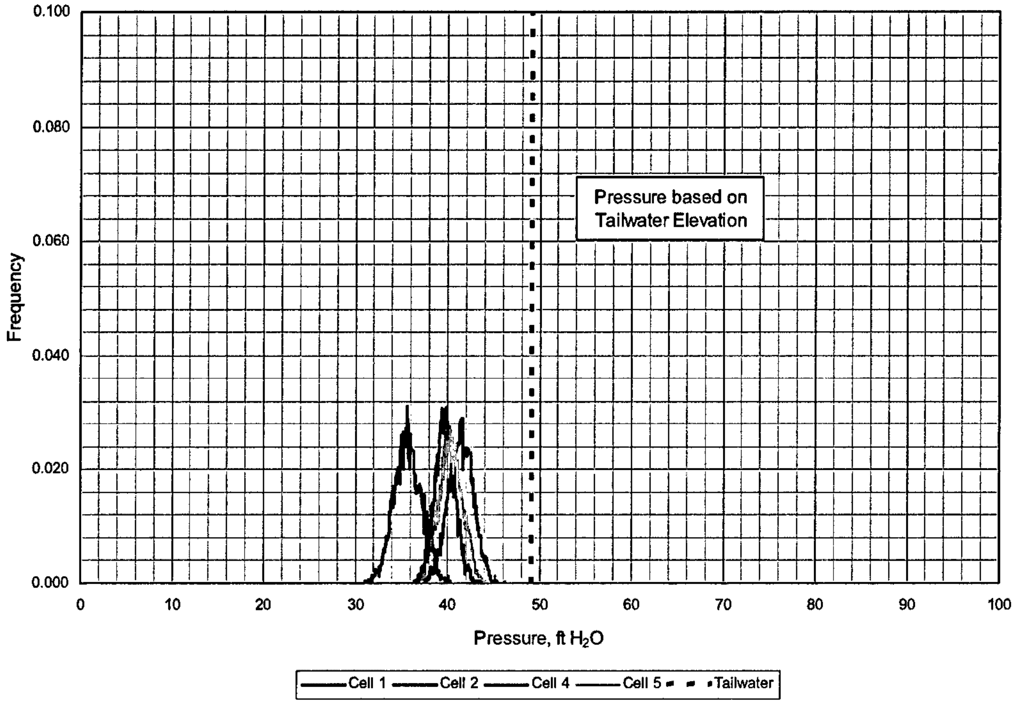


Figure H29. Lower Monumental stilling basin pressure investigation. 29 kcfs per bay, gate opening = 16.5, pool el. = 537.0, TW el = 451.0, TW at fish entrance = 448.0, end gate closed, no deflector on end bay, year 2000 scour hole



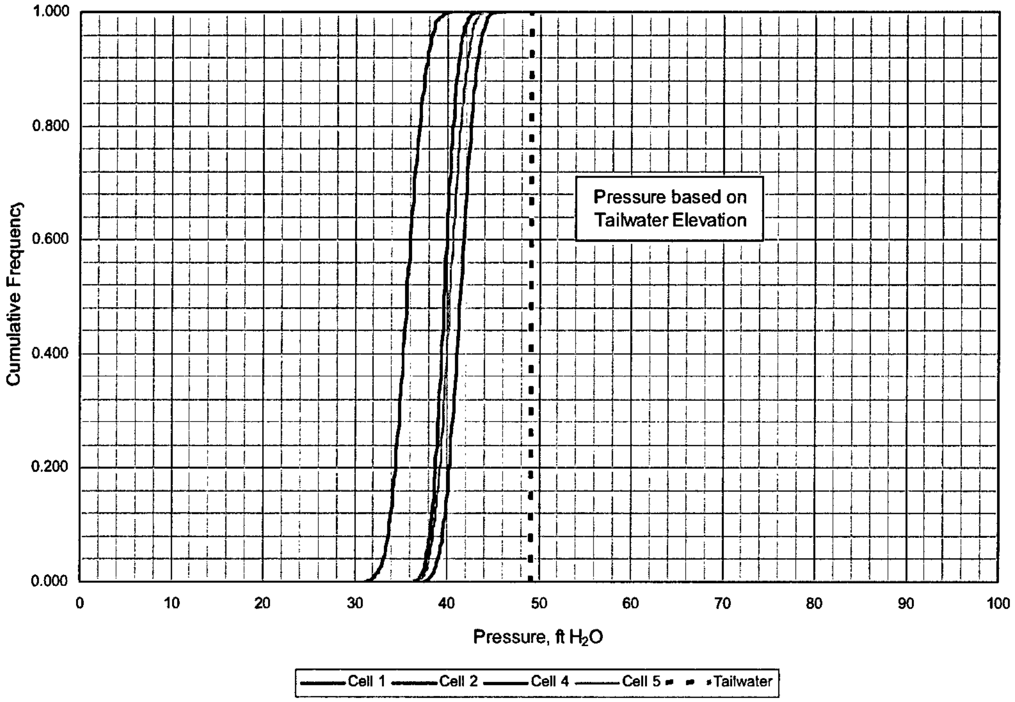
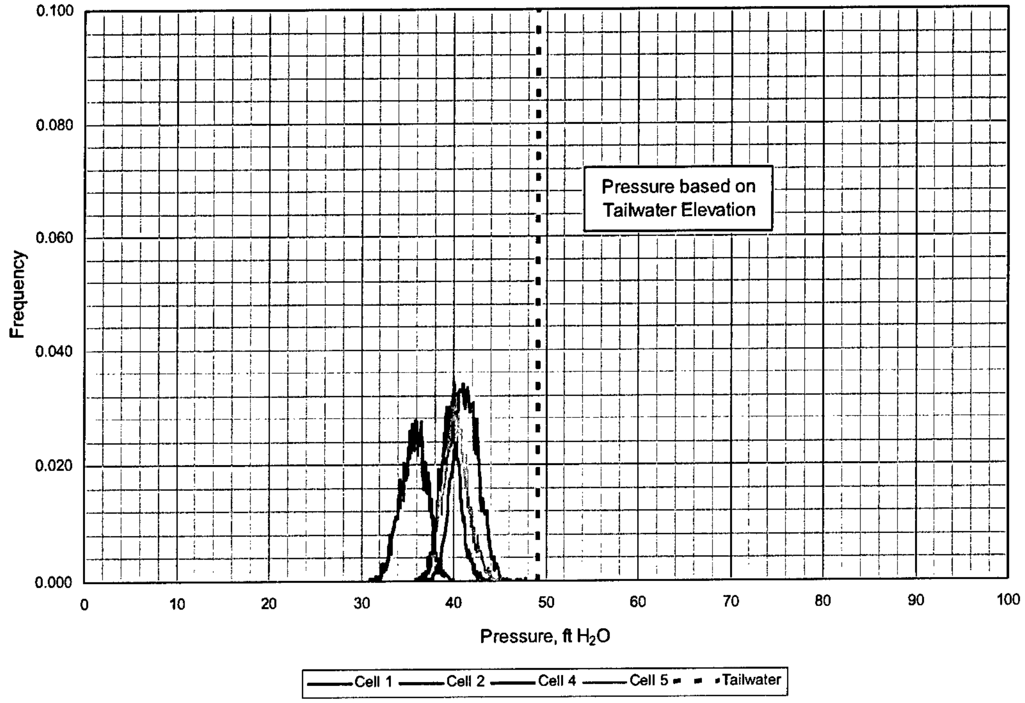


Figure H30. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, end gate closed, no deflector on end bay, year 2000 scour hole



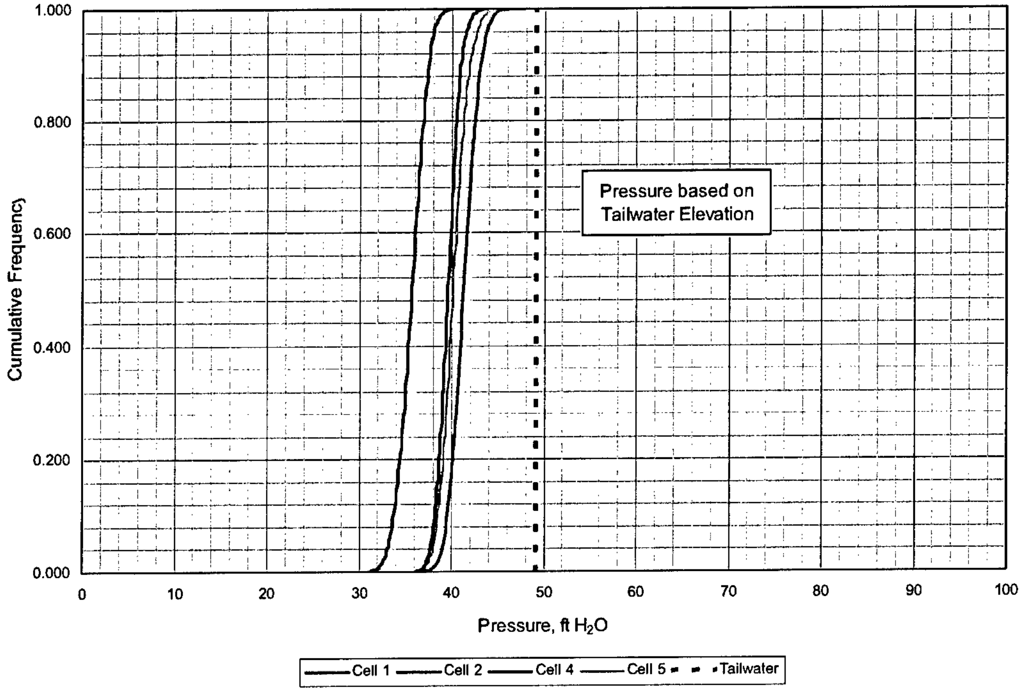
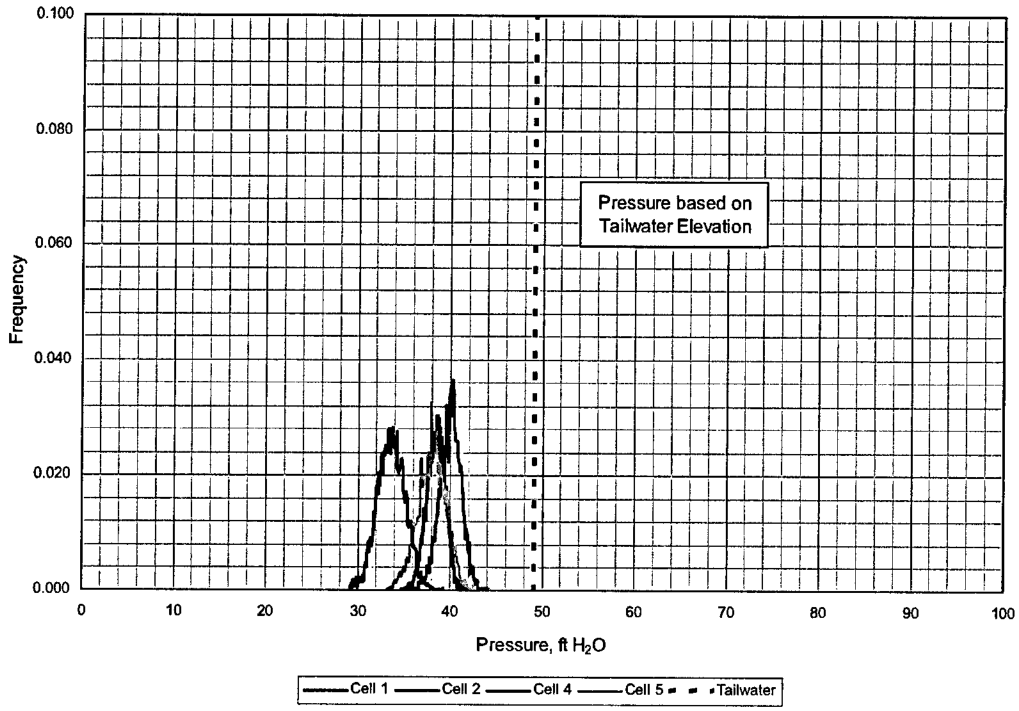


Figure H31. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, end gate closed, no deflector on end bay, year 2000 scour hole



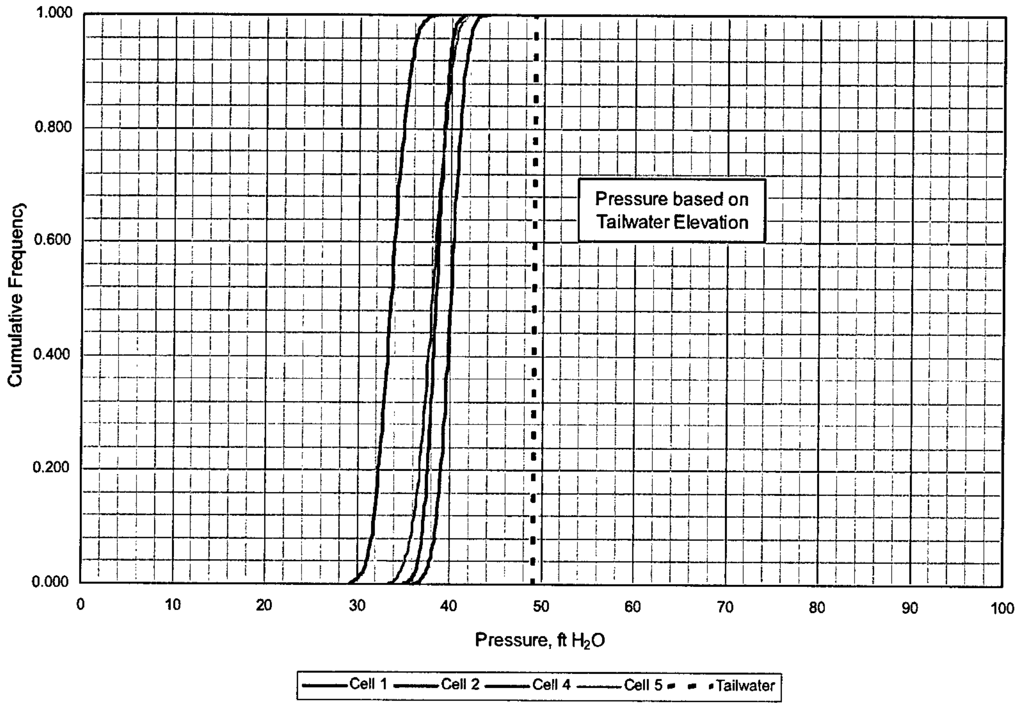
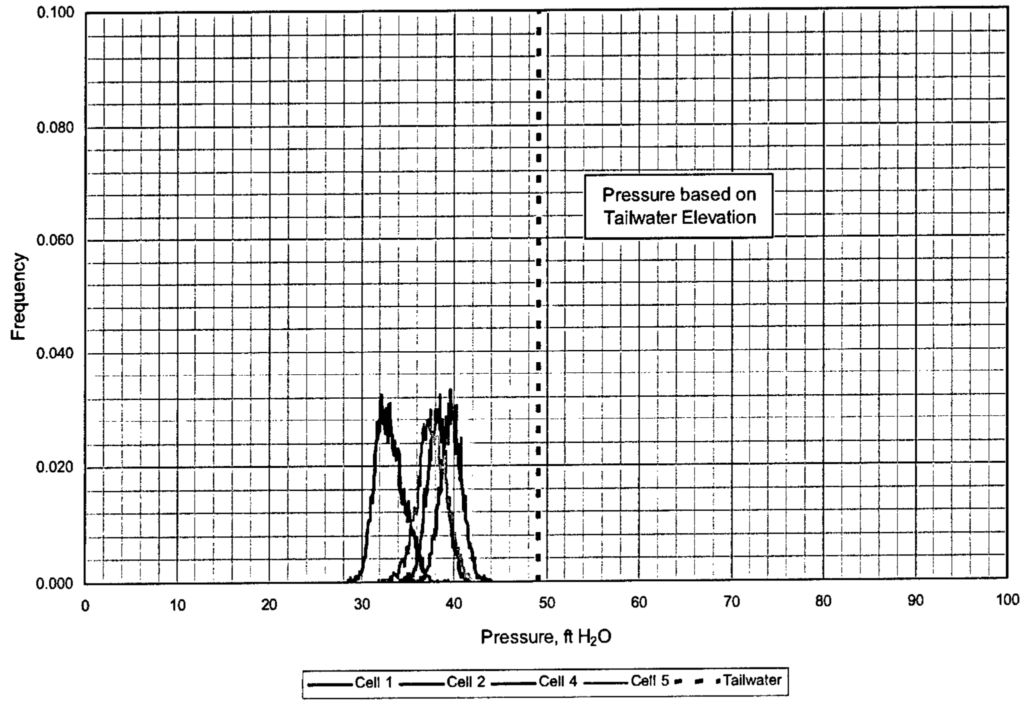


Figure H32. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, end gate opened, no deflector on end bay, year 2000 scour hole



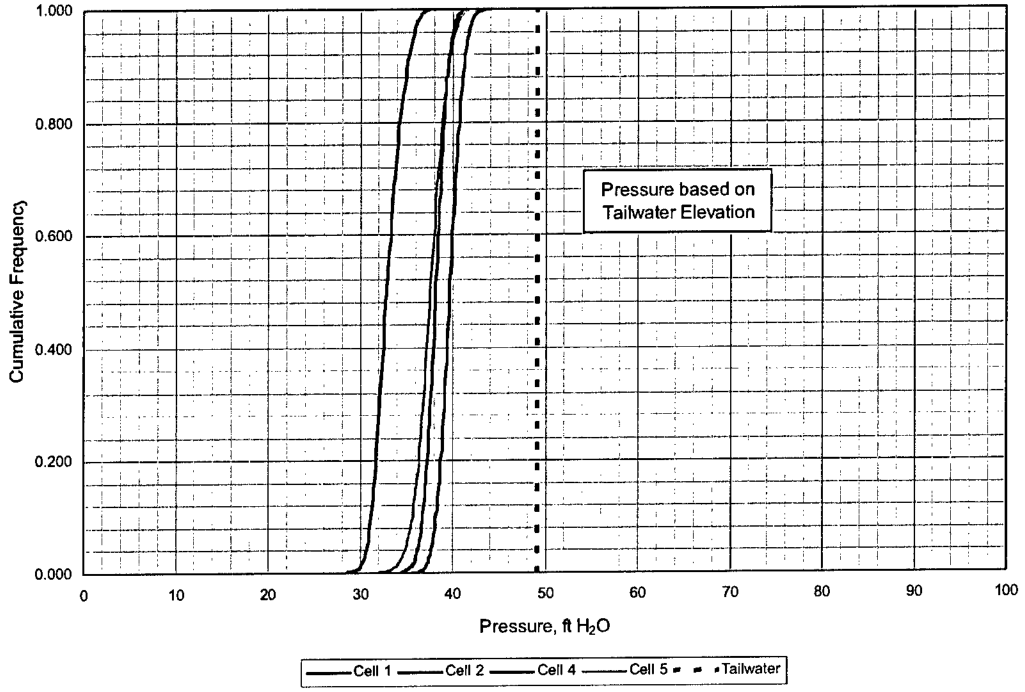
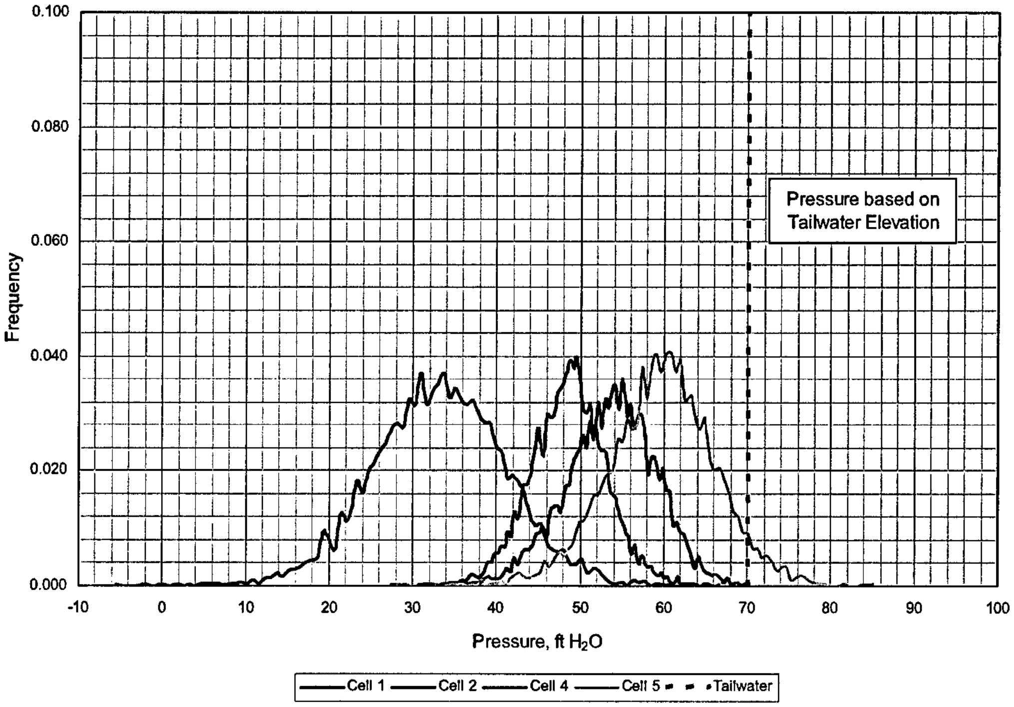


Figure H33. Lower Monumental stilling basin pressure investigation. 6.5 kcfs per bay, gate opening = 3.5, pool el. = 537.0, TW el = 441.0, TW at fish entrance = 440.8, end gate opened, no deflector on end bay, year 2000 scour hole



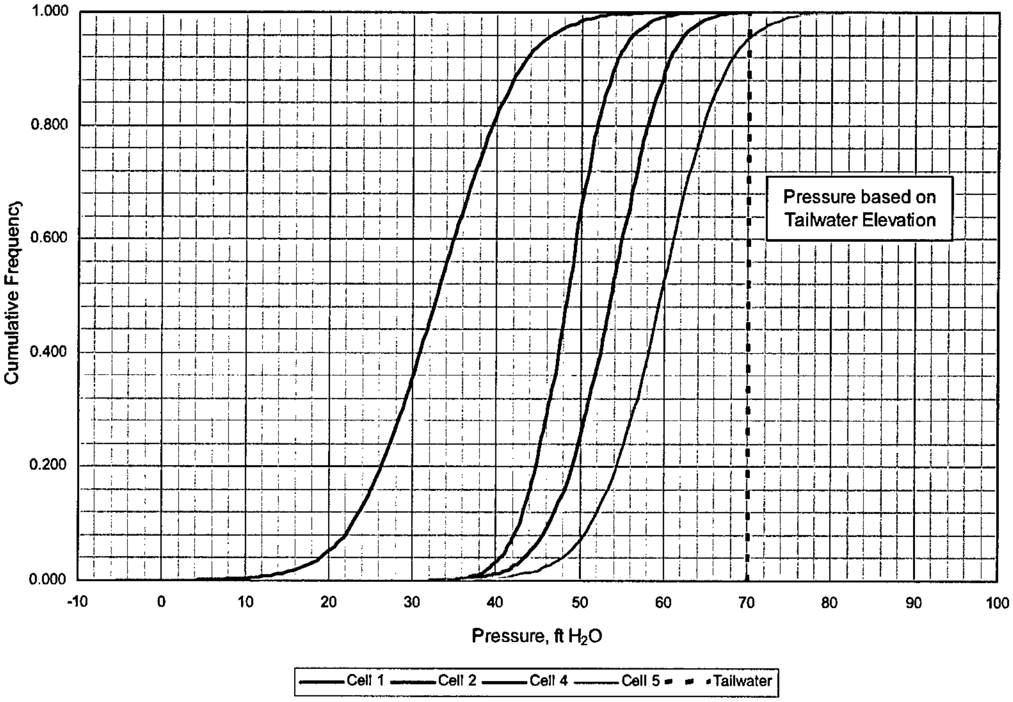
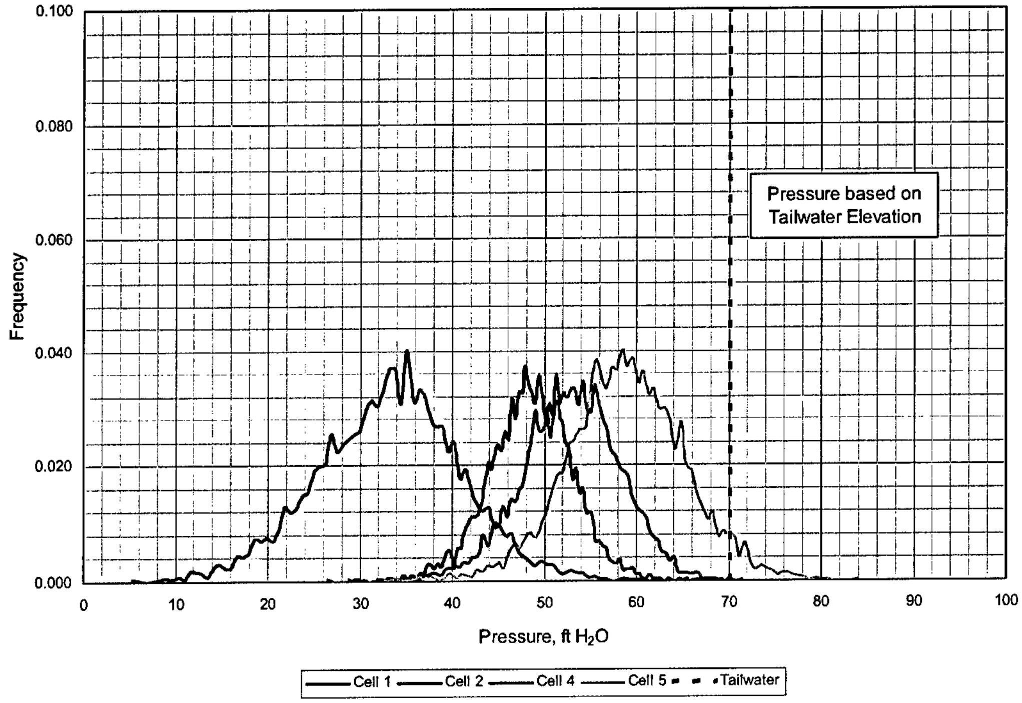


Figure H34. Lower Monumental stilling basin pressure investigation. 50 kcfs per bay, gate opening = 23.0, pool el. = 539.0, TW el = 462.0, end gate opened, no deflector on end bay, year 2000 scour hole



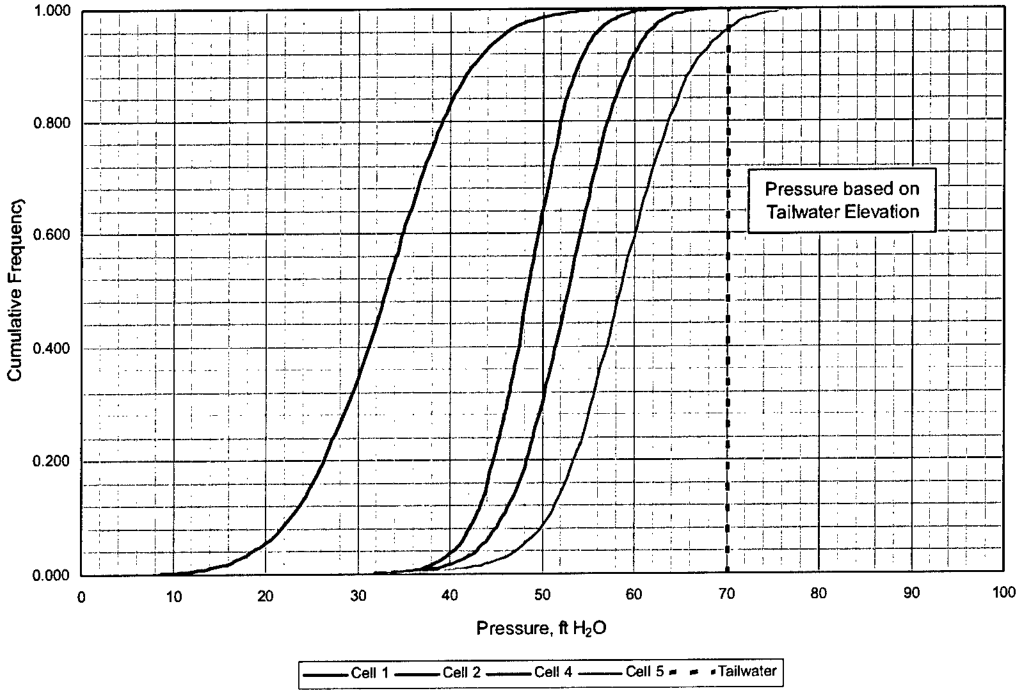
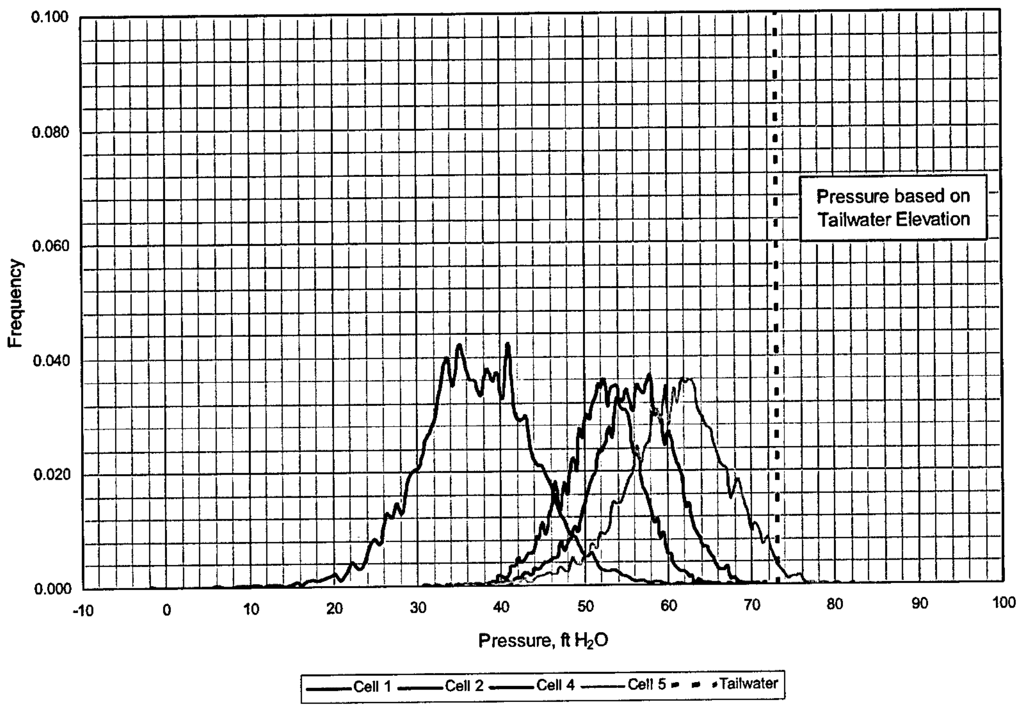


Figure H35. Lower Monumental stilling basin pressure investigation. 50 kcfs per bay, gate opening = 23.0, pool el. = 539.0, TW el = 462.0, end gate opened, no deflector on end bay, year 2000 scour hole



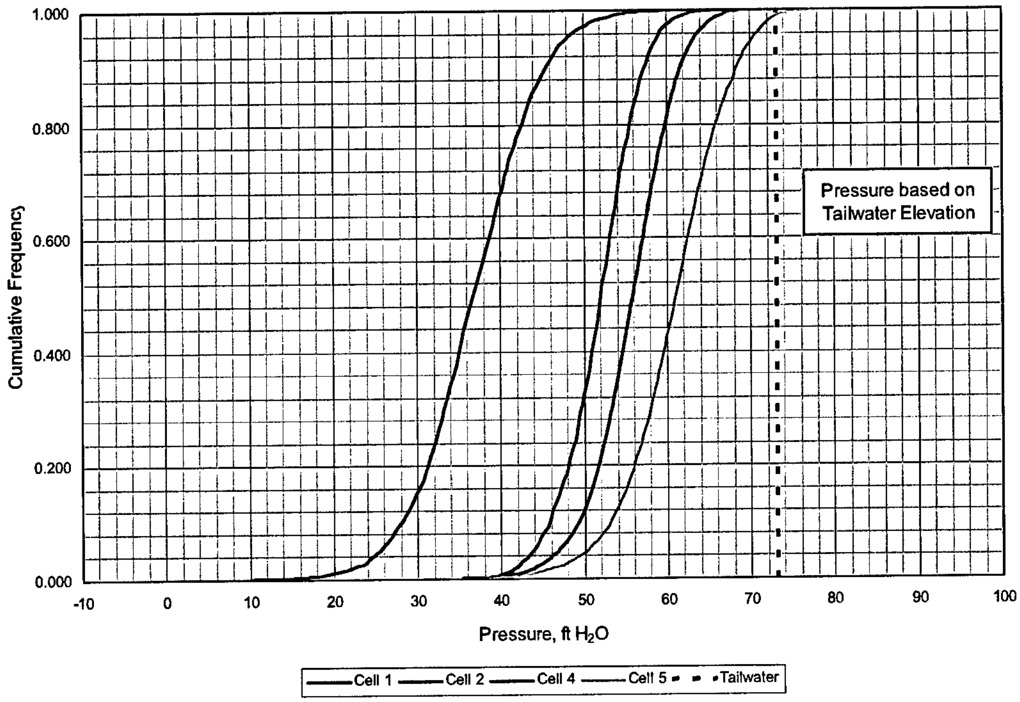
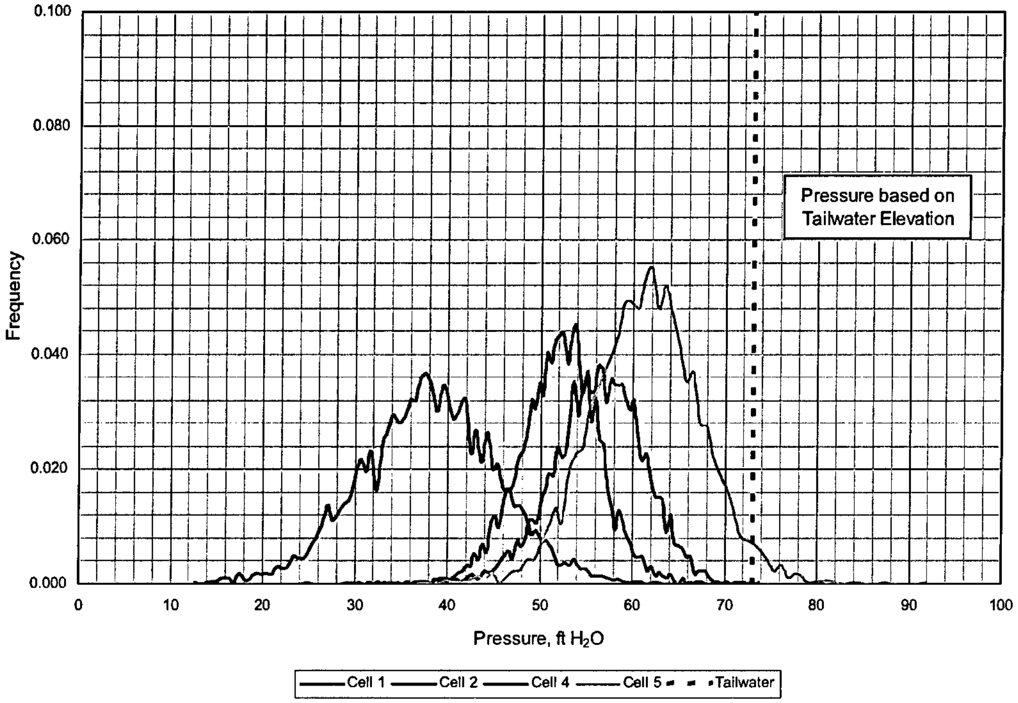


Figure H36. Lower Monumental stilling basin pressure investigation. 50 kcfs per bay, gate opening = 23.0, pool el. = 539.0, TW el = 465.0, end gate opened, no deflector on end bay, year 2000 scour hole



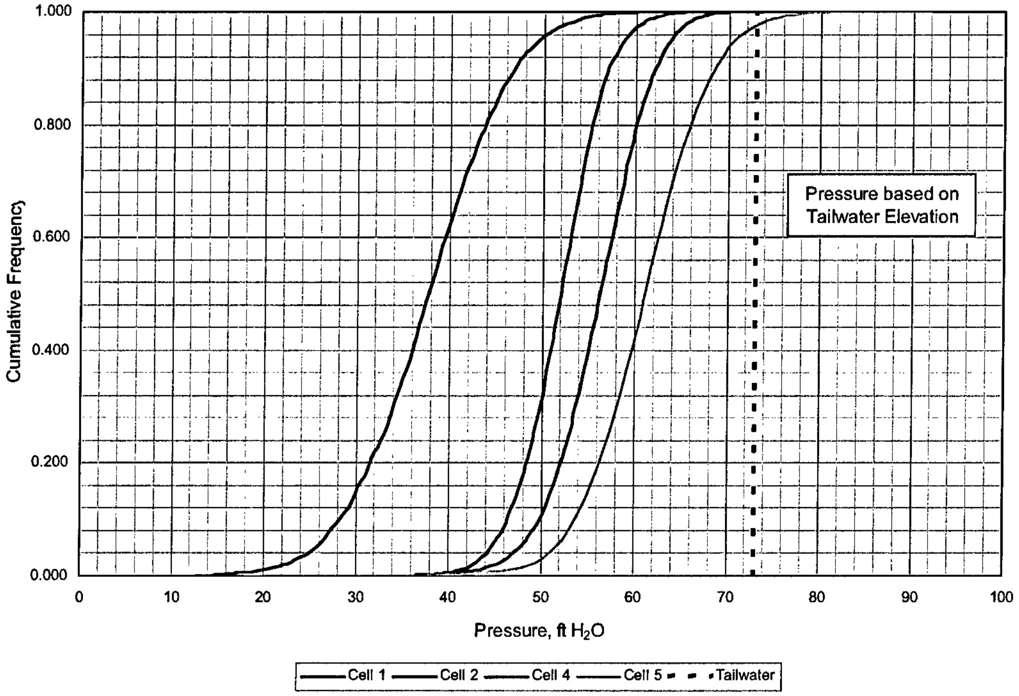
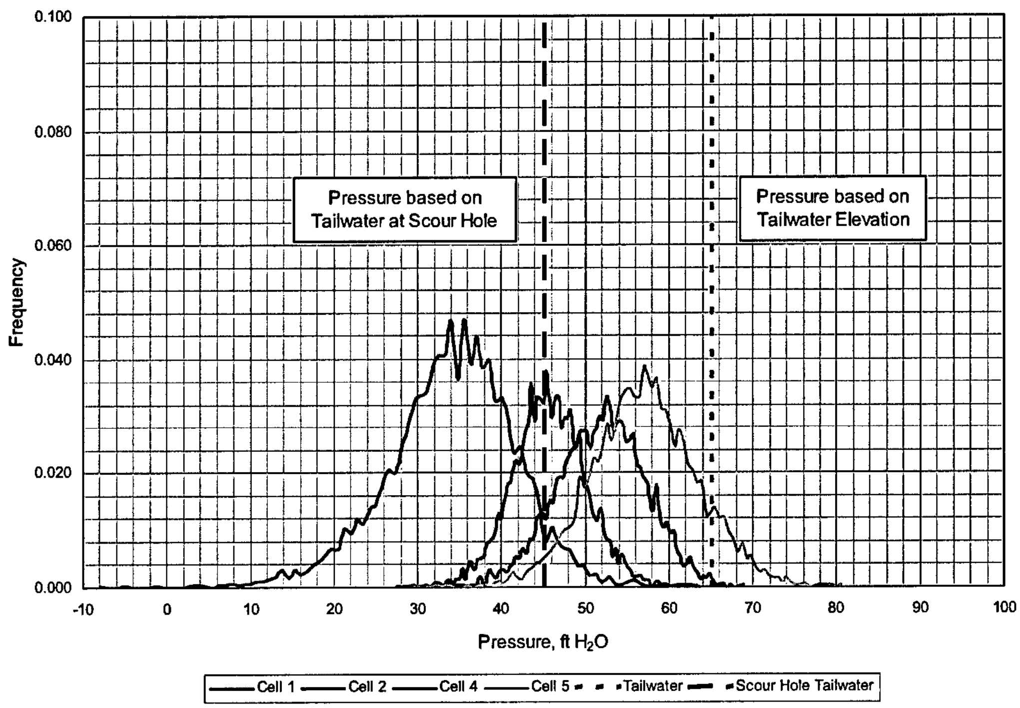


Figure H37. Lower Monumental stilling basin pressure investigation. 50 kcfs per bay, gate opening = 23.0, pool el. = 539.0, TW el = 465.0, end gate opened, no deflector on end bay, year 2000 scour hole



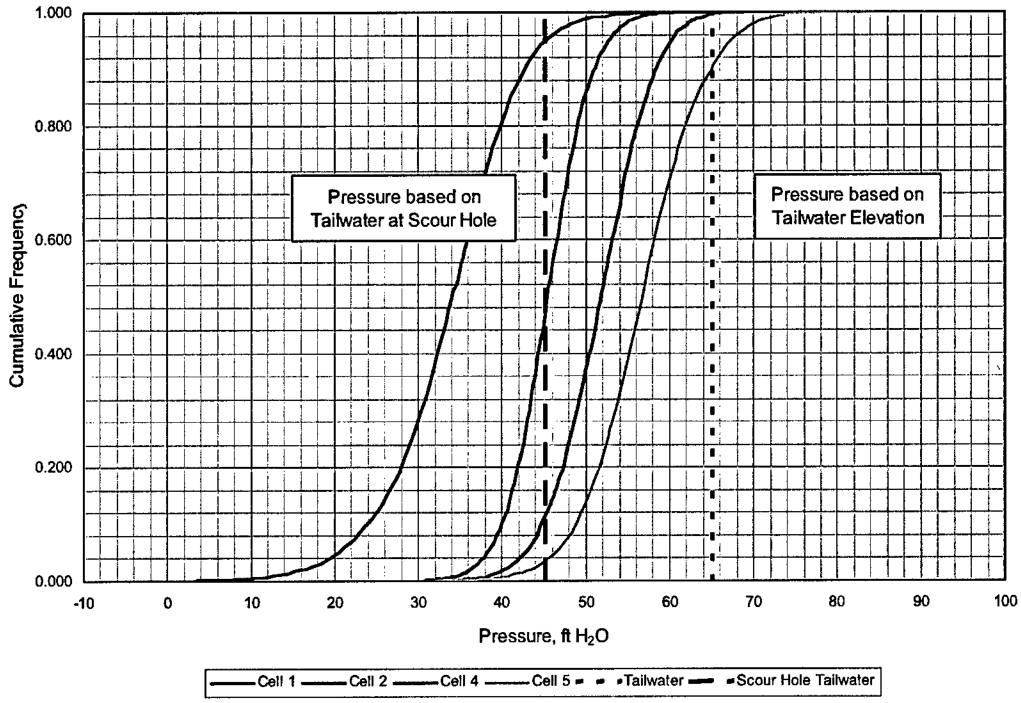
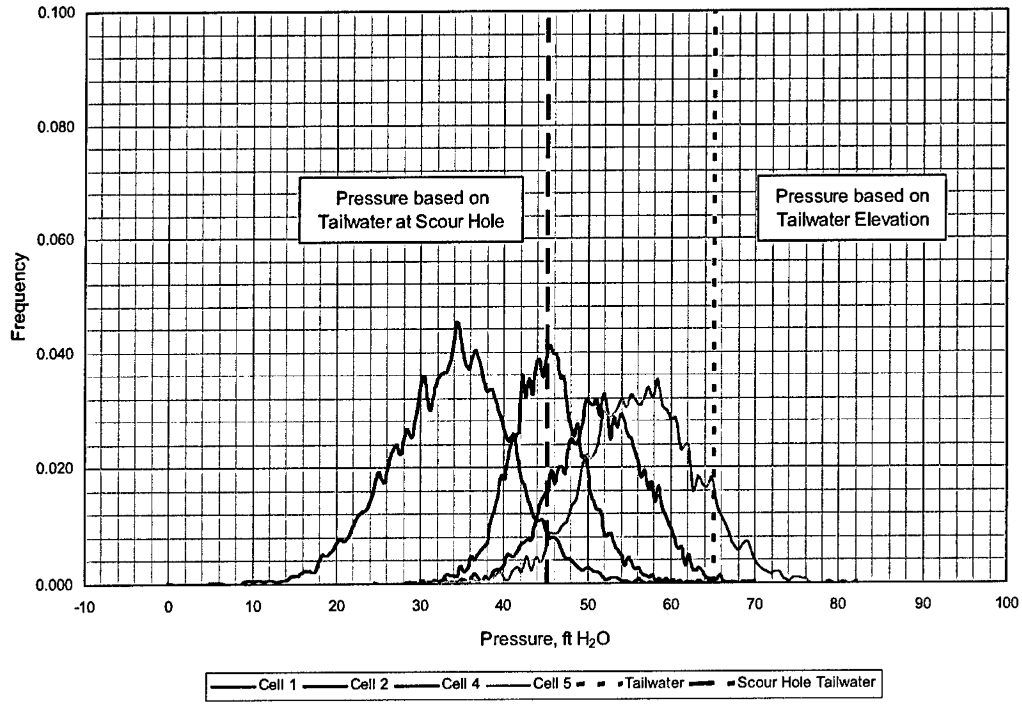


Figure H38. Lower Monumental stilling basin pressure investigation. 50 kcfs per bay, gate opening = 23.0, pool el. = 539.0, TW el = 457.0, end gate opened, no deflector on end bay, year 2000 scour hole



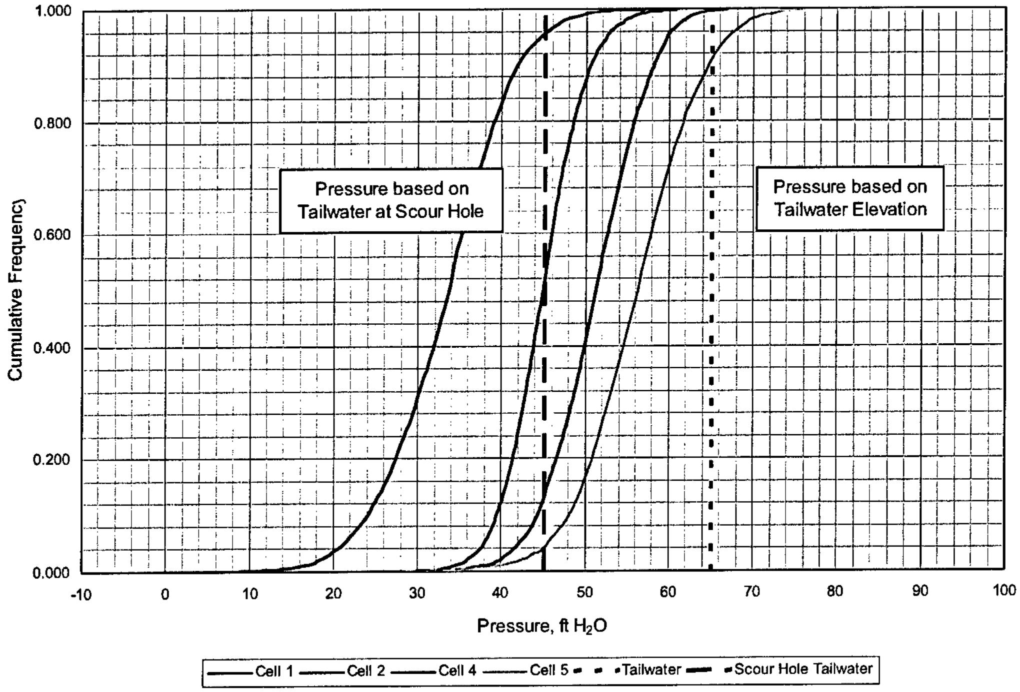
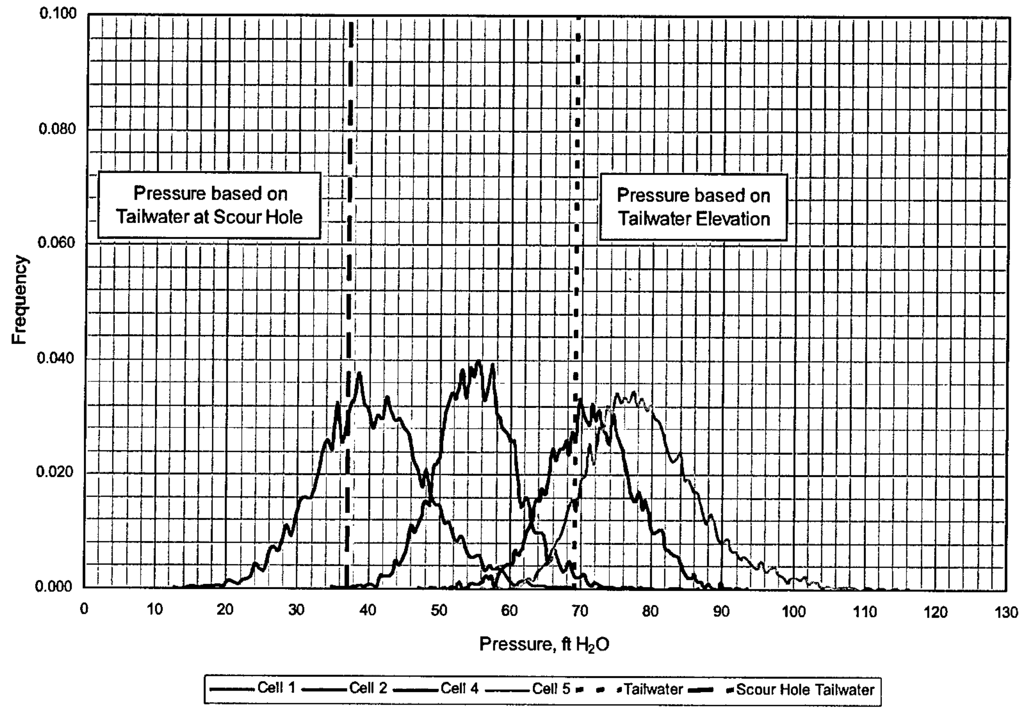


Figure H39. Lower Monumental stilling basin pressure investigation. 50 kcfs per bay, gate opening = 23.0, pool el. = 539.0, TW el = 457.0, end gate opened, no deflector on end bay, year 2000 scour hole



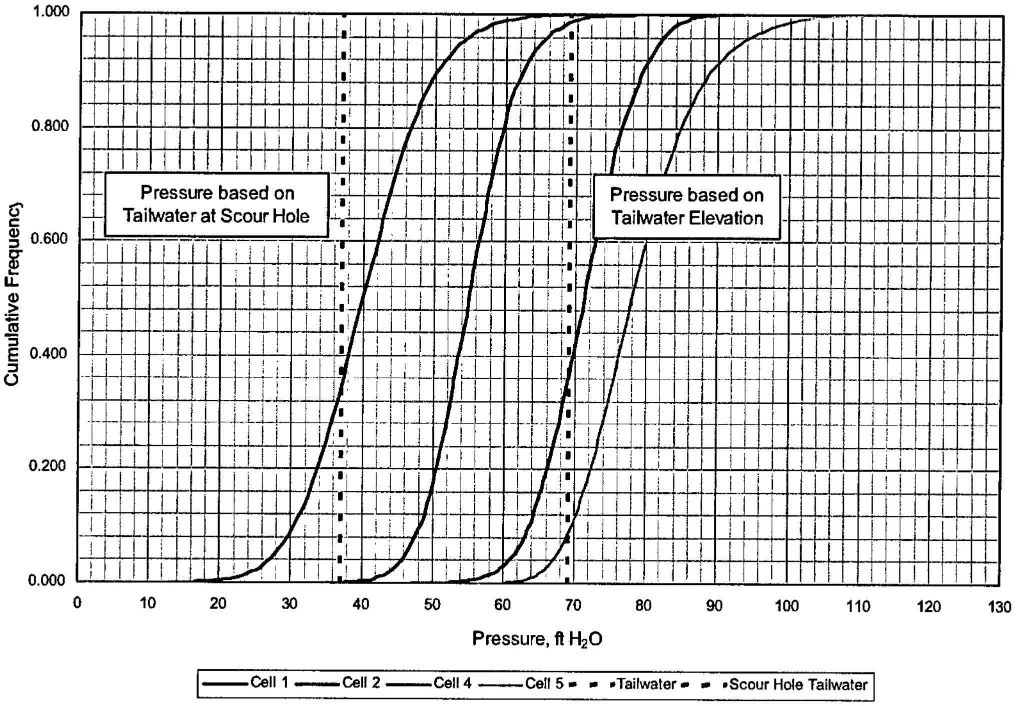
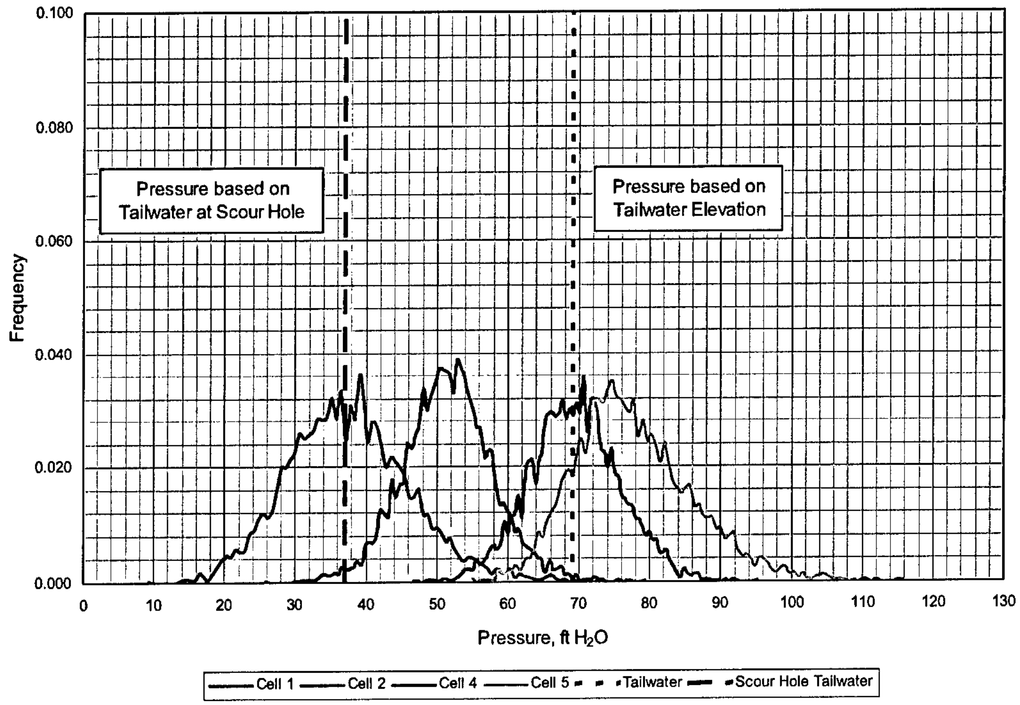


Figure H40. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 540.0, TW el = 461.0, TW at scour hole = 429.0, end gate open, no deflector on end bay, year 2000 scour hole



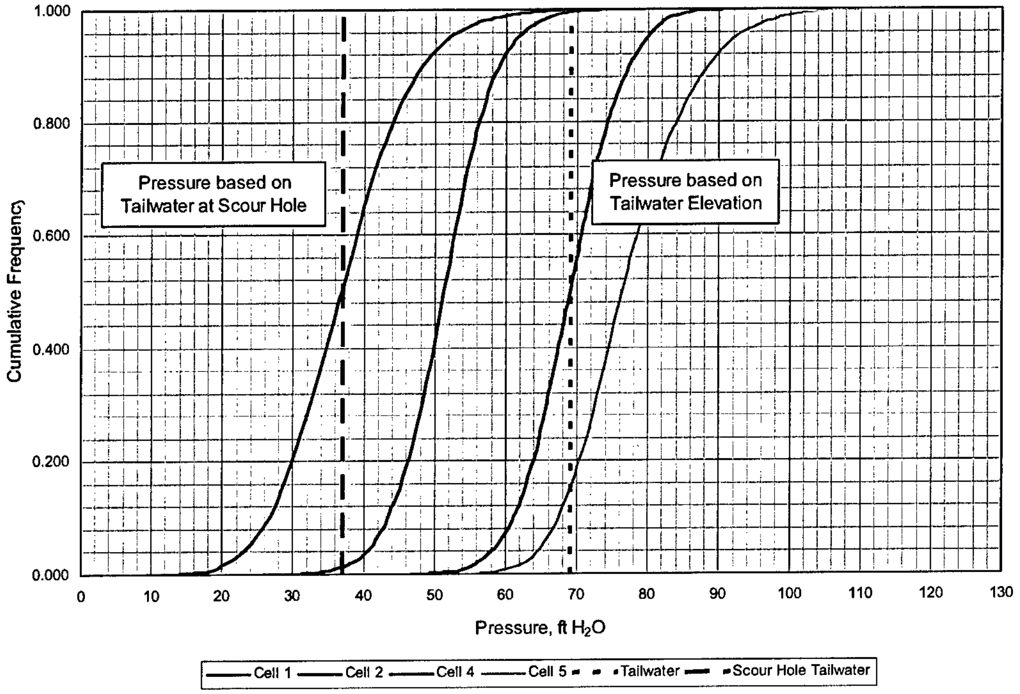
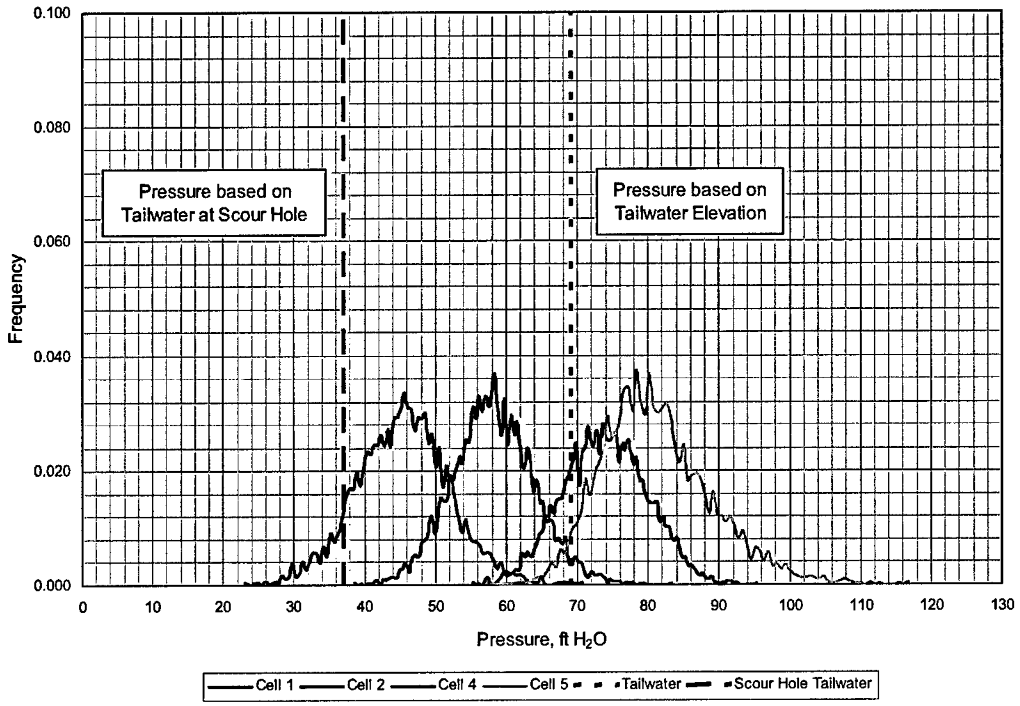


Figure H41. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 540.0, TW el = 461.0, TW at scour hole = 429.0, end gate open, no deflector on end bay, year 2000 scour hole



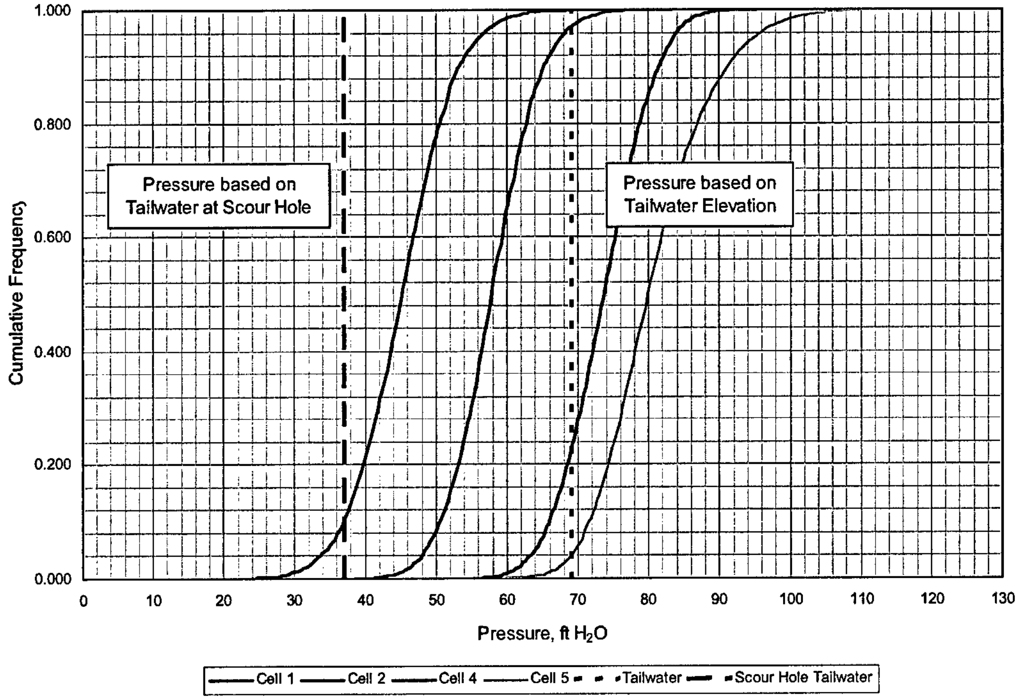
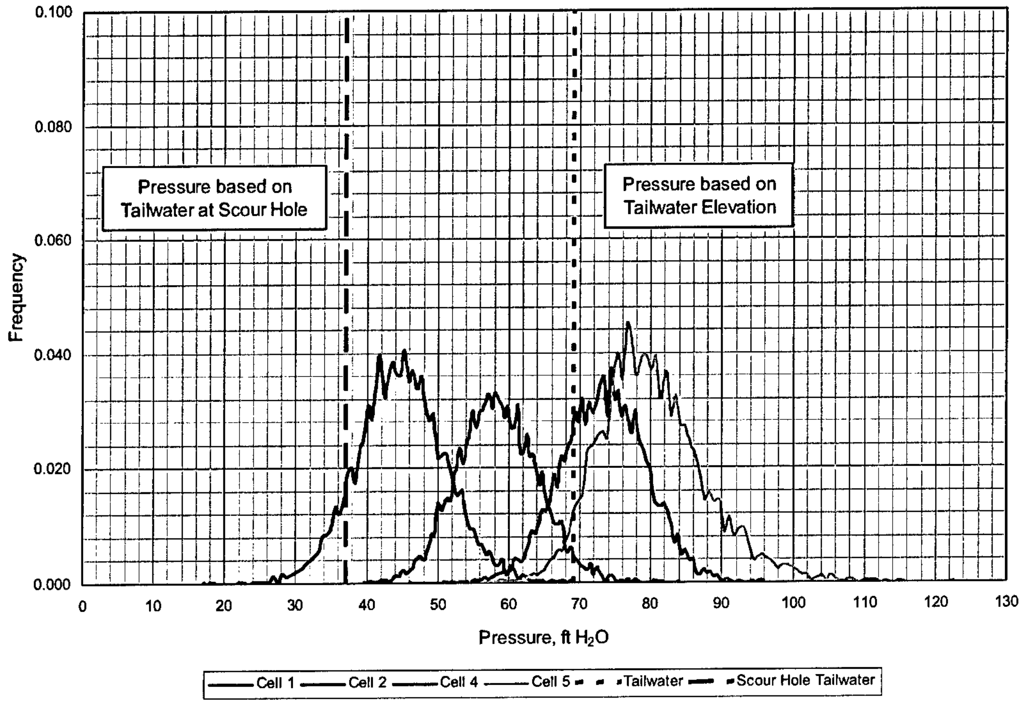


Figure H42. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 540.0, TW el = 461.0, TW at scour hole = 429.0, end gate open, no deflector on end bay, year 2000 scour hole



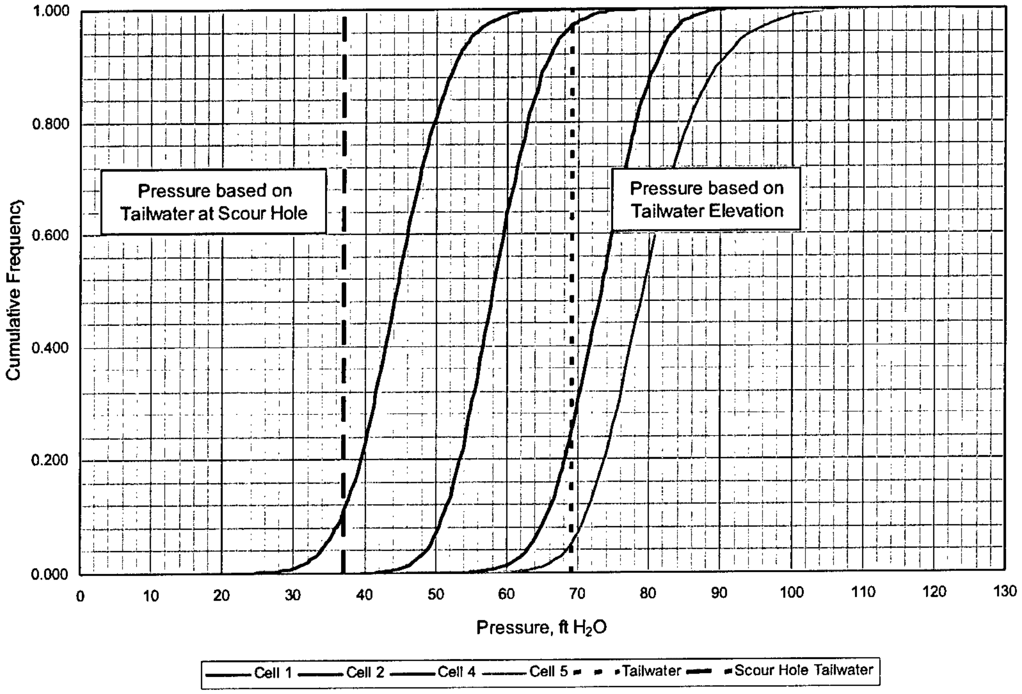
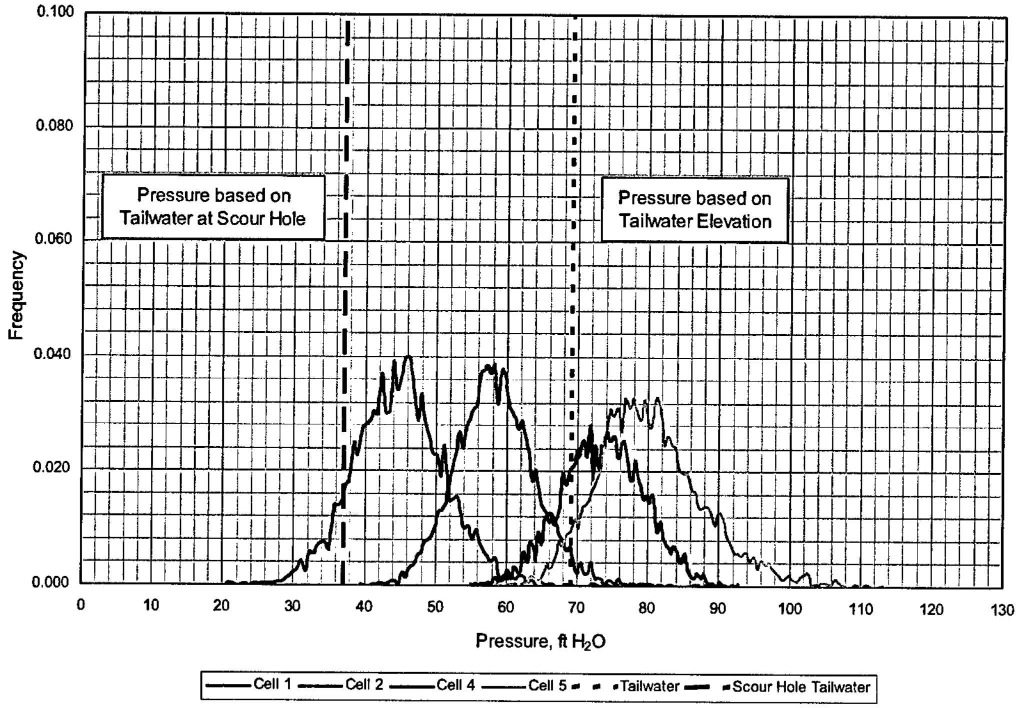


Figure H43. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 540.0, TW el = 461.0, TW at scour hole = 429.0, end gate open, no deflector on end bay, year 2000 scour hole



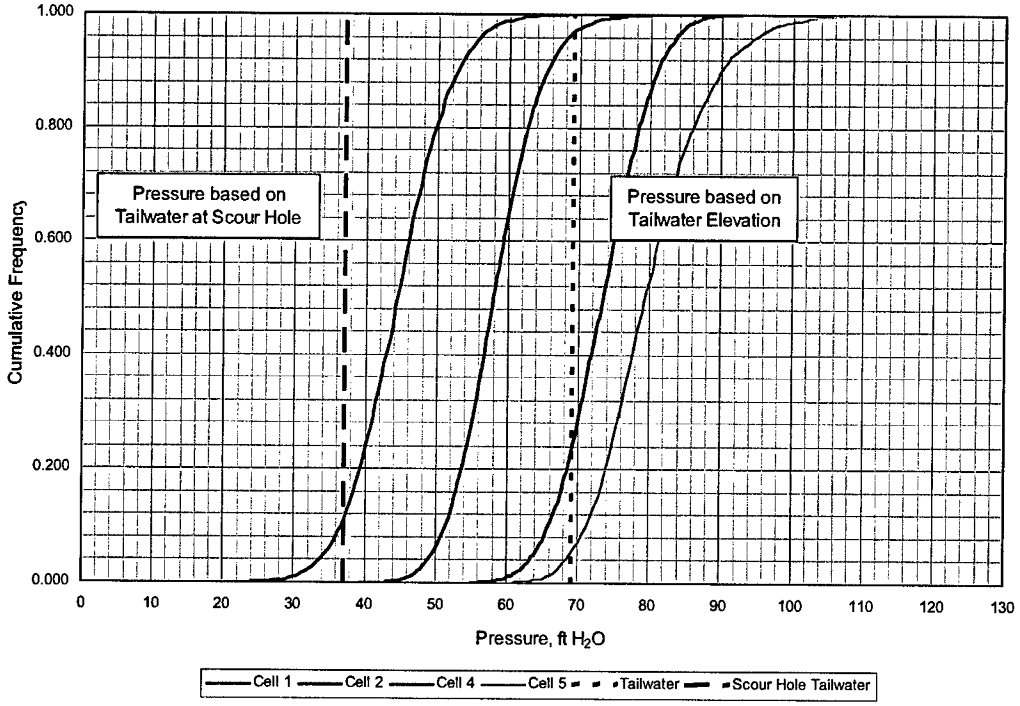
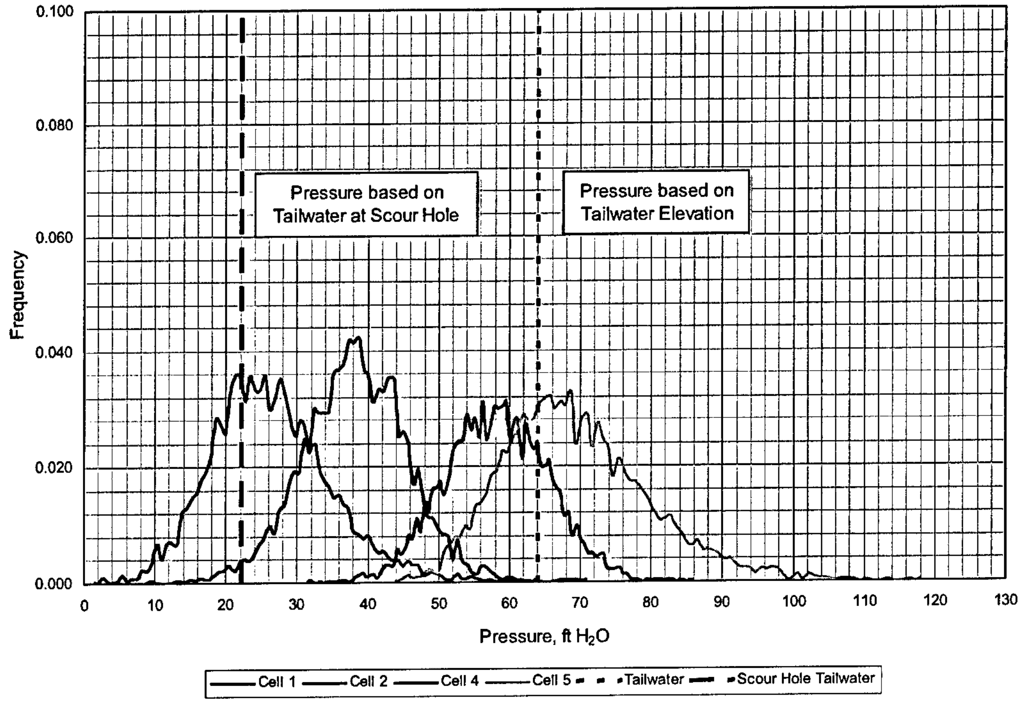


Figure H44. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 540.0, TW el = 461.0, TW at scour hole = 429.0, end gate open, no deflector on end bay, year 2000 scour hole



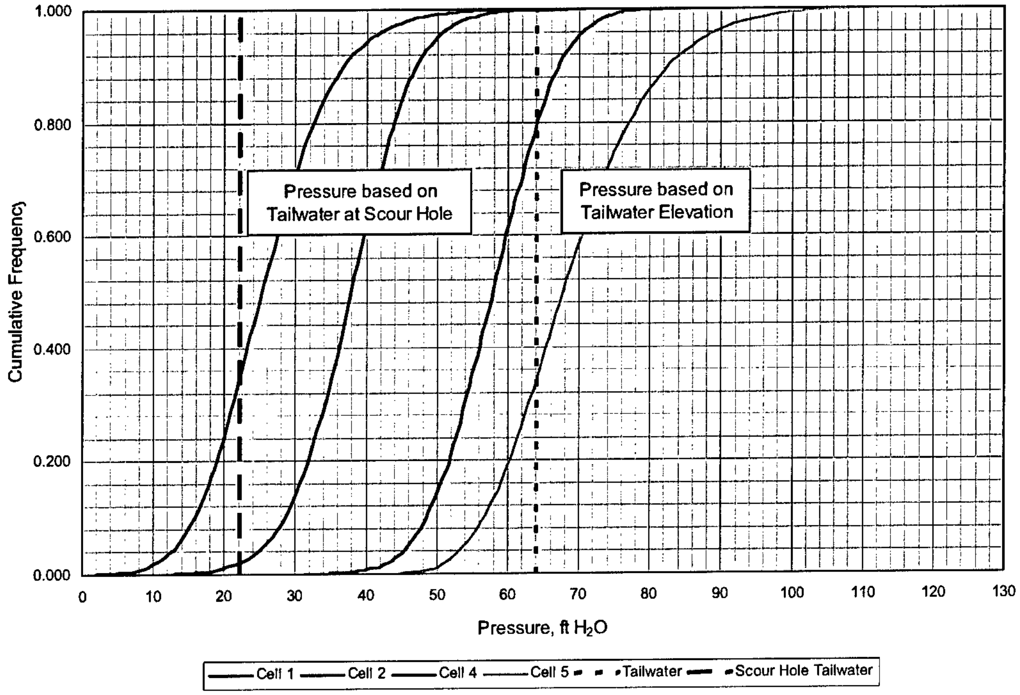
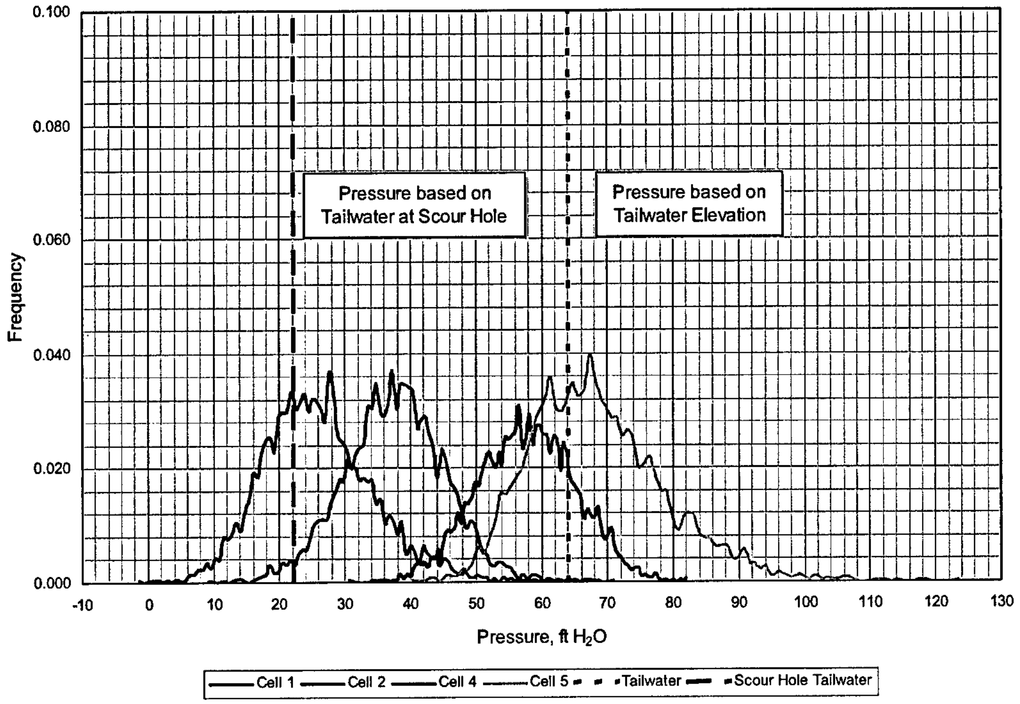


Figure H45. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 540.0, TW el = 456.0, TW at scour hole = 414.0, end gate open, no deflector on end bay, year 2000 scour hole



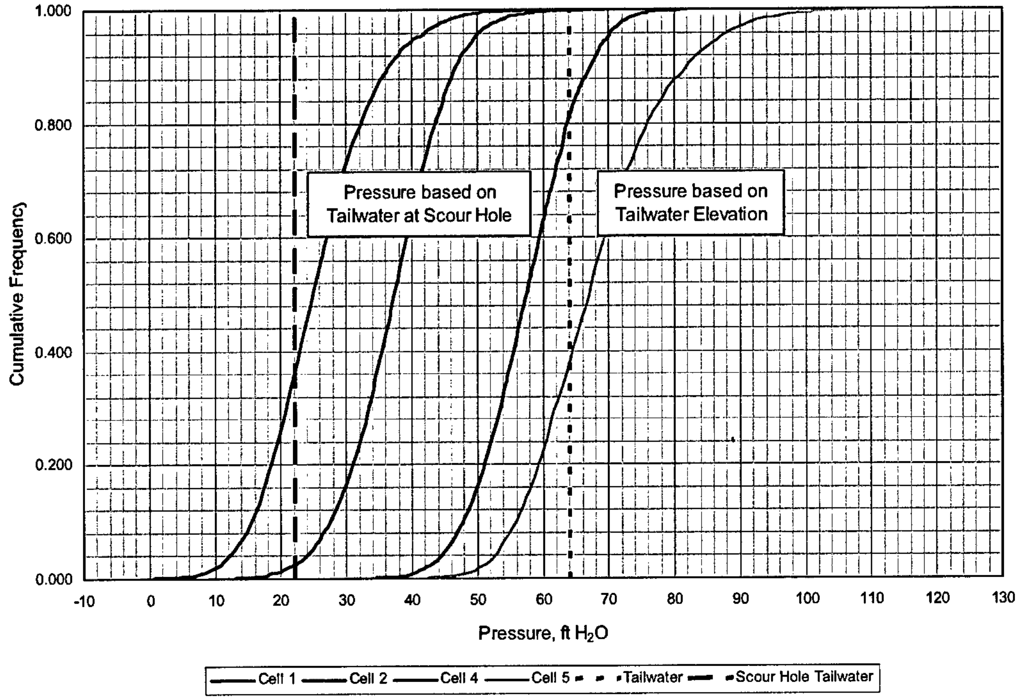
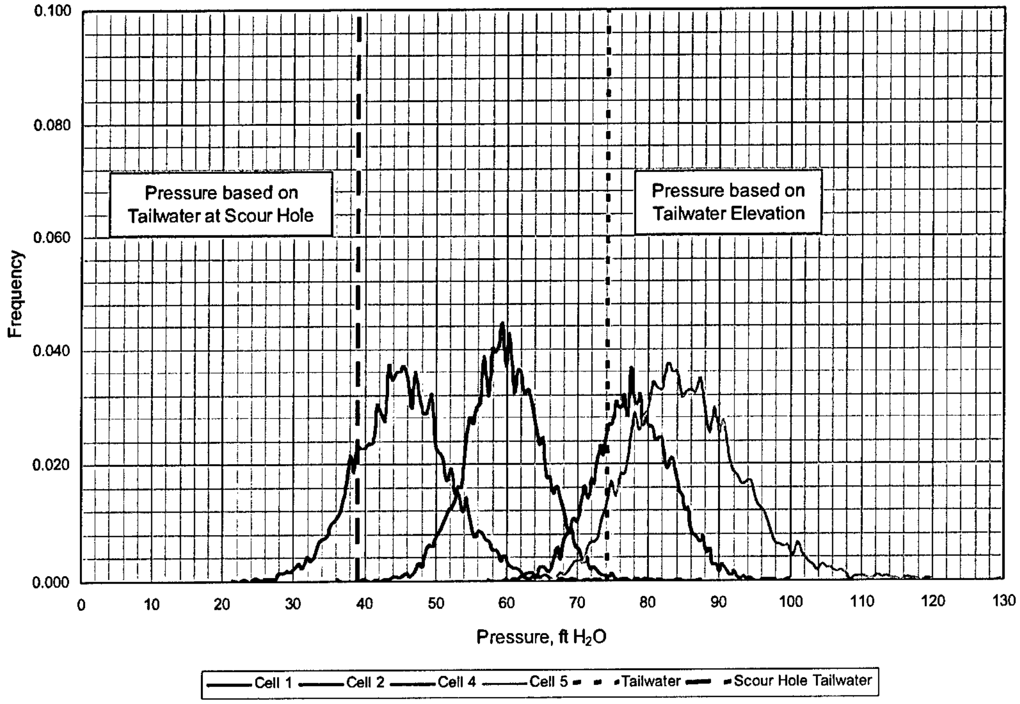


Figure H46. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 540.0, TW el = 456.0, TW at scour hole = 414.0, end gate open, no deflector on end bay, year 2000 scour hole



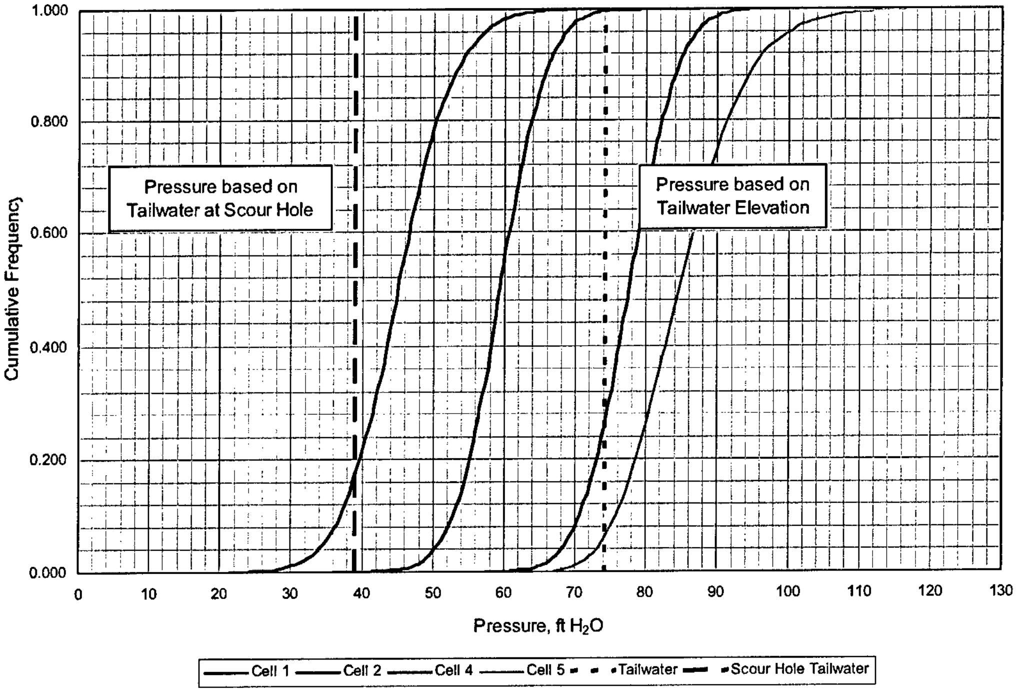
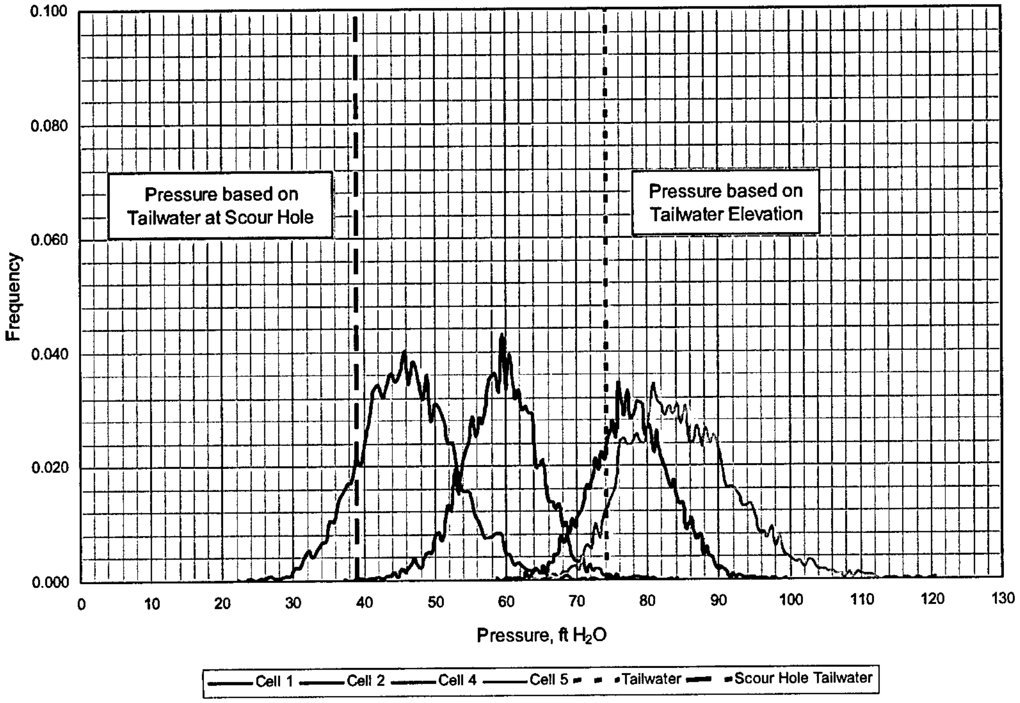


Figure H47. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 544.0, TW el = 466.0, TW at scour hole = 431.0, end gate open, no deflector on end bay, year 2000 scour hole



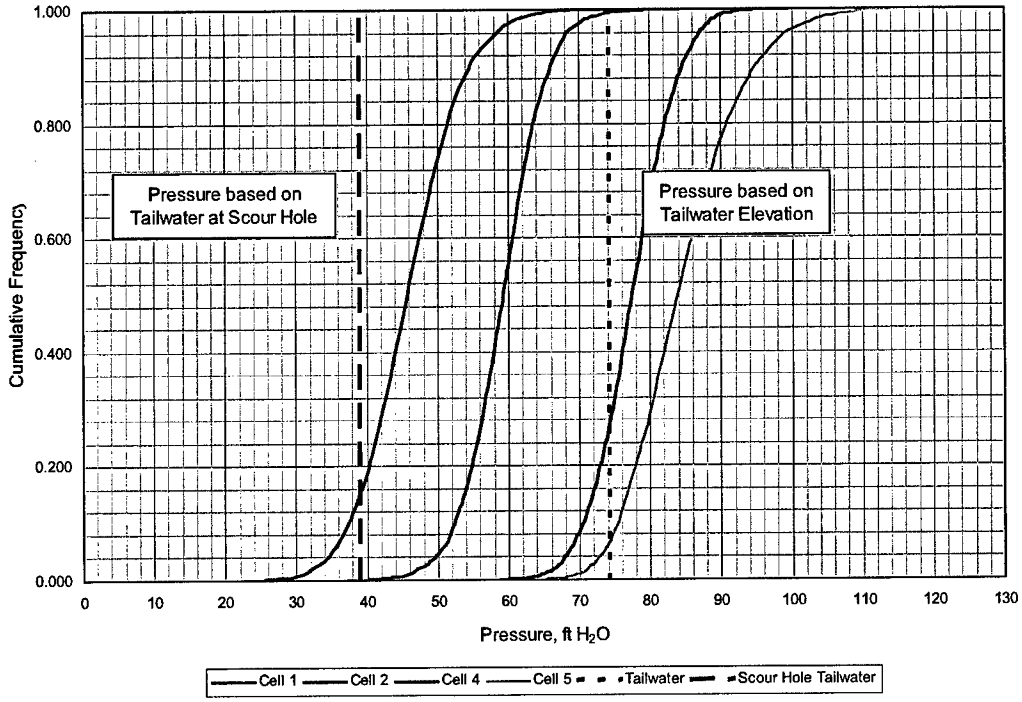


Figure H48. Lower Monumental stilling basin pressure investigation. 84 kcfs per bay, full gate opening, pool el. = 544.0, TW el = 466.0, TW at scour hole = 431.0, end gate open, no deflector on end bay, year 2000 scour hole

Appendix I
Summary of Stilling Basin Pressure Data

Table I1
Pressure Measurements along Center Line of Bay 2

Gate Opening ft	Discharge kcfs/bay	Pool Elevation ft	Tailwater Elevation ft	Cell No.	Minimum Pressure ft-H_2O	Average Pressure ft-H_2O	Maximum Pressure ft-H_2O	Standard Deviation ft-H_2O	80-Percent Exceedence ft-H_2O
6.5	29.0	537.0	451.0	1	21.02	31.62	45.08	2.98	33.90
				2	29.74	42.31	74.15	4.13	45.10
				3	25.66	44.77	73.74	4.70	48.00
				4	37.06	49.54	65.60	3.43	52.00
				5	30.88	40.11	52.79	2.59	42.00
6.5	29.0	537.0	451.0	1	18.14	28.38	41.49	2.87	30.60
				2	27.06	39.18	76.71	3.80	41.70
				3	25.99	42.32	68.70	4.85	45.80
				4	31.70	47.08	64.44	3.40	49.50
				5	27.06	37.77	51.35	2.44	39.60
6.5	29.0	537.0	451.0	1	20.54	30.82	43.38	2.84	33.00
				2	28.31	39.97	57.11	3.01	42.30
				3	26.78	41.59	60.84	3.46	44.00
				4	32.93	47.82	73.11	3.20	50.00
				5	27.08	39.78	52.57	2.75	41.70
6.5	29.0	537.0	451.0	1	18.28	30.08	42.33	2.74	32.30
				2	26.00	39.52	56.31	2.91	41.60
				3	25.79	41.30	57.97	3.28	43.60
				4	29.27	47.14	60.97	3.02	49.40
				5	28.71	38.51	47.49	2.59	40.40
3.5	6.5	537.0	441.0	1	29.42	32.37	36.84	1.13	33.20
				2	34.94	38.57	43.36	0.98	39.30
				3	33.46	36.54	40.98	1.07	37.30
				4	36.81	39.48	43.32	0.88	40.20
				5	30.37	33.31	37.78	0.92	34.00
3.5	6.5	537.0	441.0	1	29.31	32.67	38.85	1.40	34.00
				2	35.41	38.50	41.97	0.95	39.20
				3	33.28	36.67	40.40	0.99	37.40
				4	36.35	39.56	43.84	0.92	40.30
				5	30.24	33.26	37.39	0.89	34.00
3.5	6.5	537.0	441.0	1	28.37	32.26	38.09	1.40	33.40
				2	34.79	36.67	40.48	0.75	37.30
				3	33.09	35.25	39.33	0.74	35.70
				4	35.70	38.52	41.64	0.70	39.10
				5	29.14	31.45	34.88	0.76	32.00
3.5	6.5	537.0	441.0	1	28.14	31.80	36.96	1.34	32.90
				2	33.92	36.60	40.89	1.03	37.40
				3	32.50	35.06	39.13	0.95	36.00
				4	35.85	38.02	41.24	0.77	38.60
				5	28.05	30.80	35.89	0.85	31.50

(Sheet 1 of 3)

Table I1 (Continued)

Gate Opening ft	Discharge kcfs/bay	Pool Elevation ft	Tailwater Elevation ft	Cell No.	Minimum Pressure ft-H_2O	Average Pressure ft-H_2O	Maximum Pressure ft-H_2O	Standard Deviation ft-H_2O	80-Percent Exceedence ft-H_2O
16.5	29.0	537.0	451.0	1	5.45	30.08	73.85	5.01	33.10
				2	17.02	37.20	62.47	4.53	40.00
				3	17.02	36.84	58.02	3.71	39.40
				4	22.16	38.36	55.62	3.21	40.70
				5	19.25	31.44	49.11	3.47	34.00
16.5	29.0	537.0	451.0	1	9.91	29.35	59.09	4.66	31.80
				2	19.32	36.21	64.70	4.23	38.60
				3	18.05	36.25	58.20	3.80	38.70
				4	19.70	38.35	58.44	3.51	40.80
				5	14.62	31.09	47.87	4.10	34.40
16.5	29.0	537.0	454.0	1	12.30	36.14	58.74	4.26	38.50
				2	26.11	42.19	61.95	3.24	44.50
				3	21.85	41.70	57.14	3.10	43.90
				4	29.36	43.18	55.49	2.82	45.40
				5	24.10	35.97	45.63	2.88	38.20
16.5	29.0	537.0	454.0	1	41.44	63.10	84.47	4.03	65.70
				2	26.07	42.60	63.39	3.33	44.90
				3	28.34	42.04	58.42	3.04	44.10
				4	29.22	43.22	56.93	2.91	45.40
				5	25.71	36.14	46.84	3.12	38.50
20.0	34.0	540.0	451.0	1	8.88	26.59	56.46	4.33	29.60
				2	19.88	45.38	97.28	8.87	51.20
				3	26.45	50.22	78.91	7.63	56.10
				4	29.23	42.47	61.62	4.29	45.60
				5	26.50	38.19	49.41	2.66	40.10
20.0	34.0	540.0	451.0	1	7.92	25.85	54.93	4.06	28.80
				2	14.28	45.87	90.06	9.33	52.50
				3	28.78	50.98	81.75	7.85	57.10
				4	27.20	42.25	60.17	4.33	45.50
				5	26.68	37.95	51.95	2.61	39.90
20.0	34.0	540.0	455.0	1	14.56	34.51	78.70	7.13	38.60
				2	25.89	50.41	86.79	8.38	56.70
				3	33.20	52.72	86.12	5.66	56.70
				4	36.20	48.75	64.24	3.42	51.20
				5	35.45	47.47	56.92	2.39	49.30
20.0	34.0	540.0	455.0	1	16.24	34.61	85.00	7.53	38.60
				2	22.57	50.53	95.30	8.26	56.40
				3	32.40	52.72	79.55	5.48	57.10
				4	34.33	48.45	64.02	3.43	50.80
				5	36.79	47.39	59.18	2.41	49.20

(Sheet 2 of 3)

Table I1 (Concluded)

Gate Opening ft	Discharge kcfs/bay	Pool Elevation ft	Tailwater Elevation ft	Cell No.	Minimum Pressure ft-H_2O	Average Pressure ft-H_2O	Maximum Pressure ft-H_2O	Standard Deviation ft-H_2O	80-Percent Exceedence ft-H_2O
20.0	34.0	540.0	459.0	1	24.22	36.61	59.87	3.24	39.00
				2	30.11	46.29	69.49	3.52	48.80
				3	35.58	51.70	69.87	3.81	54.60
				4	34.91	52.82	67.48	3.32	55.30
				5	42.46	53.81	68.86	2.79	55.80
20.0	34.0	540.0	459.0	1	24.86	36.27	51.28	3.07	38.50
				2	35.48	46.01	62.89	3.22	48.50
				3	36.12	51.50	70.02	3.67	54.30
				4	38.59	52.88	68.81	3.05	55.10
				5	37.60	53.85	64.16	2.82	55.80
20.0	34.0	540.0	463.0	1	34.52	44.54	58.78	2.94	44.63
				2	36.00	50.59	67.00	2.88	50.67
				3	40.60	56.58	70.16	3.14	56.67
				4	45.07	58.43	71.99	2.97	58.51
				5	47.34	62.75	72.95	2.61	62.80
20.0	34.0	540.0	463.0	1	32.57	44.35	55.16	2.97	46.69
				2	38.71	50.74	62.76	2.94	53.02
				3	43.28	56.76	71.69	3.27	59.33
				4	44.19	58.77	72.02	2.80	60.75
				5	50.85	63.21	75.42	2.63	65.22
20.0	34.0	540.0	468.0	1	42.24	52.14	66.57	2.71	54.04
				2	47.50	57.95	73.64	2.90	60.17
				3	43.46	63.51	81.68	3.03	65.82
				4	54.13	65.00	78.10	2.55	66.95
				5	56.85	69.22	78.07	2.50	71.17
20.0	34.0	540.0	468.0	1	41.72	51.82	62.22	2.63	53.92
				2	46.97	57.28	71.28	2.99	59.73
				3	44.35	62.88	74.72	3.18	65.46
				4	51.49	64.56	75.46	2.85	66.71
				5	55.40	68.57	79.26	2.64	70.55
20.0	34.0	540.0	447.0	1	7.99	22.88	52.08	3.88	25.40
				2	15.64	42.91	95.72	9.90	49.70
				3	24.70	54.66	89.88	9.49	62.20
				4	26.74	44.04	60.66	4.78	47.90
				5	29.00	41.10	53.58	2.96	43.40
20.0	34.0	540.0	447.0	1	4.02	21.98	41.51	3.26	24.10
				2	14.49	41.70	103.23	9.94	47.80
				3	23.13	54.38	90.52	9.26	61.90
				4	23.75	42.89	69.57	5.00	46.90
				5	26.65	40.10	53.16	3.22	42.70

(Sheet 3 of 3)

Table I2
Pressure Measurements along Center Line of Year 2000 Scour Hole

Gate Opening, ft	Discharge, kcfs/bay	Pool Elevation, ft	Tailwater Elevation, ft	Cell No.	Minimum Pressure, ft-H_2O	Average Pressure, ft-H_2O	Maximum Pressure, ft-H_2O	Standard Deviation, ft-H_2O	80-Percent Exceedence, ft-H_2O
16.5	29.0	537.0	451.0	1	-12.2	21.8	46.5	7.4	28.0
				2	15.9	41.1	60.3	5.6	45.5
				4	24.2	40.5	56.2	4.3	43.8
				5	16.3	49.3	74.9	6.6	54.1
16.5	29.0	537.0	451.0	1	-9.1	22.6	54.7	7.3	28.2
				2	14.8	40.9	57.6	5.4	45.4
				4	25.0	40.6	64.0	4.2	43.9
				5	14.2	48.8	70.8	6.3	54.1
16.5	29.0	537.0	451.0	1	18.3	33.2	47.2	3.5	36.1
				2	22.0	35.6	51.2	3.4	38.2
				4	12.1	35.7	52.7	3.9	38.7
				5	26.5	38.6	54.3	3.5	41.3
16.5	29.0	537.0	451.0	1	22.9	33.8	52.2	3.6	36.5
				2	24.9	36.5	57.7	3.7	39.5
				4	19.1	37.7	50.6	4.5	41.3
				5	27.1	39.9	55.2	3.7	43.0
16.5	29.0	537.0	451.0	1	24.2	34.6	52.1	3.0	36.9
				2	28.8	40.4	52.3	3.1	42.8
				4	17.8	37.8	49.8	4.1	41.3
				5	25.7	38.7	49.9	3.5	41.8
3.5	6.5	537.0	441.0	1	31.0	35.7	40.4	1.5	37.0
				2	37.5	41.4	46.3	1.3	42.5
				4	36.3	39.7	44.0	1.1	40.6
				5	36.3	40.4	44.2	1.3	41.5
3.5	6.5	537.0	441.0	1	30.9	35.7	40.1	1.4	36.9
				2	36.2	41.4	47.9	1.4	42.5
				4	36.2	39.6	43.9	1.1	40.5
				5	35.8	40.2	45.2	1.3	41.3
3.5	6.5	537.0	441.0	1	29.2	33.6	39.3	1.5	34.8
				2	35.5	40.0	44.4	1.2	41.0
				4	34.7	38.5	41.8	1.0	39.3
				5	33.2	38.0	42.6	1.5	39.3
3.5	6.5	537.0	441.0	1	28.5	33.0	39.4	1.5	34.3
				2	35.6	39.7	44.0	1.2	40.7
				4	34.1	38.2	41.8	1.1	39.0
				5	31.8	37.6	42.2	1.5	38.9
23.0	50.0	539.0	462.0	1	-5.8	33.2	62.9	8.0	39.2
				2	27.3	53.6	70.4	5.5	58.1
				4	28.0	48.6	66.9	4.5	51.9
				5	27.6	59.7	85.4	6.5	64.9

(Sheet 1 of 3)

Table I2 (Continued)

Gate Opening ft	Discharge kcfs/bay	Pool Elevation ft	Tailwater Elevation ft	Cell No.	Minimum Pressure ft-H_2O	Average Pressure ft-H_2O	Maximum Pressure ft-H_2O	Standard Deviation ft-H_2O	80-Percent Exceedence ft-H_2O
23.0	50.0	539.0	462.0	1	5.1	33.2	68.4	7.9	39.0
				2	28.6	52.9	71.7	5.4	57.2
				4	29.2	48.6	65.7	4.5	52.0
				5	26.3	58.8	84.3	6.5	63.7
23.0	50.0	539.0	465.0	1	-2.2	37.1	64.6	7.0	42.3
				2	30.5	55.8	71.8	5.0	59.6
				4	33.2	51.9	70.5	4.5	55.4
				5	33.6	61.0	82.4	6.1	66.1
23.0	50.0	539.0	465.0	1	12.4	38.0	71.9	7.3	43.7
				2	30.2	56.3	74.0	4.9	60.2
				4	29.7	52.1	73.1	4.3	55.5
				5	17.8	61.4	92.2	6.0	65.8
23.0	50.0	539.0	457.0	1	24.2	34.6	52.1	3.0	40.0
				2	28.8	40.4	52.3	3.1	56.1
				4	17.8	37.8	49.8	4.1	49.0
				5	25.7	38.7	49.9	3.5	61.7
23.0	50.0	539.0	457.0	1	-8.3	34.1	66.6	7.7	39.2
				2	29.3	51.9	69.1	5.3	56.0
				4	27.6	45.7	63.5	4.4	48.7
				5	27.2	57.0	80.7	6.4	61.6
Full	84.0	540.0	461.0	1	34.6	55.4	86.9	5.8	59.5
				2	46.9	71.5	93.8	6.1	76.2
				4	12.4	40.6	75.7	7.9	46.9
				5	55.7	79.1	116.5	7.8	84.6
Full	84.0	540.0	461.0	1	25.6	51.6	79.6	6.3	56.1
				2	46.5	69.4	95.3	6.4	74.6
				4	9.0	37.5	73.5	8.6	44.2
				5	54.8	77.6	116.0	8.3	83.9
Full	84.0	540.0	466.0	1	38.3	58.1	83.4	5.8	62.9
				2	55.1	73.9	95.6	5.9	78.8
				4	22.8	45.4	70.9	6.6	50.5
				5	57.1	81.0	117.0	7.7	86.8
Full	84.0	540.0	466.0	1	39.5	58.4	84.3	5.7	63.0
				2	45.9	73.4	96.3	5.9	78.4
				4	16.9	44.9	74.4	6.3	50.0
				5	54.4	80.3	123.0	7.5	85.6
Full	84.0	540.0	466.0	1	39.2	58.4	88.5	5.6	62.6
				2	54.7	73.5	93.0	5.8	78.2
				4	20.3	44.8	76.1	6.4	49.6
				5	58.3	80.3	113.4	7.5	86.1

(Sheet 2 of 3)

Table I2 (Concluded)

Gate Opening ft	Discharge kcfs/bay	Pool Elevation ft	Tailwater Elevation ft	Cell No.	Minimum Pressure ft-H_2O	Average Pressure ft-H_2O	Maximum Pressure ft-H_2O	Standard Deviation ft-H_2O	80-Percent Exceedence ft-H_2O
Full	84.0	540.0	456.0	1	1.3	38.2	71.2	7.5	43.6
				2	31.2	58.2	86.2	7.3	63.9
				4	-6.1	26.3	63.4	8.5	32.5
				5	43.7	69.3	118.2	10.3	76.9
Full	84.0	540.0	456.0	1	9.0	37.6	71.2	7.7	43.5
				2	30.4	57.7	82.3	7.4	63.9
				4	-1.7	25.9	62.9	8.4	32.2
				5	40.0	68.4	123.8	10.3	75.6
Full	84.0	540.0	466.0	1	35.9	59.7	87.5	5.3	64.0
				2	57.1	77.8	99.9	5.5	82.2
				4	21.2	45.4	75.9	6.7	50.4
				5	63.9	85.6	129.8	7.9	91.2
Full	84.0	540.0	466.0	1	37.0	59.4	84.4	5.5	63.2
				2	58.5	77.7	99.6	5.5	82.1
				4	21.9	46.2	83.7	6.8	51.3
				5	63.1	84.9	120.8	7.8	90.5

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13. SUPPLEMENTARY NOTES
Eleven AVI files are linked to the electronic version of this report showing video images of Lower Monumental gate openings. The electronic version can be found at *http://libweb.wes.army.mil/uhtbin/hyperion/CHL-TR-03-13.pdf.*

14. ABSTRACT

A 1:40 Froudian Scale model was used to investigate the hydraulic performance of the Lower Monumental Dam spillway, stilling basin, and tailrace for dissolved gas reduction and stilling basin apron scour. The model reproduced a 2-1/2 bay section of the spillway and portion of the nonoverflow section between the spillway and navigation lock. Performance characteristics of two spillway deflectors were evaluated. The existing deflector (12.5 ft long horizontal with small fillet radius for transition from spillway to deflector) was recommended at el 434.0 because of its slightly wider tailwater range for operation in skimming flow. However, for fish passage over the deflector, the Type I deflector (12.5 ft horizontal with 15-ft radius transition) can likely be adopted with little degradation in dissolved gas uptake. Loadings on the deflector were estimated with pressure measurements on the horizontal and vertical faces. Instantaneous cavitation pressures were measured on the vertical face of the deflector due to flow separation. Only minor cavitation damage has been observed at other spillway deflectors, and thus, significant damage is not expected. Pressure measurements on the stilling basin flow show potential uplift pressure as high as 3,300 lb/ft^2. If these pressures have a pathway beneath the stilling basin apron, significant uplift force could result, ultimately causing a catastrophic failure of the apron. Debris was transported from the

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15. SUBJECT TERMS

Dissolved gas	Spillway and stilling basin	Stilling basin scour
Hydraulic model	Spillway deflectors	

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tailrace into the stilling basin for discharges above about 6.7 kcfs per spill bay (4.0-ft gate opening), when skimming flow occurred in the stilling basin. A numerical model of flow in the stilling basin showed a significant circulation cell on the stilling basin floor near the site of apron erosion, when operating the outside bay without a deflector. With a deflector on the outside bay, the circulation cell was nonexistent, indicating potential for significant reduction in apron scour. Experiments in the physical model verified the numerical model indications. Even with the outside bay deflector, some movement of debris in the stilling basin occurred. Thus, debris should be excluded from the stilling basin to completely eliminate apron scour. Several alternatives were investigating including armoring or grouting the tailrace to stabilize the debris, stilling basin wide debris trap, elevated end sill, and stilling basin splitter walls. Any alternative should be investigated in a general model.